A COMPREHENSIVE APPROACH OF GROUNDWATER VULNERABILITY AND POTENTIALITY ASSESSMENT OF MELAKA CATCHMENT IN MALAYSIA

MD. IMRAN HOSEN

FACULTY OF ENGINEERING
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ABSTRACT

The present work attempts to interpret the groundwater potentiality and vulnerability assessment of the Melaka catchment in Peninsular Malaysia. The study is also focused on the groundwater quality of the study area. Groundwater level and quality is deteriorating very fast in worldwide. Water demand is increasing day by day for the increasing population as well as for industrial and agricultural activities. In Malaysia, 97% surface water and 3% groundwater is used for different sectors. Therefore, groundwater can be used to meet the excessive demand of water in various purposes. Focusing on these issues, it is essential to rapid reconnaissance that allows assessing present groundwater condition and takes necessary actions to preserve this resource against pollution. To understand and identify the groundwater potentiality and quality;- geological, hydrogeological, geophysical, test drilling, pumping test and hydrochemical investigations are carried out. Three drilling methods namely;- Rotary Drilling with Water Circulation, Air Percussion Rotary and Air-Foam Rotary are used for this purposes. The DRASTIC method is used to assess groundwater vulnerability and risk together with Geographic Information System (GIS). The data correspond to the parameters of the methods are processed to generate the shape file and then converted into various thematic maps by ArcGIS software. The GIS is very important and effective tool for handling a large amount of geological and hydrogeological data within short time and minimal error.

Pumping test data are collected from 210 shallow and 17 deep boreholes to get well inventory information. Analysis of these data confirmed that the aquifers consisting of schist, sand, limestone as well as volcanic rocks are the most productive for groundwater in the State of Melaka. The term 'aquifer productivity' represents the potential of an aquifer to sustain various levels of borehole supply. The aquifer productivity map is classified into three categories namely;- high (>12m^3/h), moderate

(3.6-12 m^3/h) and low (<3.6 m^3/h) based on the discharge capacity. The groundwater potentiality of the study area is 35% low, 57% moderate and 8% high. Seven thematic maps defining;- depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity are generated and integrated to generate the final DRASTIC vulnerability map. The map is then overlaid on the additional land use map to generate the risk map, which method is called Modified DRASTIC method. Both methods have been validated using groundwater quality data. The vulnerability map are classified into three categories namely;- high (>159), moderate (120-159) and low (80-119). The DRASTIC vulnerability map shows that an area of 11.02% has low vulnerability, an area of 61.53% has moderate vulnerability and 23.45% of the area has high vulnerability in the Melaka State. On the other hand, risk map indicates that 14.40% of the area is low vulnerability (100-139), 47.34% moderate vulnerability (140-175) and 38.26% high vulnerability (>175) in the study area. The most vulnerability is seen around Melaka, Jasin and Alor Gajah City of Melaka. The 52 shallow and 14 deep borehole groundwater samples are analyzed for water quality. The analysis results indicate that groundwater quality is satisfactory for drinking and other purposes, however turbidity, total dissolved solids, iron, chloride and cadmium values are exceeded the limit of the drinking water quality standard in very few cases. The ranges of pH are 4 - 8.2 for shallow and 5.2 - 8.1 for deep boreholes. Therefore, groundwater in the State of Melaka can be used for drinking and other purposes, in which some major treatments are recommended in few cases.

ABSTRAK

Kajian ini mengkaji potensi air bawah tanah dan penilaian kelemahan tadahan Melaka di Semenanjung Malaysia. Kajian ini juga memberi tumpuan kepada kualiti air bawah tanah kawasan kajian. Paras air tanah dan kualiti merosot dengan sangat cepat di seluruh dunia. Permintaan air semakin meningkat hari demi hari kerana jumlah penduduk semakin meningkat serta untuk aktiviti perindustrian dan pertanian. Di Malaysia, 97% permukaan air dan air bawah tanah 3% digunakan untuk sektor yang berbeza. Oleh itu, air bawah tanah boleh digunakan untuk memenuhi permintaan air yang berlebihan dalam pelbagai tujuan. Memberi tumpuan kepada isu-isu ini, ia adalah penting untuk peninjauan pesat yang membolehkan penilaian keadaan air tanah sekarang dan mengambil tindakan yang perlu untuk memelihara sumber ini daripada pencemaran. Untuk memahami dan mengenal pasti potensi air bawah tanah dan kualiti; - geologi, hidrogeologi, geofizik, ujian penggerudian, ujian pengepaman dan siasatan hidrokimia dijalankan. Tiga kaedah penggerudian iaitu; - Penggerudian Rotary dengan Edaran Air, Udara Rebana Rotary dan Udara-Buih Rotary digunakan bagi tujuan ini. Kaedah drastik digunakan untuk menilai kelemahan air bawah tanah dan risiko bersama-sama dengan Sistem Maklumat Geografi (GIS). Data yang sesuai dengan parameter kaedah diproses untuk menjana fail bentuk dan kemudiannya ditukarkan ke dalam peta pelbagai tema oleh perisian ArcGIS. GIS adalah sangat penting dan alat yang berkesan untuk mengendalikan sejumlah besar data geologi dan hidrogeologi dalam masa yang singkat dan mengurangkan kesilapan.

Data ujian pengepaman dikumpul dari kecetekan 210 dan 17 lubang gerudi yang dalam untuk mendapatkan maklumat inventori yang baik. Analisis data ini mengesahkan bahawa akuifer yang terdiri daripada syis, pasir, batu kapur serta batu-batu gunung berapi yang paling produktif untuk air bawah tanah di Negeri Melaka. Istilah 'Produktiviti - akuifer' mewakili potensi akuifer untuk mengekalkan pelbagai peringkat bekalan lubang gerudi. Peta akuifer produktiviti diklasifikasikan kepada tiga kategori iaitu; tinggi (> 12m^3/h), sederhana (3.6 -12m^3/h) dan rendah (<3.6 m^3/h) berdasarkan kapasiti discaj. Potensi air bawah tanah kawasan kajian adalah 35% rendah, 57% sederhana dan 8% tinggi. Tujuh tema peta yang menentukan; - kedalaman aras air, aliran masuk bersih, media akuifer, media tanah, topografi, kesan zon vadose dan konduktiviti hidraulik dijana dan disepadukan untuk menjana peta kelemahan drastik akhir. Peta kemudian dilapisi peta guna tanah tambahan untuk menghasilkan peta risiko, kaedah yang dipanggil Modified kaedah drastik. Kedua-dua kaedah telah disahkan dengan menggunakan data kualiti air bawah tanah. Peta kelemahan dikelaskan kepada tiga kategori iaitu; tinggi (> 159), sederhana (120-159) dan rendah (80-119). Peta kelemahan drastik menunjukkan bahawa kawasan seluas 11.02% mempunyai kelemahan rendah, kawasan seluas 61.53% mempunyai kelemahan sederhana dan 23.45% daripada kawasan ini mempunyai kelemahan yang tinggi di Negeri Melaka. Sebaliknya, peta risiko menunjukkan bahawa 14.40% daripada keseluruhan kawasan adalah berkelemahan rendah (100-139), 47.34% berkelemahan sederhana (140-175) dan 38.26% yang berisiko tinggi (> 175) di kawasan kajian. Kelemahan yang paling ketara dilihat di sekitar Melaka, Jasin dan Alor Gajah Bandar Melaka. 52 dan 14 sampel air bawah tanah yang cetek dalam lubang gerudi dianalisis untuk kualiti air. Keputusan analisa menunjukkan bahawa kualiti air bawah tanah adalah memuaskan untuk diminum dan tujuan lain, bagaimanapun kekeruhan, jumlah pepejal terlarut, besi, klorida dan nilai kadmium melebihi had piawaian kualiti air minum dalam kes-kes yang sangat jarang. Julat pH adalah 4 – 8.2 untuk cetek dan 5.2 – 8.1 untuk lubang-lubang yang dalam. Oleh itu, air bawah tanah di Negeri Melaka boleh digunakan untuk minuman dan tujuan lain, di mana beberapa rawatan utama adalah disarankan di dalam beberapa kes.

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Md. Imran Hosen

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NOTATIONS

Notation	**Meaning**
A_r	Assigned ranges for critical parameter
AVI	Aquifer Vulnerability Index
AWHC	Available water holding capacity
CN	Curve number
C_p	Critical parameter
D_b	Diameter of basin
D_c	Discontinuity ranges
DEM	Digital Elevation Model
DI	DRASTIC Index
DISCO	DIScontinuities and protective COver parameter
E_p	Evaporation
EPIK	Epikarst, E; Protective cover, P; Infiltration conditions, I; and Karst network development, K
E_{rate}	Elution rate
F	Protection index
F_{int}	Intermediate protection factor
$\overline{F-FD}$	Rate of the average of the distance from the faults system (F) and the distance from the intersection locations between the faults and the drainage systems (FD)
Fm	Fracture Media
F_{ert}	Fertilizer input
GIS	Geographic Information System
GOD	Groundwater occurrence, G; Overall lithology of aquifer, O; and Depth of groundwater level, D

G_v	Groundwater vulnerability
H	Length of the well screen, namely the saturated thickness of the aquifer for full penetrating wells.
I_a	Initial abstraction
I_r	Weighted harmonic mean of vadose zone
I_{ri}	Rating of layer i of vadose zone
L	Contaminant loading per land use category
L_r & L_w	Land use rating and weighting
LU	Land use
MAD	Management allowable depletion (dimensionless)
n	Porosity
N and N’	The number of data layers used to compute the V and V'
N_n	Net recharge
N_{con}	Nitrate concentration in percolation water
N_w and N_r	Weight and rating that given the total on-ground nitrogen loading
P_a	Percentage of the total area covered by each land-use category
P_c	Cumulative amount of rainfall
PI	Percolation index
P_p	Annual average rainfall/Precipitation
P_r and P_w for	Weight and rating of individual DRASTIC parameters that used effective weight calculation
P_t	Protective cover ranges
Q	Actual runoff
Q_p	Pumping rate of the well
r	Rating of the parameters
R_c	Radius of the circle

R_r	Recharge rate
RF	Rainfall factor
RPR	Runoff potential ratio
RV	Recharge value
SEEPAGE	System for Early Evaluation of Pollution Potential of Agricultural Groundwater Environments
S_{sw}	Maximum watershed storage
SI	Susceptibility index
SP	Soil permeability
S_p	Slope percentage
S_v	Sensitivity analysis
S_w	Volumes of storage water
T_d	Applied transformations to a data series
T_q	Cumulative direct runoff
T_v	Total thickness of the vadose zone
t	Travel time for which volume was being calculated
T_i	Thickness of the layer i
V_p	Overall vulnerability index of a polygon.
V and V'	Unperturbed and perturbed vulnerability indices
$V_{(specific)}$	Specific vulnerability
V_i	Vulnerability index
$V_{intrinsic}$	Intrinsic vulnerability
V_{vxi}	Variation index omitting a parameter X (D, R, A, S, T, I or C)
V_{xi}	Vulnerability index calculated without a parameter, X (D, R, A, S, T, I, C)
w	Weighting of the parameters

W_e	Effective weight
W_{perc}	Percolation water
X_{ri} and X_{wi}	Range and weight for each parameter X
Z	Root zone depth
α, β and γ	Weighting coefficients of EPIK parameters

LIST OF APPENDICES

Chapter 1

INTRODUCTION

1.1 General

Groundwater is the basic need for all human, animals and plants, particularly in the region where other sources of water are lacking. Groundwater protection has become a foremost concern since late 70's for public attention (U.S. Environmental Protection Agency, 1990). Industrial wastes and chemicals also led to frequent pollution problem. Some of those chemicals are penetrated into groundwater system and causes contamination (Bedient et al., 1999). Very often groundwater is subjected to severe anthropogenic activities which lead it to vulnerable. Groundwater vulnerability refers to intrinsic characteristics that determine the sensitivity of the water to be adversely affected by an imposed contaminant load. Intrinsic vulnerability mapping of the groundwater is considered that some areas are more susceptible to contamination than others (Piscopo, 2001). National Research Council (1993) define the term "vulnerability" is the propensity or likelihood of pollutants to reach a particular position in the groundwater system in which the pollutants preface at some location above the uppermost aquifer. Specific vulnerability is more reliable and efficient than generic vulnerability to contamination. Achieving the idle conditions of the specific vulnerability is more difficult due to the adequate data sources. The term vulnerability was used to more generalize case and reconnaissance level (Haertle, 1983; Aller et al., 1987) and indicated as the potentiality of infiltration and dispersion of the pollutants from the ground level into the groundwater system.

The groundwater vulnerability assessment mainly incorporates the geological and hydro-geological settings and does not embrace pollutant attenuation. Preventive actions are always better and cheaper than remediation and renovation of groundwater contamination. Achieving these goals, the problem and its clarification can be predicted with the help of groundwater vulnerability, quality and productivity assessment.

1.2 Problem Statement

The groundwater vulnerability is playing vital issue in worldwide. The anthropogenic and agricultural activities are the most responsible for deterioration of groundwater level and increasing vulnerability. The proper steps are urgent for water resources development and to solve the problem of groundwater level deterioration and increasing water demand (Nageswara & Narendra, 2006). Groundwater has major contribution in agricultural, industrial and drinking as well as other municipal uses. Ensuring the continuous water supply demand and mitigate adverse effect, the definite strategies and guidelines are urgent for quality control, monitoring and management of groundwater resource. The vulnerability assessment of groundwater is the most feasible step regarding on these purposes.

Melaka State in Peninsular Malaysia is an important state for agricultural, industrial, commercial and tourism aspects. It is subjected to limited groundwater resources because of small land areas and comparatively low rainfall than other parts of Malaysia. The most water supply systems are mainly depended on surface water or rainfall. For the purposes of water supply, around 97% of the raw water is collected from streams or rivers including impounding reservoirs and the remaining 3% of raw water are collected from groundwater. The rural areas are not connected to sufficient treated drinking water supply schemes. The clean water is supplied in some areas via sanitary wells and gravity feed system. In this case, the house connections are not available with all water supply schemes. The conventional treatment methods namely;- aeration, coagulation & flocculation, sedimentation, filtration and chlorination are mostly used in major water treatment plants of urban areas. However, only the chlorination is used in some small water treatment plants which are not adequate. Potential water sources areas are identified by traditionally have been known for good water quality in the rural areas. If the water qualities of possible sources become satisfactory after test against the current standard, then it is allowed to use for drinking and other purposes by the community. Yet the users are also advised to boil water before consumption. Groundwater of Melaka can be made a significant contribution in terms of increasing demand of safe water and reduce the dependence on surface water. It also can be used as an important source to meet the future water demand for the public supply.

The present study incorporates the concepts, significance and applicability of GIS-based DRASTIC method for groundwater vulnerability and risk assessment. The DRASTIC is an acronym for the seven factors considered in the method: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. The DRASTC method has been used to develop groundwater vulnerability maps in many parts of the world; however, the effectiveness of the method has shown mixed success (Rupert, 2001). DRASTIC maps are usually not calibrated to measure contaminant concentrations (Rupert, 1999). It gives indication to the vulnerability of groundwater to contamination regardless of the contaminant itself. In addition, GIS technology is very helpful in facilitating data input and output processing especially in watersheds where field data are regularly updated from frequent monitoring and allows rapid visualization of raw data. The GIS is an efficient tool for analyzing, interpreting and manipulating data as well as incorporating the geological, hydrogeological and geomorphological data (Anbazhagan & Nair, 2004; Jha et al., 2006; Jha & Peiffer, 2006). Moreover, this study also enforces the groundwater productivity and quality in the study area as well as emphasized on the validation system of the DRASTIC method.

1.3 Research Objectives

[a] To investigate the geological, hydrogeological, lithological and meteorological settings as well as land use conditions of the study area.

[b] To assess the groundwater productivity and potentiality of the study area.

[c] To assess the groundwater vulnerability of the State of Melaka in Peninsular Malaysia using the DRASTIC method and GIS techniques.

[d] To develop the modified DRASTIC method based on additional land use parameter combining with conventional DRASTIC method.

[e] To assess the groundwater quality of the study area.

1.4 Outline of the Thesis

Chapter one is the introduction, where general background and research objectives are provided. Chapter 2 reviews the literature on the DRASTIC method and GIS techniques, where the original and modified DRASTIC parameters rating ranges and weight are well described. The methodology that is used in order to complete the research explained in chapter 3. In chapter 4, results and discussions are included. The detail various thematic maps and results are described systematically. Chapter 5 concludes the research findings and suggests the future direction of research.

Chapter 2

LITERATURE REVIEW

2.1 General

DRASTIC is the most reliable method for groundwater vulnerability assessment. Firstly, the term vulnerability was used by a French hydrogeologist J. Margat in the late 60's in hydrogeology. After that it has been widely used in different parts of the world since the last 1980's (Haertle, 1983; Aller, et al., 1987; Foster & Hirata, 1988). Under this chapter, some previous research methodologies and outcomes were discussed on the DRASTIC model and groundwater quality. Most of the cases, Remote Sensing (RS), GIS, geological, hydrogeological, topographical, lithological, land use and meteorological data were used. In some cases and regions, the researchers modified or added or remove one or more parameters from conventional DRASTIC method and proposed the new rating and weight range values. Sensitivity analysis enriched the DRASTIC method’s accuracy and indicated the individual impotency of each parameter. Anthropogenic impacts added to groundwater vulnerability and quality assessment which had a significant effect on groundwater contamination. The concepts, significance and applicability of GIS also described through the DRASTIC method for groundwater vulnerability assessment.

2.2 Conventional DRASTIC Method

The DRASTIC method generally used seven hydrogeological parameters to assess groundwater vulnerability. The parameters were considered as depth to groundwater table (D), net recharge (R), aquifer media (A), soil media (S), topography (T), impact of vadose zone (I) and hydraulic conductivity (C). The input information such as borehole data, meteorological data, hydrological data, geology data, soil data, lithology data, contour map, topography map were used to develop the GIS database. The method was used considering various circumstances such as arid or semi-arid regions, agricultural, industrial, municipal, coastal, septic tank and landfill areas. The parameters were rated and weighted due to their relative importance to contamination. Weighting and rating ranges were considered from 1 to 5 and 1 to 10, respectively. A multiplier defined as weight was multiplied with each parameter rating for each interval and then the products were summed up to calculate the final DRASTIC index. This index indicated the relative degree of groundwater vulnerability of an area. Higher the index value indicated the greater possibility to contamination. Final vulnerability map was generated by integrating all the thematic maps of DRASTIC parameters through the GIS environment.

ArcGIS software was a powerful tool to generate different thematic maps, GIS database, format conversion, overlaying maps, integrating maps and so on. Some extension tools (Spatial analyst, 3D analyst and Geostatistical analyst) of GIS software are extensively used in the DRASTIC method. Many researchers and scientists assessed groundwater vulnerability using the Equation 2.1 based on the above concept (Kim & Hamm, 1999; Ibe et al., 2001; Withowski et al., 2003; Tovar & Rodriguez, 2004; De Silva & Hohne, 2005; Jasrotia & Singh, 2005; Shahid & Hazarika, 2007; Chitsazan & Akhtari, 2009; Moghaddam et al., 2010).

$$\textit{DRASTIC Index (DI)} = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.1)$$

Where, w = weight of the parameters and r = ratings of the parameters. Groundwater vulnerability assessment in the coastal region was an important issue. The colluvial-alluvial sediment region was more vulnerable to contamination (Junior Silva & Pizani, 2003). The input data sources were used as groundwater depth, aquifer recharge, lithology, soil types, topography and permeability. Anthropogenic activities and sea water intrusion were prevailing factor for groundwater vulnerability. Conventional DRASTIC method was used in the arid region of Barka region of Oman (Jamrah et al., 2008). The study showed the long-term changes of vulnerability index for 1995 and 2004. Groundwater samples were analyzed for major ions, nutrients, COD (Chemical Oxygen Demand), BOD (Biochemical Oxygen Demand) and bacteria to cross check the DRASTIC vulnerability index. Major anions such as No_3^-, No_2^-, Cl^-, So_4^{2-}, Po_4^{2-}, F^-, and Br^- were analyzed to develop the correlations with vulnerability index values for checking the DRASTIC method accuracy.

2.3 Sensitivity Analysis of the DRASTIC Parameters

Sensitivity analysis was carried out to show the relationship between the effective and theoretical weight of the DRASTIC parameters. The analysis helped to avoid the subjectivity to nature for vulnerability assessment which provided very important information to assign the weighting and rating ranges of the parameters. Generally, map removal sensitivity and single parameter removal sensitivity analysis were carried out to indicate the most sensitive parameter for groundwater vulnerability. First one represented the sensitivity of the final vulnerability map by removing one or more map layers and worked out Equation (2.2). The single parameter removal sensitivity analysis test indicated the influence of each parameter on final vulnerability measurement. Effective weight of each subarea was estimated by the Equation (2.3). From the sensitivity analyzed results, researchers can be understood that their assign weight was perfect or need to modification. Both the conventional DRASTIC method and sensitivity analysis were used to groundwater vulnerability assessment by many researchers and scientists (Kwansiririkull et al., 2004; Babiker et al., 2005; El-Naqa et al., 2006; Ckakraborty et al., 2007; Bazimenyera & Zhonghua, 2008; Rahman, 2008; Hasiniaina et al., 2010; Al Hallaq & Elaish, 2011; Samake et al., 2011).

$$Sensitivity,\ S = \left[\left(\frac{V/N - V'/n}{V}\right)\right] \times 100 \qquad (2.2)$$

Where, V and V' = the unperturbed and the perturbed vulnerability indices, respectively. N and n = the number of data layers used to compute the V and V'. The differences of theoretical weight and effective weight (W) also calculated by the Equation (2.3):

$$W = \left(\frac{\mathrm{P_r} P_w}{V}\right) \times 100 \qquad (2.3)$$

Where, P_r and P_w= the respective parameter's rating and weights, V = the overall vulnerability index of that polygon. A GIS based groundwater vulnerability assessment carried out in the Russeifa area of Jordan. There was a most concern that the study area was situated at the landfill site. DRASTIC index was calculated due to pesticide effect and included the map removal sensitivity by statistical analysis. The study indicated that the groundwater was highly vulnerable due to the landfill of surrounding study area (El-Naqa, et al., 2006).

2.4 Different Equations for Net Recharge Calculation of the DRASTIC Method

Different types of equations were used to calculate the net recharge of the DRASTIC method in many parts of the world based on the variation of geology, hydrogeology, lithology, land use categories, topography, climatic and other conditions. The following Equation (2.4) was used for net recharge (N) calculation by (Bazimenyera & Zhonghua, 2008).

$$N = (R - E) \times r \qquad (2.4)$$

Where, R = rainfall, E = evaporation, and r = recharge rate. Net recharge was calculated using other Equations 2.5 and 2.6 considering gravel sand and loamy sand geology, respectively (Al Hallaq & Elaish, 2011).

$$PI = \frac{(P - 10.28)^2}{P + 15.43} \qquad (2.5)$$

$$PI = \frac{(P-15.05)^2}{P+22.57} \quad \text{.......} \quad (2.6)$$

Where, PI = the percolation index and P = the annual average rainfall. Jayasekera et al. (2011) estimated the recharge value by sum up the rainfall and irrigation return flow, and subtracting the evapotranspiration. Soil moisture content was accounted to calculate the irrigation return flow. The volume of storage water available for plants (S) was calculated using Equation (2.7):

$$S = \frac{\pi D_b^{\,2}}{4} \times \frac{AWHC}{100} \times MAD \times Z \quad \text{.......} \quad (2.7)$$

Where, D_b = diameter of basin, Z = root zone depth; $AWHC$ = available water holding capacity, MAD = management allowable depletion (dimensionless). The assumptions were $Z = 0.5$ m; $AWHC = 8\%$ and $MAD = 1.0$ for desert plants and 0.5 for others plants. It was used the approximate infiltration fraction as 0.4 based on rainfall (Kuruppuarachchi, 1995). The calculated fraction of irrigation water recharge to groundwater table was 0.63 over the area. Fault system, fault density, the distance between fault system intersection and drainage system intersection, rainfall amount, slope of the area and soil permeability were greatly considered (Al-Hanbali & Kondoh, 2008) to estimate the net recharge using Equation (2.8).

$$RV = RF + S + SP + \overline{F - FD} \quad \text{.......} \quad (2.8)$$

Where, RV = recharge value, RF = rainfall factor, $\overline{F - FD}$ = the rate of the average of the distance from the faults system *(F)* and the distance from the intersection locations between the faults and the drainage systems *(FD)*. S = slope percentage, SP = soil permeability. A study was carried out by greatly considered the net recharge calculation method and its rating system by (Kim & Hamm, 1999). In this case, Soil Conservation Service *(SCS)* method was used (Morel-Seytoux & Verdin, 1981) to define the net recharge rate. Cumulative direct runoff *(T_q)* was calculated by the Equations (2.9 to 2.11):

$$T_q = \frac{\left(P - I_a\right)^2}{P - I_a + S} \qquad (2.9)$$

$$Again, I_a = 0.2S \qquad (2.10)$$

$$S = \frac{25400}{CN} - 254$$

(2.11)

Where, P = cumulative amount of rainfall, I_a = initial abstraction, S = maximum watershed storage and CN = curve number. CN value was depended on the watershed soil types and land use categories. The soil was classified according to SCS classifications and land use was classified according to US geological survey. Under SCS method, runoff potential was determined based on Antecedent Moisture Conditions (AMC). CN and S_p values were taken with respect to AMC classification which taken from SCS chart. Finally, cumulative direct runoff (T_q) was calculated for each land-use category using the Equation (2.12):

$$T_q = \frac{\left(P - 0.2S\right)^2}{P + 0.8S} \qquad (2.12)$$

The net recharge rating ranges (Table 2.1) were developed based on Runoff Potential Ratio (RPR) which calculated on each land use category and by the following Equation (2.13):

$$RPR = \frac{T_q}{P}$$

(2.13)

To evaluate the relative weight of RPR value, the actual runoff (Q) was calculated using Equation (2.14):

$$Q = \frac{P_a}{100} \times T_q \qquad (2.14)$$

Where, *Pa* = the percentage of the total area covered by each land-use category. The new rating ranges of net recharge were selected based on (RPR), whereas RPR mainly depended on land use categories. The study showed that shallow aquifers were more vulnerable due to higher recharge, hydraulic conductivity and coarse soil. The domestic and industrial waste water were the main sources of pollution.

Table 2.1: Recharge rating table (Kim & Hamm, 1999)

RPR (%)	Runoff	Land use	Rating
0–15	Low	Forest and agricultural land	5
15–25	Moderate	Barren land and alluvium	4
25–30	High	Residential area and channel deposit	2
130	Very high	Water	1

A recession curve displacement method was used to estimate the net recharge. Stream flow data within the study area were used for recession curve displacement method (Fritch, et al., 2000) and suggested the three concepts for vadose zone rating ranges. (i) If overlaying material's thickness of the aquifer was less or equal to the thickness of weathered zone, then vadose zone media was considered as materials of the aquifer media. (ii) If overlaying material's thickness of aquifer was greater than the weathered zone, but less or equal to vadose zone , then the vadose zone could be adequately described as a weighted average: [(the aquifer material media rating × its thickness) + (the overlying material media rating × its thickness)]/total thickness of the vadose zone. (iii) If overlaying material thickness of the aquifer was greater than the weathered zone and vadose zone, then vadose zone should be rated according to the overlaying materials characteristics.

2.5 Modified DRASTIC Approach

Land use had a potential impact on groundwater vulnerability and risk mapping which were produced as consequence of groundwater contamination. Modified DRASTIC method was used to assess the groundwater vulnerability and risk mapping including land use (Secunda et al., 1998; Al-Adamat, et al., 2003), and considered D, R, A, S, T and I parameters because of lacking the hydraulic conductivity data. The fixed value 68 assumed instead of ($D_rD_w + A_rA_w + I_rI_w$) index value. Since the possible minimum and maximum DRASTIC index was 24 and 220 and divided into four vulnerability classes (i) 24–71 (No risk), (ii) 72–121 (Low), (iii) 122–170 (Moderate) and (iv) 171–220 (High). Final modified DRASTIC index ($MD_{i)}$) was calculated using the following Equation (2.15):

$$MD_{(i)} = DI + L_r L_w \quad \text{.......... } (2.15)$$

Where, DI = the DRASTIC index. L_r and L_w = the land use rate and weight, respectively. Khan et al. (2010) focused on the land use and impact of vadose zone effect on groundwater vulnerability and risk assessment using DRASTIC method. Land use weight was considered as 5 and hydraulic mean approach (Hussain et al., 2005) was used to calculate the impact of vadose zone parameter. The following Equation (2.16) was used to achieve the approach and final vulnerability index calculated using the Equation (2.1):

$$I_r = \frac{T}{\sum_{i=1}^{n}\left(\frac{T_i}{I_{ri}}\right)} \quad \text{.......... } (2.16)$$

Where, I_r= the weighted harmonic mean of the vadose zone, T = the total thickness of the vadose zone, T_i= thickness of the layer I, and I_{ri}= the rating of the layer i. Al-Hanbali & Kondoh (2008) also used the Equation (2.1) to assess groundwater vulnerability. Modified DRASTIC parameters and rating ranges were used in most cases of arid and semi-arid regions. Weight and rating ranges were changed due to hydrogeologic settings, land use, rainfall, climatic and other conditions. In some cases, some parameters of DRASTIC were removed or added to develop the modified DRASTIC method by many researchers. Modified equations, weight and rating ranges were given satisfactory result for groundwater vulnerability assessment in different regions. The new weight values were considered as 5, 4, 3, 5, 3, 3 and 2 for *D, R, A, S, T, I* and *C* factor, respectively based on pesticide contamination (Al-Zabet, 2002). A fixed index value 10 was assumed instead of “depth to groundwater level” and “impact of vadose zone” parameters to calculate the DRASTIC index (Hasiniaina, et al., 2010). The study area was belonging to oil field and minerals region. The conductivity map generated by two components (aquifer thickness and conductivity) and greatly considered the relation $T=Kb$. Where, T = transmissivity, k = hydraulic conductivity and b = the thickness of the aquifer. Modified DRASTIC method was applied considering the land use parameter and except hydraulic conductivity in Azraq basin (Jasem & Alraggad, 2010). The new weighting and rating ranges were used for each DRASTIC parameter which is shown in Table 2.2(a).

A case study was carried out on the aquifer vulnerability assessment to Arsenic pollution using DRASTIC and GIS techniques at North Bengal plain in West Bengal of India (Ckakraborty, et al., 2007). The assumption was that the contaminants move vertically downwards with water and reaches groundwater table. The new ratings ranges were proposed for *D, R, T* and *I* parameters of DRASTIC method in Table 2.2(b).

Table 2.2(a): Modified weighting and rating values of DRASTIC parameters

References/ Parameters	D		R	A		S		T		I		C	LU	
	Range (m)	Rating		Aquifer media types	Rating	Soil type	Rating	Range (Slope)	Rating	Vadose zone	Rating		Land use types	Rating
Jasem and Alraggad, 2010	0-2	10	-	Limestone	1	Clay	1	> 2%	7	Uncovered	4	-	Rain fed agriculture	1
	2-10	8		Sandstone bed	2	Silty loam	2	2-6%	6	Soil	3		Irrigated agriculture	3
	10-20	6		Sands & gravels	3	Loam	3	6-10%	5	Unconfined unit	2		Urban areas	5
	20-40	4		Basalt	5	Sand	4	10-16%	3	Confining unit	1		Barred rocks	1
	40-60	2		Limestone chalk	4			16-25%	2	-	-		WWTP	4
	>60	1		-	-	-	-	>25%	1	-	-		Streams & WWTP	6
	-	-		-	-	-	-	-	-	-	-		Streams	3
	-	-		-	-	-	-	-	-	-	-		Dams	5
	Modified weight	9	8	5		4		1		5		-	7	
Stigter et al., 2006	Pesticide weight	5	4	3		5		3		4		2	-	
	SI weight	0.186	0.212	0.259		-		0.121		-		-	0.222	

Table 2.2(b): Modified rating values of DRASTIC parameters

References/ Parameters	D		R		A	S		T		I		C	
	Range (m)	Rating	Range (inch/hr)	Rating	-	Soil types	Rating	Range (Slope)	Rating	Vadose zone	Rating	Range (m/d)	Rating
Ckakraborty et al., 2007	<3	10	<0.2	2	-	-	-	0-2%	10	Clay and silt	3	-	-
	3-4	9	0.2-0.6	4	-	-	-	2-4%	9	Sandy clay	4	-	-
	4-5	8	0.6-2.0	6	-	-	-	4-6%	8	Clay sand	6	-	-
	5-6	7	2.0-6.0	8	-	-	-	6-8%	7	Sand & gravel	8	-	-
	6-7	6	> 6.0	10	-	-	-	8-10%	6	-		-	-
	7-8	5	-	-	-	-	-	10-12%	5	-		-	-
	8-9	4	-	-	-	-	-	12-14%	4	-		-	-
	9-10	3	-	-	-	-	-	14-16%	3	-		-	-
	10-11	2	-	-	-	-	-	16-18%	2	-		-	-
	11-12	1	-	-	-	-	-	>18%	1	-		-	-
	>12	1	-	-	-	-	-	-	-	-		-	-
Javadi et al., 2011	0-1.5	10	0-2	2.54	-	Clay Loam	3	-	-	Silty sand	3.3	0.4-4.1	1.67
	1.5-4.6	2.3	2-4	3	-	Silty Loam	4.2	-	-	Clay	5.3	4.1-2.3	3.3

DRASTIC-Fm (Fracture Media) method was applied to assess the groundwater vulnerability for the structural characteristics of fractured bedrock aquifers (Denny et al., 2007). The fractured media was strictly considered for the identifying its effect on groundwater vulnerability. The fractured media was classified as three categories

(Fracture orientation, Fracture length and Fracture density) and also the rating ranges were assigned for those categories. The Fm factor was rated according to the rating range in Table 2.3. The weight of Fm factor was considered as 3.

Table 2.3: Modified DRASTIC-Fm rating values

30° fault orientation classification and associated DRASTIC-Fm ratings				Length classifications and associated DRASTIC-Fm ratings		Fracture density classifications and associated DRASTIC-Fm ratings	
	Min^{m}	Max^{m}	Rating	Fracture length (m)	Rating	Fracture density (fractures/m)	Rating
Extension	285	315	7	20000-25000	10	0-2	2
	315	345	10	15000-20000	8	2-4	4
	345	15	7	10000-15000	6	4-6	6
	105	135	7	5000-10000	4	6-8	8
	135	165	10	0-5000	2	>8	10
	165	195	7	-	-	-	-
Contraction	195	225	4	-	-	-	-
	225	255	2	-	-	-	-
	255	285	4	-	-	-	-
	15	45	4	-	-	-	-
	45	75	2	-	-	-	-
	75	105	4	-	-	-	-

2.6 Calibration of the DRASTIC Method

Groundwater vulnerability was assessed in many parts of the world considering nitrate contamination. Nitrogen is the basic need for agricultural plants to ensure the high production (Lake et al., 2003; Schröder et al., 2004; Shirazi et al., 2011). Groundwater greatly affected by the nitrate contamination all over the world (Birkinshaw & Ewen, 2000; Saâdi & Maslouhi, 2003; Kyllmar et al., 2005; Liu et al., 2005). Nitrate contamination mainly occurred in the agricultural areas due to application of fertilizers. The soil compositions (soil leaching potential) have a great effect on Decision Support System to minimize the pollution of groundwater from agrochemicals (Brown et al., 2003; Holman et al., 2004). The nitrate concentration in groundwater depends on soil nitrate levels, and the timing and amount of surface loading (Di & Cameron, 2002). One of the non-point source pollution of groundwater is caused by nitrate in the agricultural areas (Hubbard & Sheridan, 1994; Mclay et al., 2001; Shamrukh et al., 2001; Harter et al., 2002; Almasri & Kaluarachchi, 2004; Chowdary et al., 2005). On-ground nitrogen concentration was considered to assess the groundwater vulnerability. Nitrogen database was very effective to validate the intrinsic vulnerability (Holman et al., 2005). The on-ground nitrogen loading was rated and weighted, and then added with DRASTIC index. Finally, the composite DRASTIC index (CDI) was calculated by the following Equation (2.17):

$$CDI = DI + N_w N_r \qquad (2.17)$$

Where, DI = the conventional DRASTIC index, N_w and N_r= the weight and rating that given the total on-ground nitrogen loading. The intrinsic vulnerability was assessed to nitrate contamination and considered five parameters for the modification of the DRASTIC method (Mishima et al., 2011). Only vertical movement of contamination was considered for this modification. In this case, the aquifers were shallow and aquifer media was in narrow range. Soil media was governed by the aquifer media parameter. Hydraulic conductivity and aquifer media were less effective for contamination. The more recharge value was considered as less rating value and less recharge value was considered as high rating value which was opposite of original DRASTIC and the Equation (2.18) was used to calculate the nitrate concentration:

$$N_{con} = \frac{E_{rate} \times F_{ert}}{W_{perc}} \qquad (2.18)$$

Where, N_{con} = nitrate concentration in percolation water (mg/L), E_{rate} = elution rate, F_{ert} = fertilizer input (kg/ha), W_{perc} = percolation water (mm/year). Finally, Modified DRASTIC index was calculated by Equation (2.19):

$$G_v = D_r D_w + R_r R_w + S_r S_w + T_r T_w + I_r I_w \qquad (2.19)$$

Where, G_v = groundwater vulnerability, r and w = rating and weighting of the parameters. The new weighting and rating ranges were proposed for five parameters of

DRASTIC based on agricultural areas (Javadi et al., 2011). The new rating ranges are shown in Table 2.2(b).

DRASTIC method was improved by calibrating the point rating scheme, which measured nitrate (NO_3) & nitrite (NO_2) concentration in groundwater (Rupert, 1999). Statistical correlations were developed between the land use, soil, depth to groundwater level and nitrate & nitrite concentrations. GIS and statistical techniques were applied to enumerate the correlations. Based on the correlations the probability map of nitrate & nitrite were generated. Then conventional DRASTIC map and probability map were compared with the independent set of nitrate & nitrite data. The comparison showed that poor correlations were found between the conventional DRASTIC map and nitrate & nitrite concentrations. There was no significance difference of nitrate & nitrite concentration in groundwater between the low, medium, high and very high vulnerability category areas. Good correlations were found between the probability map and nitrate & nitrite concentration. The significant difference of nitrate & nitrite concentration in groundwater indicated between the low, medium, high and very high vulnerability category areas. The study suggested that groundwater vulnerability and probability maps can be used to develop the prevention guidelines for high susceptible to contamination areas. Groundwater vulnerability was assessed considering the severe human impact, semi-arid climate and very little slope variation (Chitsazan & Akhtari, 2009). The most aquifer systems of the study area were unconfined. DRASTIC method was evaluated by the nitrate concentration value of the study area. The correlations were shown between the DRASTIC parameters and nitrate concentration value using the multivariate statistical method.

2.7 Comparison of the DRASTIC with Other Methods

A regional scale of groundwater vulnerability assessment was carried out based on nitrate contamination using the conventional DRARTIC and SEEPAGE (System for Early Evaluation of Pollution Potential of Agricultural Groundwater Environments) method (Navulur, 1996). The vulnerability map showed that 24% area was high vulnerability and 28% very high vulnerability according to the assessment of DRASTIC and SEEPAGE method, respectively. The Bayesian probability map also developed for both methods for computing the probabilities of nitrate occurrence. The probability maps showed that 26% and 21% area with a probability of nitrate recognition > 50% using DRASTIC and SEEPAGE factors, respectively. The water quality data indicated that 76% of the nitrate recognitions were within the areas with probability of recognition > 50%. The study suggested that statistical techniques can be used to generate the regional scale risk map where data availability is limited and DRASTIC performance is better than SEEPAGE.

DRASTIC and AVI (Aquifer Vulnerability Index) methods were used to assess groundwater vulnerability mapping and checked the validation of DRASTIC method (Leal & Castillo, 2003). To validate the weighting and rating ranges of the parameters, the raw data maps and parameter rating maps were compared. Overlaying isoline map pair's technique was used to compare between different maps. If major variations were detected then the rating ranges were modified. Depth to groundwater table parameter was adjusted and proposed for rescaling the rating ranges. The simplification was represented by the matrix form as Equation (2.20):

$$\left[T_d\right]\left[A_r\right]=\left[C_p\right] \qquad (2.20)$$

Where, A_r = geological maps, well log data, pump test data. T_d = the applied transformations to a data series, and C_p = critical parameters. Again, critical parameter C_p affected by the weight function W and it presented by Equation (2.21).

$$[W]\left[C_p\right]=[Vi] \quad (2.21)$$

Where, W = the assigned weight, and Vi= the vulnerability index. Effective weight (W_e) was calculated (Napolitano & Fabbri, 1996; Gogu & Dasargues, 2000) based on the Equation (2.22).

$$W_e=\frac{X_{ri}\times X_{wi}}{V_i}\times 100 \quad (2.22)$$

Where, X_{ri} and X_{wi}= the ranges and weight for each parameter X, and V_i= the vulnerability index. The vulnerability variation was calculated (Lodwik et al., 1990) based on Equation (2.23) and proposed new rating for depth to groundwater table parameter.

$$V_{vxi}=\frac{\left(V_i-V_{xi}\right)}{V_i}\times 100 \quad (2.23)$$

Where, V_{vxi} = variation index omitting a parameter *X (D, R, A, S, T, I or C),* V_i = vulnerability index in the point *i,* and V_{xi} = vulnerability index calculated without a parameter, *X (D, R, A, S, T, I, C).* The comparison between different vulnerability assessment method such as AVI, GOD (Groundwater occurrence, G; Overall lithology of aquifer, O; and Depth to groundwater level, D), DRASTIC and EPIK (Epikarst, E; Protective cover, P; Infiltration conditions, I; and Karst network development, K) were conducted for diffuse flow carbonate aquifers (Vias et al., 2004). The aquifer was high vulnerable according to the AVI method and moderate vulnerable according to the other three methods. The vulnerability maps indicated that AVI method was not suitable whereas GOD method was adequate for vulnerability assessment of diffuse flow carbonate aquifers. Lithological parameters were the most significant for groundwater pollution potential while depth to groundwater level had minor influence. High vulnerability area was resulting by EPIK method for the fractured zones which contradicted with very low karst areas. Among above methods, EPIK is adequate for karstification areas and GOD is adequate for poor karstification carbonate areas. Moreover, DRASTIC and AVI methods are more suitable for land use management. Susceptibility Index (SI) method and nitrate concentration map were used to evaluate the DRASTIC model for groundwater vulnerability assessment (Stigter, et al., 2006). It was assigned the weights of the parameters according to Table 2. The DRASTIC index and Susceptibility index (SI) calculated using the following Equations (2.24 and 2.25):

$$DRASTIC\ Index\ (DI) = 5D + 4R + 3A + 2S + T + 5I + 3C \quad (2.24)$$

$$SI = 0.186D + 0.212R + 0.259A + 0.121T + 0.222LU \quad (2.25)$$

The DRASTIC vulnerability map, *SI* index map and nitrate concentration map were compared to each other and large discrepancies were found. To remove these discrepancies, a new map was generated by subtracting the assessed vulnerability class from the nitrate concentration vulnerability class at all location. Where the class differences were minus one (-1) or zero (0) or one (1), the vulnerability was considered as correct. Where the differences were two, three or more and above the nitrate concentration class, it was considered that vulnerability assessed by overestimated or extremely overestimated. The DRASTIC model was optimized using the statistical method and GIS (Panagopoulos et al., 2006). To modify the weight of DRASTIC parameters, the correlations were established between the DRASTIC parameters and nitrate concentration. Based on the correlation value, negligible parameter removed from DRASTIC model and developed new Equation (2.26) for groundwater vulnerability assessment.

$$V_{(intrinsic)} = 3D + R + 5A + 2T + 2.5I \quad (2.26)$$

Where, $V_{intrinsic}$= the intrinsic vulnerability. The land use weighting and rating ranges were assigned based on nitrate concentration of the study area. The buffer zone radius of nitrogen was calculated based on the Equation (2.27).

$$R_c = \sqrt{\frac{Q_p \cdot t}{\pi \cdot n \cdot H}} \qquad (2.27)$$

Where, R_c = the radius of the circle, Q_p = the pumping rate of the well, t = the travel time for which volume was being calculated, n = the porosity and H = the length of the well screen. Finally, specific vulnerability of groundwater was calculated considering land use parameter and by the Equation (2.28):

$$\textit{Aquifer Pollution Risk,}\ V_{(specific)} = 3D + R + 5A + 2T + 2.5I + 5L \qquad (2.28)$$

Where, L = the contaminant loading per land use category. EPIK and DRASTIC model were used to assess the groundwater vulnerability and indicated the protection zone (Hammouri & El-Naqa, 2008). The EPIK was a multi-attribute method which was mainly used in karst region. The factor E and K were determined with respect to geological and morphological information, whereas the P and I factor were determined from soil and land use maps. The final protection index F was calculated by the Equation (2.29):

$$F = \alpha E + \beta p + \gamma I + \delta K \qquad (2.29)$$

Where, E = development of the Epikarst, P = effectiveness of the protective covers, I = infiltration condition, K = development of the Karst network. Again α, β, γ and δ = weighting coefficients. The DRASTIC model is a straightforward method and generally it is applicable where the hydrological data are available. EPIK is used the region which is subjected to karst features (holes, caves, sinkholes).

Groundwater vulnerability based approach was used to delineate the groundwater protection zones around springs of fracture media (Pochon et al., 2008). Non-consolidated porous media were used as protective materials. Considering the hydrological diversity, individual solution was applied for each hydrological setting. Distance method and isochrone protection method were applied for low vulnerability and slightly vulnerability springs which consist of three protection zones such as S_1, S_2

and S_3. Zone S_1 suggested that the distance must extended at least 10 m around or upstream of the springs which integrated drains, draining trenches and galleries. Zone S_2 suggested the outer distance of S_1 and S_2 zones must at least 100m and zone S_3 suggested that the distance between the external limits of S_2 and S_3 zones equal to the same distance between the outer limits of S_1 and S_2 zones. DISCO (DIScontinuities parameter, protective COver parameter) method was applied for highly vulnerable springs which include characterization of hydrogeological properties of the fractured aquifer and evaluation of the thickness and permeability of protective cover. The method was applied at four stages. Firstly, the discontinuities and protective cover parameters maps were prepared for whole catchment area and rated the value of 'D' (range 0-3) and 'P' (range 0-4) based on hand drilling, on-site soil analysis, geo-morphological map, geophysics and infiltration test. Secondly, intermediate protection factor (F_{int}) was calculated by the Equation (2.30):

$$F_{\text{int}} = 2D_c + P_t \quad\text{.......} \quad (2.30)$$

Where, D_c = discontinuity range, and P_t = protective cover range. Then intermediate protection map was prepared. Thirdly, final protection map was modified by updating the intermediate protection map based on runoff parameter, slope gradient and soil permeability. Fourthly, protection map was converted into protection zones using some conversion factor. The discontinuity and protective cover factors were considered to generate the discontinuity map and protection zone map for the study area. In conclusion, the effectiveness of the study needs to verify from data of long term groundwater quality monitoring and further case studies.

2.8 Overview of the DRASTIC Method

Groundwater vulnerability is a widespread problem in worldwide. Two main components are considered for the DRASTIC method;- (i) the map able units which are called hydrogeologic settings, and (ii) the application of numerical values of the relative ranking of the hydrogeologic factors. This chapter attempts to present the application of the DRASTIC method for groundwater vulnerability assessment, moreover some comparison between the DRASTIC and other related methods are presented. The GIS techniques are provided the great facilities to accomplish and handle the complex and extensive databases for groundwater vulnerability assessment. The salient literature overviews are summarized below:

[a] The modified DRASTIC method is better than conventional DRASTIC method in the arid, semi-arid, basaltic, and agricultural and land fill regions.

[b] Sensitivity analysis is very helpful for DRASTIC method. It indicates which parameter has the most significant contribution to groundwater vulnerability. The differences between theoretical and effective weights of DRASTIC parameters are demonstrated by sensitivity analysis.

[c] Extensive approaches are established to net recharge calculation based on different geological and hydrogeological conditions.

[d] The DRASTIC method is calibrated by nitrate concentration in groundwater or others related method. The evaluation system is the comparison between vulnerability index maps of various methods or correlation between the vulnerability index values and nitrate concentration values over the study area.

[e] In some cases, the DRASTIC parameter's weighting and rating ranges can be modified and one or more parameters also can be added or subtracted from conventional DRASTIC method based on the geology, hydrogeology, land use categories, climatic and others conditions.

[f] In agricultural areas, it is better to rescale the weighting and rating ranges of conventional DRASTIC parameters due to land use and nitrate concentration resulting from pesticides and fertilizers.

Chapter 3

METHODOLOGY

3.1 General

The chapter describes the approach and the development of conventional and modified DRASTIC methods as well as drilling methodology to assess the groundwater vulnerability, potentiality and quality of the State of Melaka in Peninsular Malaysia. The preparation of data is discussed in detail for the development of groundwater vulnerability and potentiality maps. The study focuses the modified DRASTIC method, which included the land use parameter. This chapter contains of three sections, in which first section addressing the drilling methodology, second the conventional DRASTIC method and third the modified DRASTIC method.

3.2 Description of the Study Area

3.2.1 Location

Melaka is ranked as the third smallest state in Peninsular Malaysia with a land area of 1650 Sq. Km. The location is between latitudes 1°06’ and 2°30’ N and longitudes 101°58’and 102°35’ E (Figure 3.1). Melaka located on the southwestern coast of Peninsular Malaysia opposite Sumatra, with the states of Negeri Sembilan to the north and Johor to the east. The capital town of Melaka is strategically situated between the two national capitals of Malaysia and Singapore. The State of Melaka is included three important Districts, which are Alor Gajah, Melaka Tengah and Jasin. The Districts are divided into 81 mukims (parishes). The population of Melaka is about 0.605 million and the density is 385 persons per Sq. Km. (Statistics Department of Malaysia, 2000).

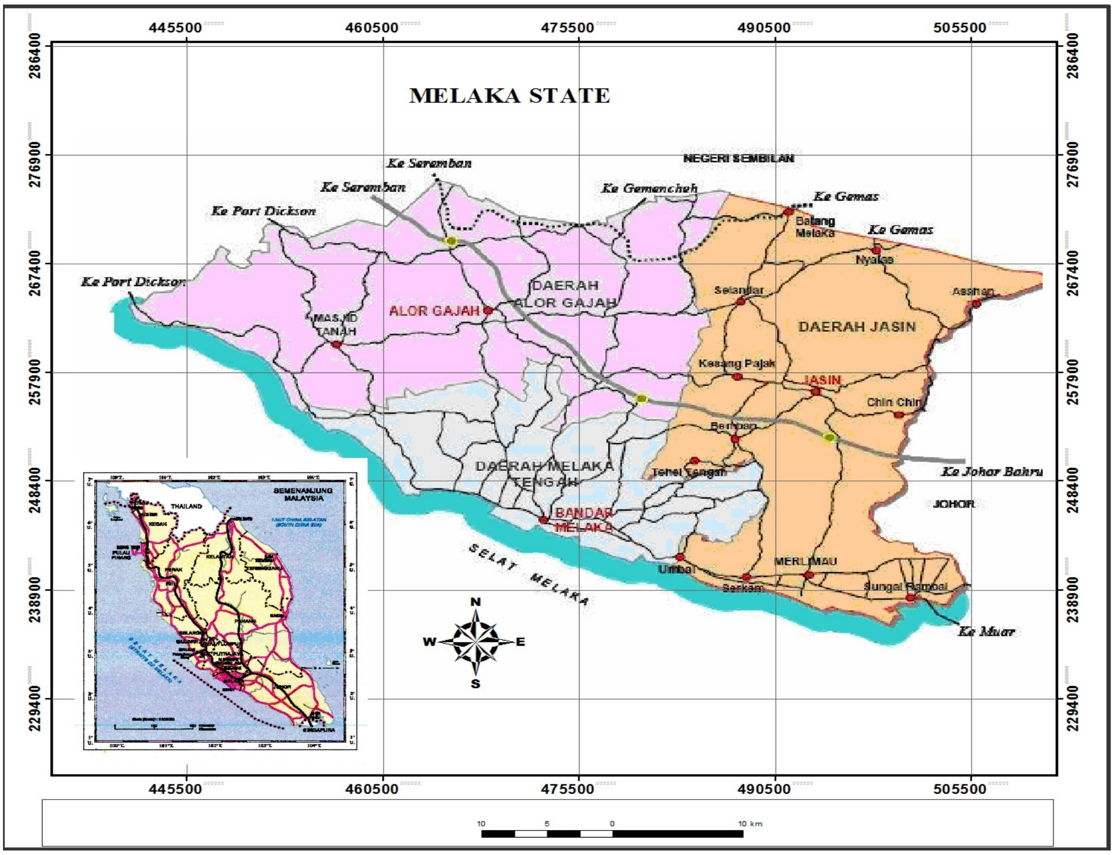

Figure 3.1: Melaka state of Peninsular Malaysia as study area

3.2.2 Climate

The weather of Melaka state is humid and hot through the year with heavy rainfall. The rainfall is not uniform all over the year. It varies slightly month to month. Melaka State is mostly wetted in September to December. Generally, it rains in the afternoon resulting from the humid and hot temperature conditions. The ranges of temperature are 30°C - 35°C during the day, and 27°C - 29°C at night.

3.2.3 Dam and Water Plant

A dam is a barrier which impounds water or underground streams. Primary purpose of dam is to retain water, while the other structures such as floodgates or levees are used to manage or prevent water flow into specific land regions. Another function of dam is used to generate electricity. Furthermore, it also uses to collect or storage water which distributes this storage water into the various locations. The main water utility sources of Melaka are some dams and water treatment plants. Melaka state has some important dams and water treatment plants such as Durian Tunggal dam, Jus dam, Jerneh dam, Cincin water plant, Merlimau water plant, Bertam water treatment plant, Gadek water treatment plant and Asahan water treatment plant. Among these, the Durian Tunggal and Jus dam are the main two dams in Melaka for water supply. The capacity of the Durian Tunggal is 32,600 ML and the area of water catchment is 41.4 Km/m^3 which is 8% of 505.5 Km/m^3 of Melaka River water catchment. Jus is the largest dam in Melaka and located in Jasin district. It's capacity is 45000 ML. Jas dam is filled by raw water from the Durian Tunggal dam via Machap Pump Station with capacity of 100 ML per day through the pipeline of 12.4 Km. About 80 to 90% water demand of Melaka is supplied by the Melaka and Kesang River and the rest is imported from the Muar River in Johor.

3.3 Drilling Methodology

The groundwater potentiality and quality assessment methodology include the observation of the boreholes drilling operations in the study area. The boreholes were drilled until reaching the fractured zones, which was the high potential for groundwater storage. In order to understand and identify the groundwater quality and potentiality;- geological, hydro-geological, geo-physical, test drilling, pumping test and hydro-chemical investigations were carried out. The Melaka State Government built 238 shallow boreholes (depth < 20 m), which were distributed in the territory of Alor Gajah, Central Melaka and Jasin, while more than 20 deep boreholes (depth > 50m) were mostly drilled by the private sector under the supervision of Melaka territory.

The upper portion of the deep boreholes was formed by a 355 mm diameter steel casing with a 200 mm PVC pipe casing being used in the lower parts. The drilling methods were Rotary Drilling with Water Circulation, Air Percussion Rotary and Air-Foam

Rotary. The maximum drilling depth was around 200m. Rotary drilling with the water circulation method was applied for the upper soft residual soil, sedimentary and weathered bedrock. Air percussion rotary drilling was applied to drill the medium hard and semi-weathered or unweathered bedrock for the 350 mm diameter borehole. An air compressor was used to bring the rock chips to the ground surface generating 250 psi pressure in which the borehole diameter was 210mm. Boreholes which were able to meet the satisfactory discharge rate to be developed as production wells. The development was conceded using the airlift method. The operation carried out for at least 6 hrs or until the airlifted water became clean and sand free. The optimum yields of the boreholes were estimated using the constant discharge rate and step drawdown method. The rate of discharge was estimated by measuring the height of the water flow over a 90º V-notch weir using the following Equation (3.1):

$$Q = 1.34H^{2.48} \quad \text{..........} \quad (3.1)$$

Where, Q = the rate of discharge (m^3/day), and H = the vertical distance in meters from the crest of the weir to the free water surface. The groundwater samples were collected for quality analysis during the pumping tests. The quality analysis carried out according to the Standard Method (APHA, 1981).

3.4 The DRASTIC Model Description

3.4.1 DRASTIC Approach

The DRASTIC vulnerability index is a linear combination of seven hydrogeological factors. It is one of the most widely used methods to assess the intrinsic vulnerability of groundwater to contamination (Rupert, 1999). The DRASTIC is also defined as Point Count System Model (PCSM) or a Parameter Rating and Weighting Method. A multiplier called weight is attributed to each DRASTIC parameter based on its relative importance to contamination. The rating value of each parameter for each interval is multiplied by the weight value and the resultant values are summed up to get the final vulnerability index. The final index values indicate a relative degree of vulnerability to contamination of the area. The vulnerability degrees of the different areas are compared to each other, and the higher degree indicates the higher vulnerability or sensitivity to contamination. One of the most difficult aspects of this method remains to classify the different vulnerability classes (high, moderate, low, etc.) due to the final index scores.

3.4.2 Description of the DRASTIC Method

Generally, the process based methods, statistical methods, and overlay & index methods are used to assess groundwater vulnerability in the most parts of the world. The limitations of process based model are availability of adequate data and quality for the capture of physical, chemical, and biological reactions which occur from the surface through the groundwater regimes. The statistical method includes uncertainty and tries to minimize the error and used parameter's coefficient instead of weight. The lack of this method is proper monitoring data. This method is only applicable to those regions where the groundwater contamination is dominated by similar factors. Overlay & index methods are the most suitable method for groundwater vulnerability assessment overcoming all the limitations mentioned above. Some common overlay & index methods are DRASTIC, SEEPAGE, AVI, GOD and EPIK recognized worldwide for groundwater vulnerability assessment. The SEEPAGE method is more adaptable in agricultural environment (Navulur, 1996) whereas GOD and EPIK methods are most suitable for poorly karstification carbonate areas and fully karstification areas, respectively (Vias et al., 2004). AVI, GOD and EPIK also have another drawback that these methods are used comparatively less parameter than DRASTIC method and unable to reflect the actual sceneries for vulnerability assessment. In DRASTIC method, the rating and weight values are assigned precisely according to the range and individual categories of the each parameter in which the parameters are more interrelated. So, if any case some data are unavailable or missing, it does not show the great discrepancy in final vulnerability results. The DRASTIC method is based on the assumptions that some known major factors control the groundwater vulnerability and those can be weighted. It is very costly and time consuming to assess groundwater vulnerability for a specific site, whereas DRASTIC method is more economic and less time consumable to assess wide range of regional groundwater vulnerability overcoming sloppy, uncontrolled development of land and undesirable activities. The method was first developed by Aller et al. (1987) combined with the National Well Association and the US Environmental Protection Agency (EPA) for evaluating the groundwater susceptibility to contamination on a regional scale. Then the method has been modified by many researchers and scientists based on geological or hydro-geological settings, climate conditions and other specific situations. The most widely used groundwater vulnerability mapping method to assess the groundwater vulnerability for a wide range of contamination is an empirical model called DRASTIC (Evans & Myers, 1990; Knox et al., 1993; Kim & Hamm, 1999; Fritch et al., 2000; Piscopo, 2001; Al-Adamat et al., 2003; Thirumalaivasan et al., 2003; Murat et al., 2004; Herlinger & Viero, 2006; Stigter et al., 2006; Rahman, 2008).

The method is being used more and more in Europe and Latin America (Leal & Castillo, 2003; Lobo-Ferreira & Oliveira, 2003). The aim of the model is to identify the areas, where a particular attention and more protection attempts are needed. The set of variables are grouped into three categories; land surface factors, unsaturated zone factors and aquifer or saturated zone factors which are the important considerations for the DRASTIC model (Hasiniaina et al., 2010). The model has four assumptions;- (1) The contaminants are induced at the ground surface, (2) Contaminant is flushed into the groundwater system by precipitation, (3) The contaminant has the mobility of water, and (4) The area being evaluated by DRASTIC is 100 acres or larger. The DRASTIC parameters are weighted according to the assumption of Aller, et al. (1987) and presented in Table 3.1.

In Melaka catchment, the DRASTIC method is used because the study focused on a large region not on a specific local small field or special contaminants. Moreover, the method is every cost effective and availability of required data.

Table 3.1: The DRASTIC model parameters

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

The final vulnerability index is calculated based on the each parameter rating ranges and its corresponding weights. The rating and weight ranges varies from 1 to 10 and 1 to 5, respectively. Each parameter is rated and weighted due to their relative importance on groundwater contamination. The higher tendency to pollution is assigned as the higher rating and weighting value of the respective parameter. Final DRASTIC Index is calculated applying a linear combination of all parameters based on the following Equation (3.2).

$$DRASTIC\ Index = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (3.2)$$

Where *D, R, A, S, T, I,* and *C* represents the seven hydrogeological parameters and the subscripts *r* and *w* represents the corresponding rating and weighting of the parameters, respectively. The DRASTIC groundwater vulnerability mapping procedures are incorporated with the help of GIS. The GIS is a computerized mapping and spatial data analysis system, which enables to manipulation and analysis of spatially referenced information. Though the DRASTIC method is not originally designed as a GIS-based tool, the model lends itself for implementation (Merchant, 1994). GIS applications and its variations in the DRASTIC method have been widely reported in the literature (Trent, 1991; Lusch et al., 1992). The GIS is used for a number of procedures in this study, including:- (i) converting all hardcopy map into a digital format, (ii) creating thematic maps of DRASTIC parameters using water depth records, soil & well location information, geological, hydrogeological, lithological, meteorological and pump test data, and (iii) finally all the individual characteristic maps are overlaid to generate the final vulnerability map. The flow chart of the model is shown in Figure 3.3.

3.5 Development of the Modified DRASTIC Method

3.5.1 Modified Approach

The development of risk map is the main focus in this section using the Modified DRASTIC method. Additional land use activities and its impact are considered together with other hydrogelogical settings to develop the modified DRASTIC method. The intention is to help direct resources and land use activities to the appropriate areas.

3.5.2 Land Use

Most parts of Melaka are dominated by agricultural land, especially palm oil crop, seasonal crops, forests and urban (Land and Mines Department of Melaka, 2003). The main economic source of Melaka is tourism and manufacturing. Land use and water demand increases day by day to meet the demands of the increasing population as well as agricultural, industrial and tourism purposes. Water quality parameters can be greatly hampered by land use pattern. Agricultural activities, septic system, dumping station, industrial and commercial waste can change the characteristics of the groundwater quality parameters (Nordin and Mohamed, 2003; Mohamed et al., 2009). Groundwater quality, storage and flow paths are significantly hampered by mining operations (Vaht et al., 2011). The combination of land use data with slope, soil texture map, rock properties, drainage map, rainfall, and other factors like evapotranspiration and rainfall distribution are very effective for identifying the groundwater potential zone (Amiri et al., 2006). From the Melaka land use classification, it can be seen that major parts of the area are used for agricultural activities. Other categories are governed by urban, industrialization, horticultural land, forest land, swamps and marsh land and wetland forest. The land use classification of the State of Melaka is shown in Table 3.2.

Table 3.2: Types and areas of land use in Melaka

Land use Classification	2007		2008		2009	
	Area (Hectares)	Percentage	Area (Hectares)	Percentage	Area (Hectares)	Percentage
Forest	5079.66	3.06	5079.66	3.05	5079.66	3.05
Agriculture	99754.00	60.25	99754.00	59.98	99754.00	59.98
Urban and Industrial	7033.08	4.25	7033.08	4.23	7033.08	4.23
Aborigines Reserve	667.07	0.40	667.07	0.40	667.07	0.40
Federal Land	8159.63	4.93	2413.76	1.45	2413.76	1.45
State Land	716.83	0.43	706.38	0.42	706.38	0.42
Others	48157.57	26.68	50646.05	30.45	50646.05	30.45
Total	165567.88	100.0	166300.00	100.00	166300.00	100.00

Source: Department of Land and Mines, Melaka

3.5.3 Description of the Modified DRASTIC Method

The risk map is generated using the additional parameter (land use) combined with conventional DRASTIC method, in which the method/technique has been called modified DRASTIC method and the resulting index values are called modified DRASTIC index (MDI). Risk map indicates the land use effect on the groundwater vulnerability. Agricultural, industrial and urbanization impacts on the groundwater are greatly focused in the risk map. To develop the risk map, the land use map is rated according to the land use classifications as shown in Figure 3.2. Land use map indicates that urban settlements are mostly concentrated surrounding of the Melaka city. The most areas of the Melaka state are associated by permanent crops, grass land, palm oil and other trees. Some areas also indicate forest land as well as horticultural activities. Moreover, animal husbandry activities are significant in the study area. Agricultural, urban, animal husbandry, horticultural and permanent crops land have higher possibility to groundwater contamination by the various activities associated in those areas. So, the higher rating values are assigned for the mentioned areas to calculate modified DRASTIC index while water body, forest land, wetland, swamps and marsh land are considered low rating values because of less susceptible to groundwater contamination as shown in Table 3.3.

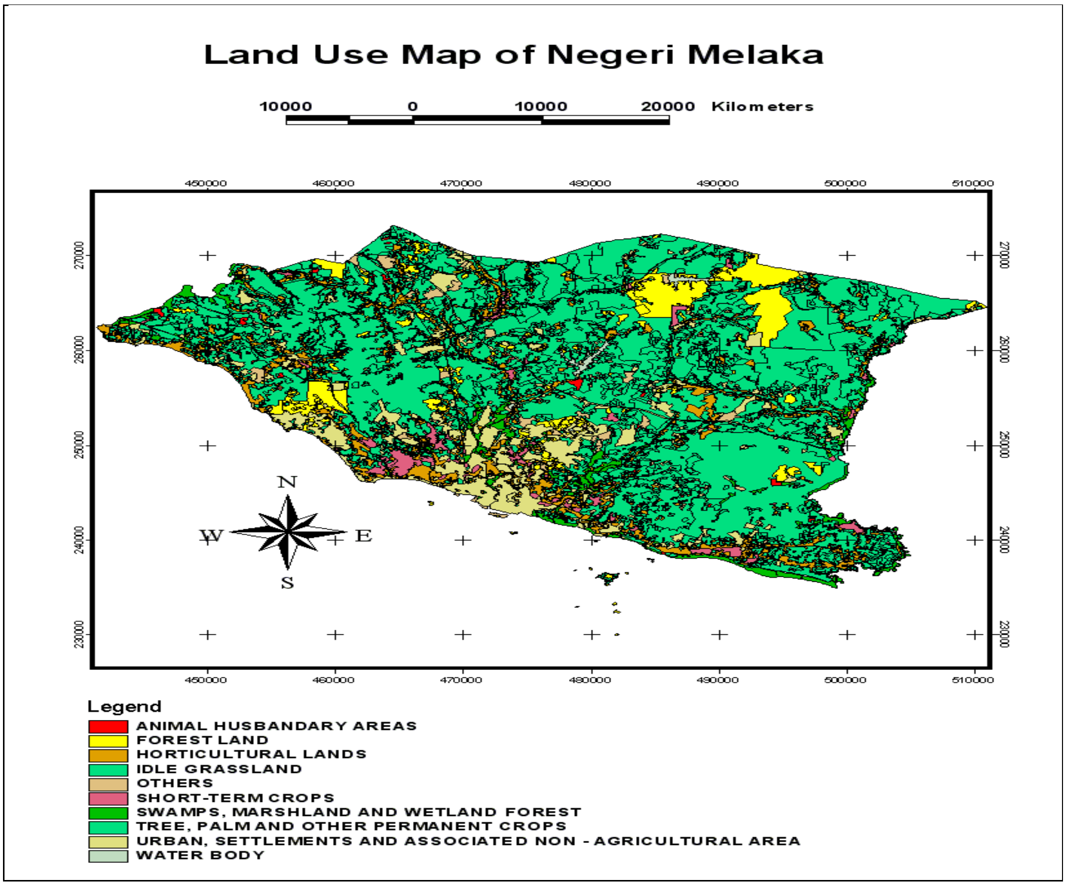

Figure 3.2: Land use map of Melaka State

Table 3.3: Land use classification and rating

Land Use Classification	Rating
Animal Husbandry, Horticulture, Urban and Agricultural Areas	8
Palm Tree and Other Permanent Crops Land	5
Water Body	3
Swamps & Marsh land, Grass & Wetland and others	2
Forest Land	1

Land use map is converted into raster grid and multiplied by the weight of the land use parameter (Lw = 5). The spatial relationship is established between land use and groundwater vulnerability by overlaying the land use map on the conventional DRASTIC vulnerability map. Final resultant grid coverage is added with conventional

DRASTIC index (DI). Modified DRASTIC Index (MDI) is calculated using the Equation (3.3) and respective flow diagram is shown in Figure 3.3.

$$MDI = DI + L_r L_w \quad \text{......} \quad (3.3)$$

Where, *r* and *w* represent the rating and weight of the land use parameter.

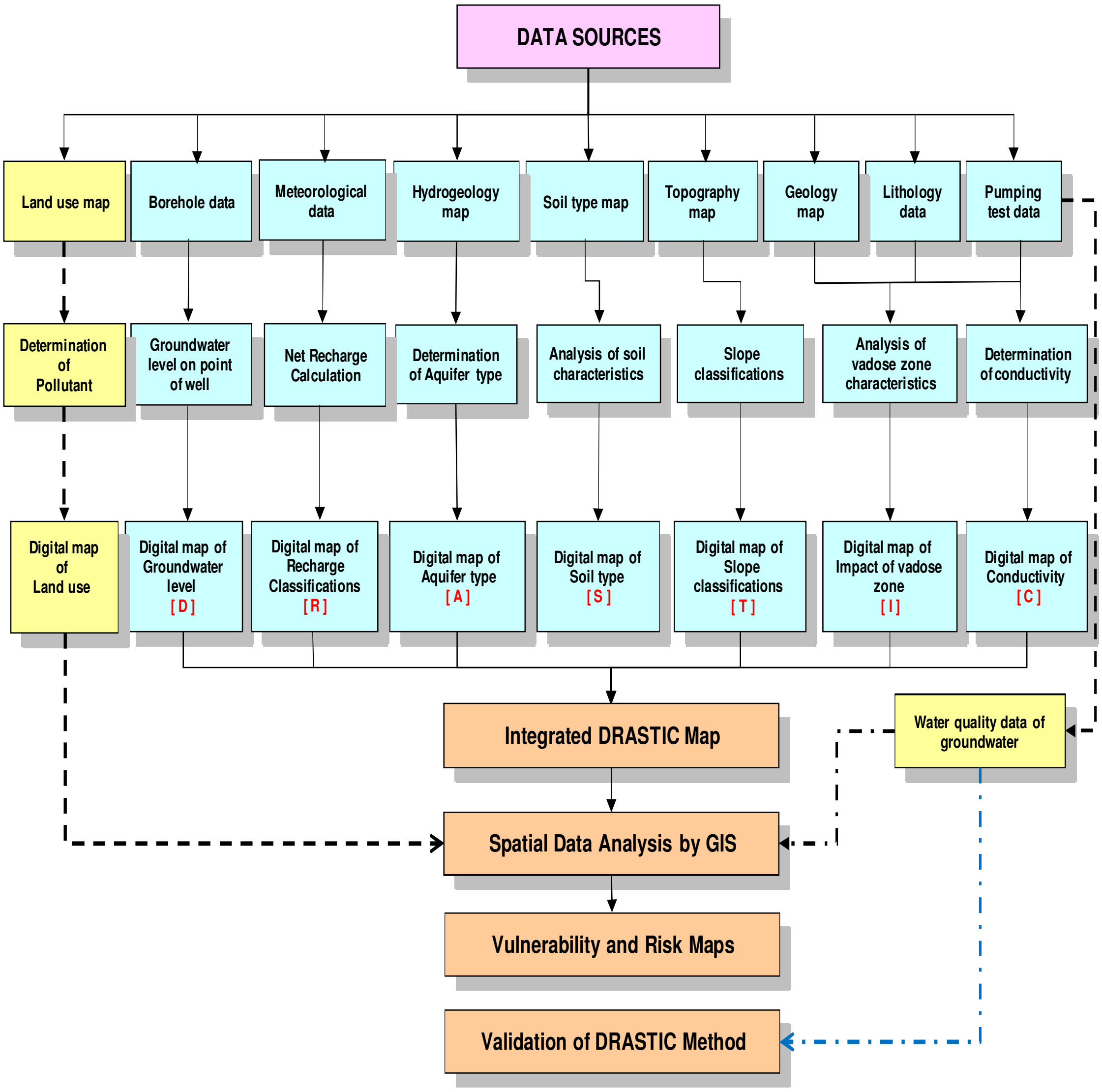

Figure 3.3: Study flow chart

Chapter 4

RESULTS AND DISCUSSIONS

4.1 General

As mentioned earlier in this thesis, the DRASTIC method relied on seven hydrogeological parameters for generating the intrinsic vulnerability map. Since the method involves the evaluation and characterization of highly distributed input data, GIS was heavily utilized in data development and processing. This chapter describes the development and processing of data for the DRASTIC method along with the development of the vulnerability map in Melaka catchment and the associated results and analysis. It also includes the groundwater potentiality and quality assessment results of the study area. Different types of maps and histograms are generated to present the results. Statistical analyses are also carried out for different groundwater quality parameters.

4.2 Groundwater Potentiality Investigation

The details geological, hydrogeological, lithological, meteorological and pumping test data are analyzed to evaluate the groundwater potentiality of the study area. Hydrogeological settings and meteorological conditions are the main two factors for groundwater occurrence and storage.

4.2.1 Geology

The geological features of Melaka were assessed in detail to obtain an overview concerning the nature of the underlying formations and capabilities in terms of groundwater potential (Appendix, B). The three major underlying geological formations of the study area were metamorphic, sedimentary and igneous rock (Geological Survey, 1985). The geological formation of the most study area is governed by phyllite, schist and slate. Second major parts were governed by acid intrusive rocks and granite. The east boundary parts of Jasin District to Johor State were formed by sedimentary deposits such as sand, limestone and alluvium as well as volcanic rock and metamorphic rock (schist). These geological features of Melaka are shown in Figure 4.1. A case study of Aboisso area (South-East of Cote d'ivoire) showed that the sedimentary rock formations had rich storage of groundwater resources in the hard rock region (Dibi et al., 2010). The small part of the study area consisted of sandstone and volcanic rock. Satisfactory groundwater potential zones were found in the hard rock terrain corresponding to the fracture valleys, pediments and high lineaments (Vijith, 2007). A study carried out on groundwater potential zone in India and reported the most probable groundwater potential zones were existed in the flood plains, filled valley and deeply buried pediplain of the alluvial aquifer (Ganapuram et al., 2009). Another study carried out by (Abiye & Kebede, 2011) for identifying groundwater potential zone in Blue Nile River Basin Ethiopia and reported that quaternary lava deposits and alluvium sediments bedrock were the most productive for groundwater.

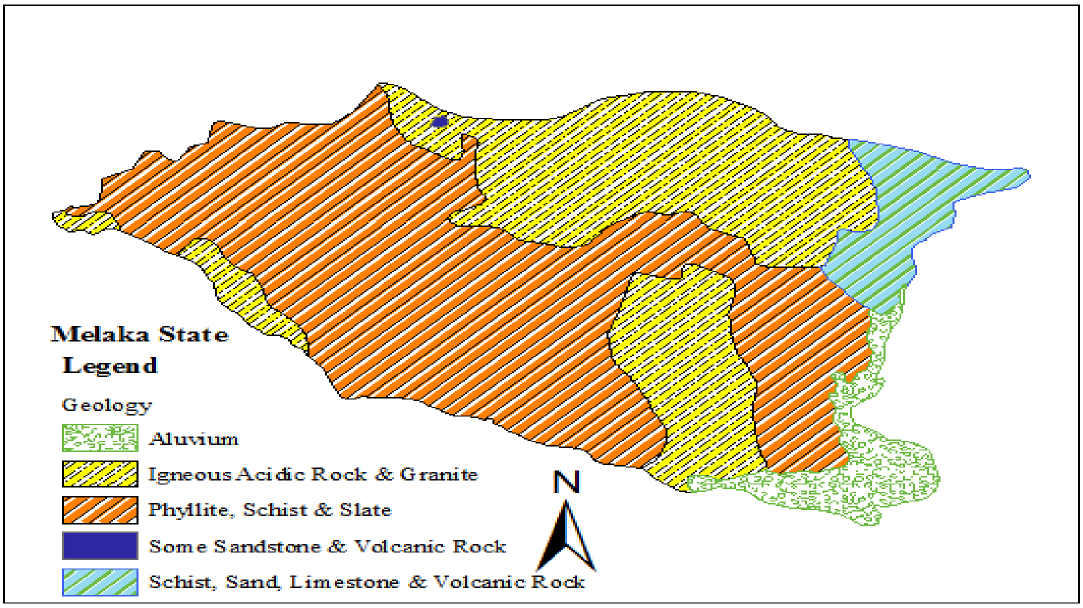

Figure 4.1: Geological map of Melaka

4.2.2 Rainfall

The weather of Melaka is hot and humid throughout the year with a maximum temperature of around 30ºC and dropping a few degrees at night. The rainfall intensity slightly varies between the interior and coastal areas. Meteorological data of the study area (at four stations Mardi Kuala Linggi, Felda Bukit Senggeh, Devon Estate and Melaka) were collected from the Malaysian Meteorological Department and assessed to estimate the average annual rainfall, net recharge and evaporation. In the interior land, rainfall is observed to be 1500mm/year while for the coastal region it is 2000mm/year. Rainfall also slightly varies according to season. The minimum rainfall occurs from December to February and the rest of the year it is wet. In addition, the annual average runoff depth in Melaka is about 500mm/year to 600mm/year whereas; in other parts of Peninsular Malaysia it is about 1000mm/year. The annual average rainfall of Melaka was between 1430mm/year (Min^m) to 2152mm/year (Max^m) for years 1999 to 2009 as shown in Figure 4.2. The correlation between rainfall and net recharge of the study area are presented in Figure 4.3. The correlation is demonstrated that the net recharge significantly increases with the increasing rainfall at around the Melaka rainfall station because of fractured aquifer media and shallow aquifer, while the remaining area around other three stations steadily increases.

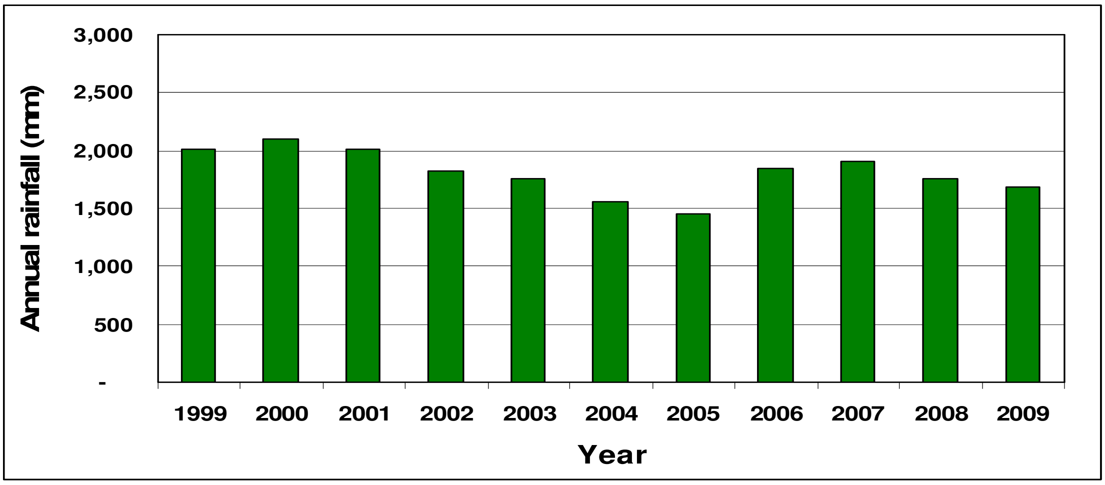

Figure 4.2: Annual rainfall in Melaka

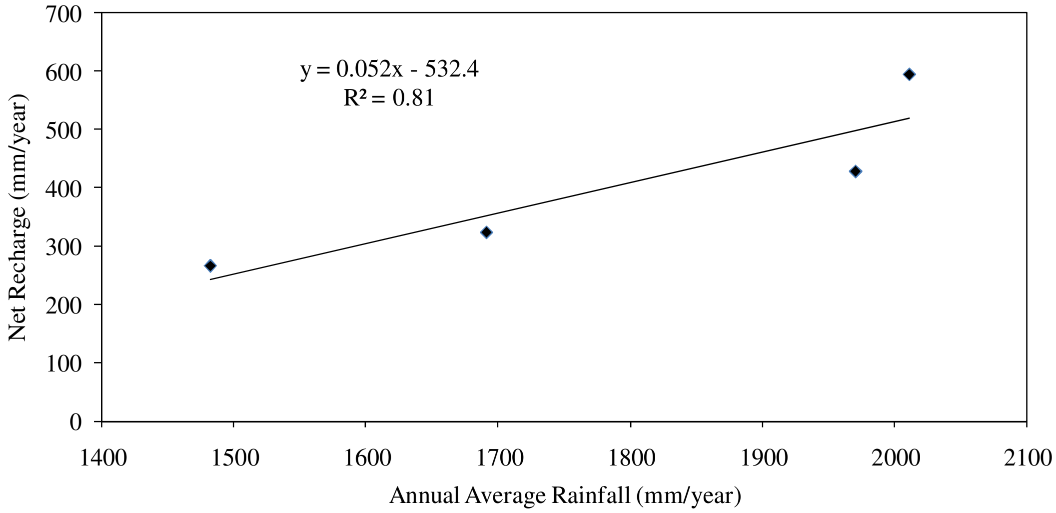

Figure 4.3: Correlation between rainfall and net recharge

4.2.3 Evaporation

Generally, the effect of a cloudy day is less sunshine and thus less radiation resulting in less temperature and evaporation, while the dry condition causes a high evaporation rate. Malaysia is an equatorial country and the temperature fluctuation rate is very low throughout the year. The annual temperature variation is less than 3°C for the east coast in Peninsular Malaysia and other areas are less than 2°C. The average daily temperature in Melaka State is around 26°C and the humidity range varies from around 90% in the morning to 60% in the evening (Source: Meteorological Department, Melaka). In Melaka, cloudiness and temperature, which are interrelated, are the most important among all the factors affecting the rate of evaporation. The evaporation ranges of the State were 4.0 to 4.9 mm/day between the years 1999 and 2009 as shown in Figure 4.4. The figure shows that the evaporation rates do not varies significantly in the study area because of the almost same weather condition of equatorial country through the whole year.

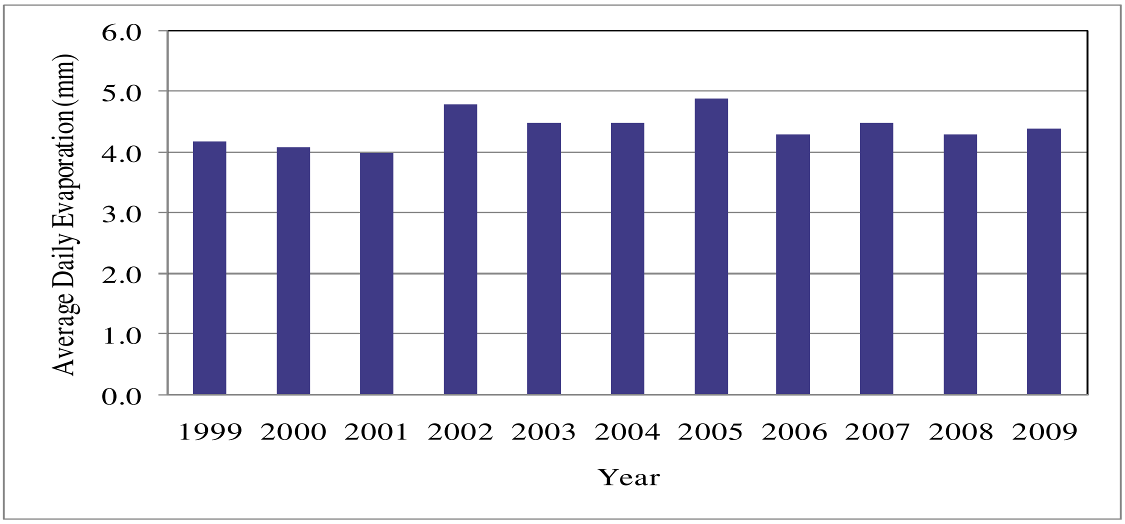

Figure 4.4: Average daily evaporation in different years of Melaka

4.2.4 Hydrogeological Investigation

The hydrogeological investigations on hard rock aquifers mainly focused on their structure (Taylor & Howard, 2000; Wyns et al., 2004; Dewandel et al., 2006) and on the methodologies for developing aquifer mapping and groundwater management at a large scale (Lachassagne et al., 2001; Maréchal et al., 2006; Courtois et al., 2010; Dewandel et al., 2010). Rangzan et al. (2008) conducted a study on well site selection in Iran and reported that the most suitable areas for groundwater exploration were in the sedimentary rocks. The inventory data for the 210 shallow and 17 deep boreholes of Melaka were collected from the Mineral and Geosciences Department, Malaysia (Appendices C, D and F). These data were assessed to identify the occurrence, movement, quantity and quality of groundwater. Hydraulic conductivity, flow path and gradient were greatly controlled by the aquifer media. Larger grain size and more fractures within the aquifer increase the permeability and productivity of the aquifer. In Melaka, lithological logs convey that the media of the deep aquifers were mainly formed by phyllite, schist, slate, coarse sand, medium sand, fine sand, clay, laterite and quartz, while the media for the shallow aquifers were mainly formed by granite, metasediment, clay, coarse sand, medium sand, fine sand and peat. The typical lithological formations of the study area are presented in Figures 4.5 and 4.6 for deep and shallow aquifers, respectively.

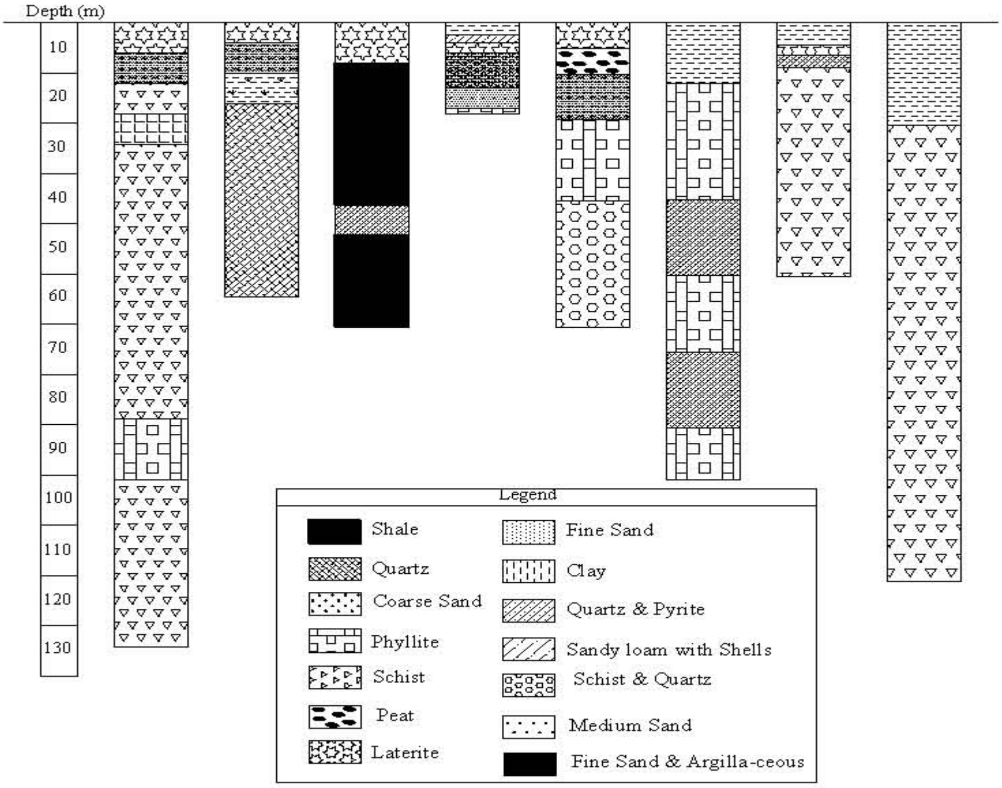

Figure 4.5: Typical lithology of deep aquifers in Melaka

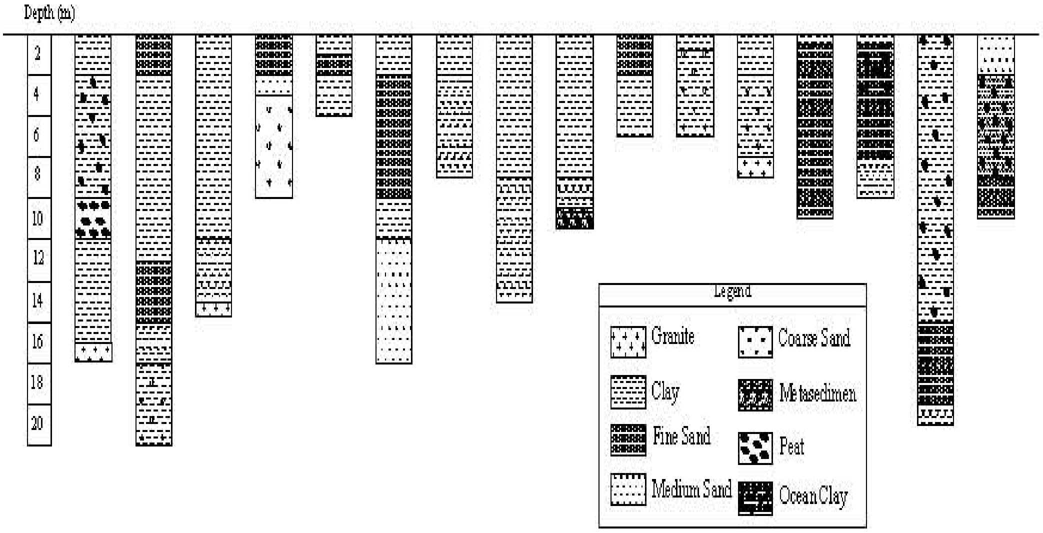

Figure 4.6: Typical lithology of shallow aquifers in Melaka

4.2.5 Pump Test and Aquifer Productivity

Based on the preliminary field survey and collected pump test data of Melaka, it is possible to provide an overview of the groundwater condition of the study area (Appendices C, D and F). The Productivity of the aquifer in the study area was tested by pumping tests and deep drilling. The term 'aquifer productivity' represents the potential of an aquifer to sustain various levels of borehole supply. Pumping test data were used to determine the aquifer parameters in order to ensure the aquifer potentiality (Patra et al., 1993; Singhal et al., 1998). The pump tests results of Melaka showed that the study area was largely dominated by phyllite, slate, schist and granite. The rock type in each borehole was categorized from the pump test data and hydrogeological map.

The aquifer productivity classifications are presented in Table 4.1 based on the judgments of the typical long-term discharge rate in cubic meter per hour from the reliable site and constructed boreholes. It is a comparative classification of productivity among the boreholes of the study area. The aquifer productivity is classified by having a typical yield ranges of <3.6 m^3/h (low), 3.6-12 m^3/h (moderate) and >12 m^3/h (high).

Table 4.1: Aquifer productivity classification of the State of Melaka

District	Total No. of Boreholes	No. of Active Boreholes	Productivity Classes High (>12 m^3/h)	Moderate (3.6-12 m^3/h)	Low (<3.6 m^3/h)	Area (%)	Total Discharge (m^3/h)
Alor Gajah	80	5	12.3-18			8	274
		31		3.6-12		54	
		22			0.2-3.5	38	
Melaka Tengah	107	2	13.5-18			4	138
		36		4-8.2		68	
		15			0.5-3.5	28	
Jasin	71	5	13.6-18			10	211
		24		4-12		50	
		19			0.5-3.5	40	

* The productivity rating refers to the estimated typical long-term yield from properly sited and constructed boreholes of the study area.

Investigation in the area of Alor Gajah indicated that the bedrock of shallow aquifers was governed by phyllite, schist and granite. About 73 shallow boreholes gave different discharge results. Most of the boreholes discharge was 3.6-12 m^3/h and the discharge of only a few shallow and deep aquifers gave a satisfactory result (>12 m^3/h). Groundwater potentiality was limited in the region of Central Melaka based on lithology data and pump test. Among the 107 units, only 53 drill holes discharged at 138 m^3/h. Moderate productivity aquifers were composed of phyllite, schist, and slate which is a thin layer of metamorphic rock that is easily split. This layer has lower permeability than the well-sorted, coarser and high productivity deposits that reduces their potential for yielding large volumes of groundwater. Granite and acid intrusive rocks were dominant in the low productivity aquifer bedrock which was not suitable for the storage of groundwater.

The high potentiality of groundwater in the Jasin area had found in the schist, sand, limestone and volcanic rocks region. Among the 63 shallow boreholes, it was possible to extract groundwater from 50. The ranges of discharge of the most aquifers were 0.5-12 m^3/h. The discharge capacity of the aquifers was tested by drilling deep to find out the value of the transmissivity coefficient (T) and hydraulic conductivity (K). A pumping test was continuously carried out for 6 hours, before waiting for the groundwater elevation to rise. The results were found to be 10m^2/day for the transmissivity coefficient (T) and 0.63 m/day for the hydraulic conductivity (K). The aquifer productivity results for groundwater potential at Melaka indicated that 35% area is low, 57% is moderate and 8% is high. The potential zones and existing well locations in the study area are presented in Figure 4.7.

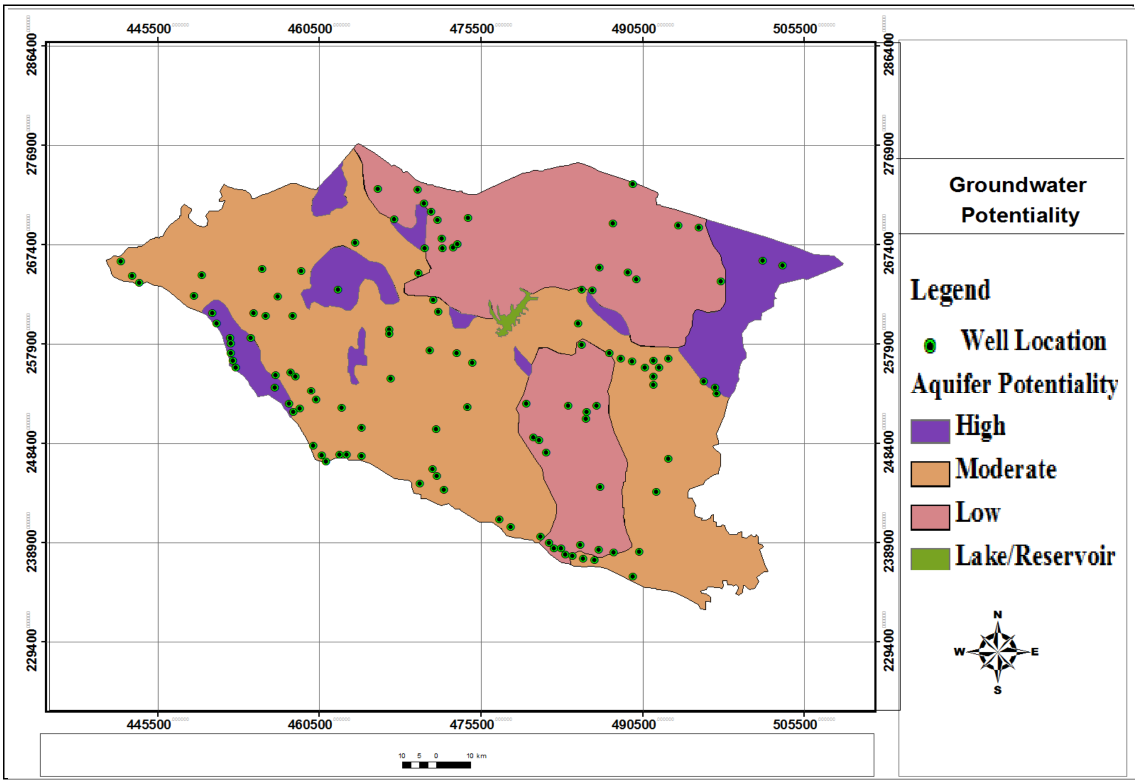

Figure 4.7: Well locations and aquifer potential map of Melaka

4.3 Preparation of DRASTIC Parameter Maps

Seven thematic maps are generated based on hydrogelogical settings (Appendices B-D and F) to carry out the aquifer vulnerability assessment using the DRASTIC method and GIS. DRASTIC method mainly comprises two factors; hydrogeological settings and relative ranking of the parameters. The method is considered the generic pollutant rather than specifics of the particular pollutant. The successive steps for preparing the thematic maps for the DRASTIC parameters have been described in following order to generate the final vulnerability map of groundwater.

4.3.1 Groundwater Depth

The depth of water table is defined as the distance in which the pollutants move through the soil media before reaching the groundwater table. If depth to water table increases, it facilitates the significant contaminant attenuation as the contaminant needs to travel long distance and get enough time to contact with flow media. Depth of groundwater is also important for oxidation process by atmospheric oxygen. Hence, the pollutant elapsed time and attenuation depends on the soil media and the depth to the water table, which has a significant effect on assigning the rating value of the parameter. Depth to water table was calculated from the each groundwater level data and the well location. The respective information was collected from boreholes log information, existing groundwater level from shallow aquifers and drilling wells. The values of groundwater depth are used to compute the rates according to the categories, which are summarized in Table 4.2 and relevant information in Figure 4.8. The figure showed that the depth to groundwater table distance was very low (1.0 m) along the bank of the Melaka Straight and the depth increases from bank to the inland, where maximum water depth was 5 meters. The high rating value was assigned for shallow aquifer around the bank of Melaka straight, while comparatively less rating value was assigned for the remaining area due to increase distance of groundwater table.

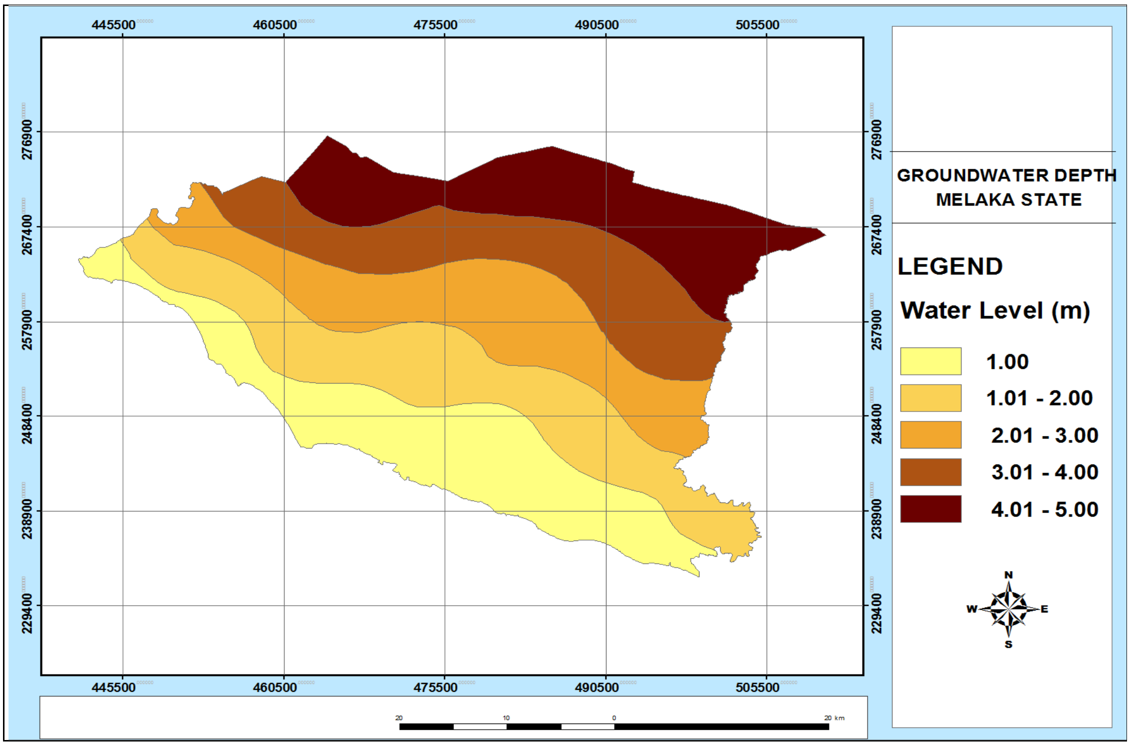

Figure 4.8: Depth to groundwater map of Melaka

Table 4.2: DRASTIC parameter rating and weighting values

Rating	D x (5) Depth of Water (m)	R x (4) Net Recharge (mm/year)	A x (3) Aquifer Media
10	0-1.5		Krast limestone
9	1.5-4.5	>250	Basalt
8		180-250	Sand and gravel
7	4.5-9.0		Massive sandstone, massive limestone
6		100-180	Bedded sandstone, limestone, shale
5	9-15		Glacial
4			Weathered metamorphic / igneous
3	15-23	50-100	Metamorphic / igneous
2	23-31		Massive shale
1	>31	0-50	-

4.3.2 The Recharge

The net recharge is defined as the amount of water that reached into the groundwater system resulting from the precipitation and artificial sources available. The recharge is controlled by land cover, slope, rainfall, permeability of soil, drainage system and lithological conditions. Recharge water a significant vehicle to percolating and transferring of contaminants into the groundwater system. The dispersion and dilution of pollutants in the vadose zone and saturated are controlled by net recharge. High recharge indicates the high pollution potential to contamination. The groundwater pollution and potentiality depend on the rate of net recharge through the faults and fractures (Travaglia & Dainelli, 2003). In the study area, the shallow aquifers were subjected to high recharge, which was mainly governed by precipitation. Most of the cases, shallow aquifers recharged by direct rainfall, and recharge rate were greater than the deep aquifers. The recharge map is generated from the rainfall data and using the following Equation (4.1):

$$\textit{Net Recharge} = (\textit{Rainfall} - \textit{Evaporation}) \times \textit{Coefficient of Thiessen} \quad (4.1)$$

In the Thiessen method (Thiessen and Alter, 1911), all the gauge locations are plotted on the map at an appropriate scale. Next, the straight lines are drawn to connect the gauges without crossing any other lines. Each connecting line is then bisected and a perpendicular line is drawn through the connecting line. Each gauge is near the center of a polygon whose size varies according to the spacing of the gauges. The area of each polygon is then measured. The Coefficient of Thiessen is defined as the ratio between the individual polygon area and the summation of all the polygon area. The 22 years mean of annual rainfall (mm/year) and evaporation (mm/year) data were used to prepare the recharge map based on Thiessen method. The net recharge distribution map is presented in Figure 4.9 and respective information in Table 4.2. The map illustrated that most parts of Melaka and East parts of the Alor Gajah district were subjected to high recharge ranges from 475-714 mm/yr, mainly formed by Phyllite, Schist, Slate and granite, while major part of Jasin district showed the recharge range from 382-474 mm/yr, formed by Schist, Sand, Limestone, Igneous rock and Granite. The remaining area was under comparatively less recharge and mostly affected by high land.

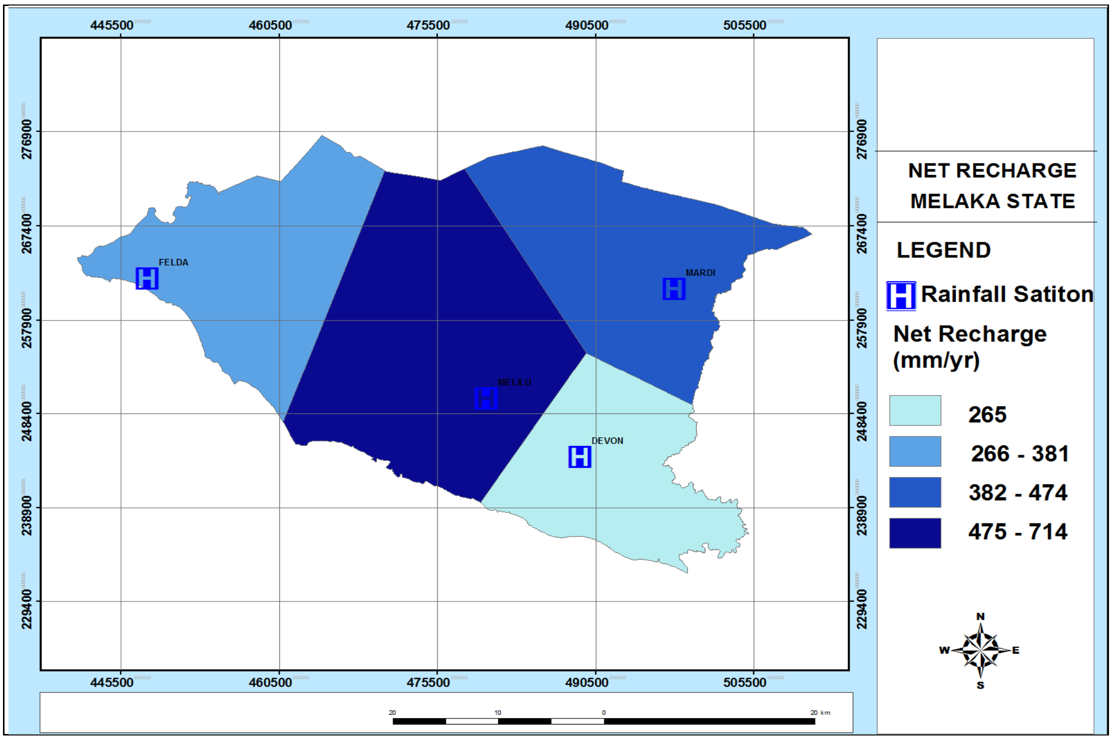

Figure 4.9: Net recharge map of the study area

4.3.3 Aquifer Media

An aquifer is defined as a subsurface rock unit which will yield sufficient quantities of water for use. It also defines the consolidated and unconsolidated rock, in which water contained by fractures and pore spaces. Aquifer media controls the water flow through the aquifers. The rate of contaminant transformation is controlled by flow path (Aller, et al., 1987). Aquifer media has significant effect to control hydraulic conductivity as well as contaminant attenuation process such as sorption and dispersion to occur while contaminants pass through it. In order to assess the impact of the aquifer media on the vulnerability of groundwater resources, GIS database are prepared from the data of subsurface lithology. Each media is rated and weighted according to their relative importance to contamination. Based on the number of 238 shallow and 20 deep boreholes available data, the aquifer media map is generated which is shown in Figure 4.10 with relevant rating information in Table 4.2. The figure showed that the aquifer media of the study area was mostly formed by Phyllite and its rating value assigned as 2. Second major formation was Acid Intrusive rock and third was Shale, Mudstone and Siltstone, which rating values assigned 5 and 7, respectively due to their high porosity and fracture characteristics for water storage.

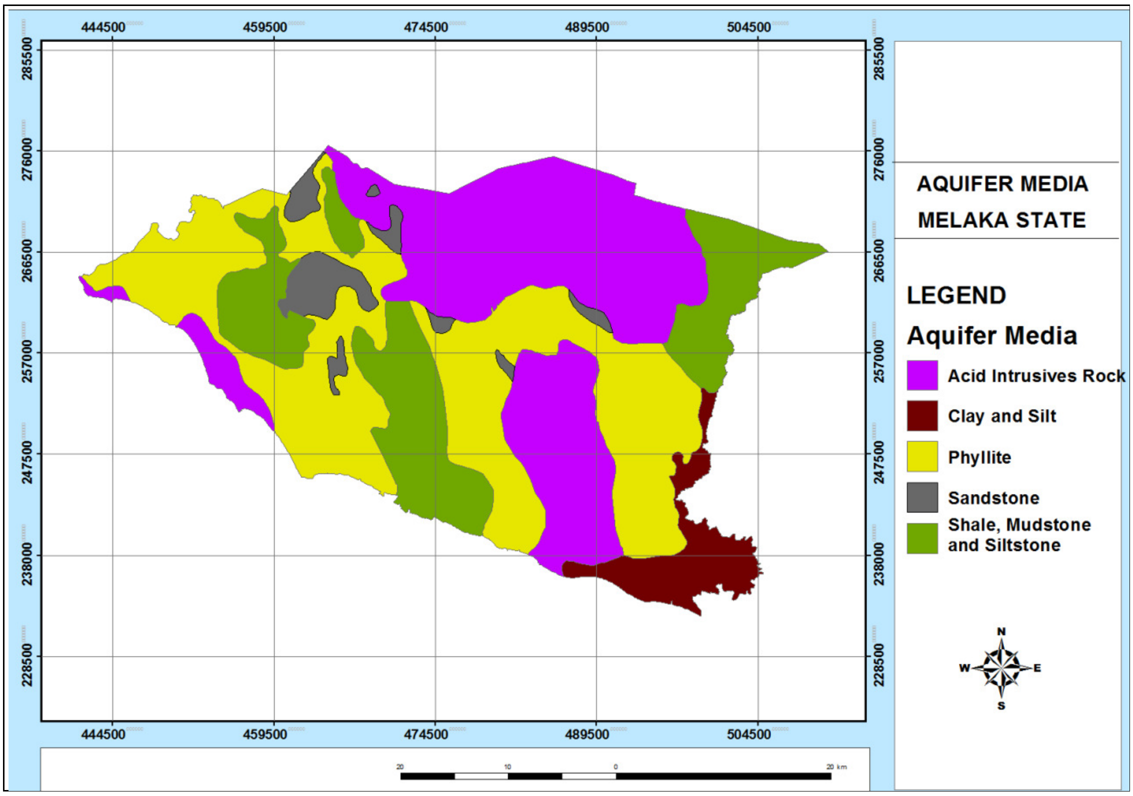

Figure 4.10: Aquifer media map

4.3.4 Soil Media

Soil media is defined as the upper most layers of vadose zone characteristics by considerable biological activities. It is the upper weather layer which has significant effect for infiltration of runoff water and attenuation of contaminants. If soil media is formed by fine textured media, it significantly reduces the infiltration as well as migration of contaminants. Soil media has a significant impact on the amount of recharge and attenuation of contaminants that can infiltrate to the groundwater system. Active contaminant remediation and attenuation take place at the high rate in the soil zone. The presence of fine textured materials, such as silts and clays, can decrease relative soil permeability and restrict contaminant migration. Soil media map is represented in terms of its textural classification and susceptibility of pollution. It is generated from the collected data of the soil surveys, borehole data and the annual report of the Department of Agriculture, Malaysia. The map has included five major soil classifications as shown in Figure 4.11 and the rating classification is presented in

Table 4.3. The map clearly indicates that the soil media mainly formed by Phyllite, Schist and Slate in the major parts of the study area and its rating value was assigned 5, while the maximum rating values were assigned as 7 and 9 for Alluvium and Volcanic rocks, respectively.

Table 4.3: Rating values of soil media in the study area

Rating	S x (2) Soil media
10	Thin or absent, gravel
9	Sand stone and volcanic
8	Peat
7	Shrinking and/or aggregate clay/Alluvium
6	Sandy loam, sys, sand, karts, volcanic
5	Loam
4	Silty loam
3	Clay loam
2	Muck, acid , granitoid
1	Non shrink and non-aggregated clay

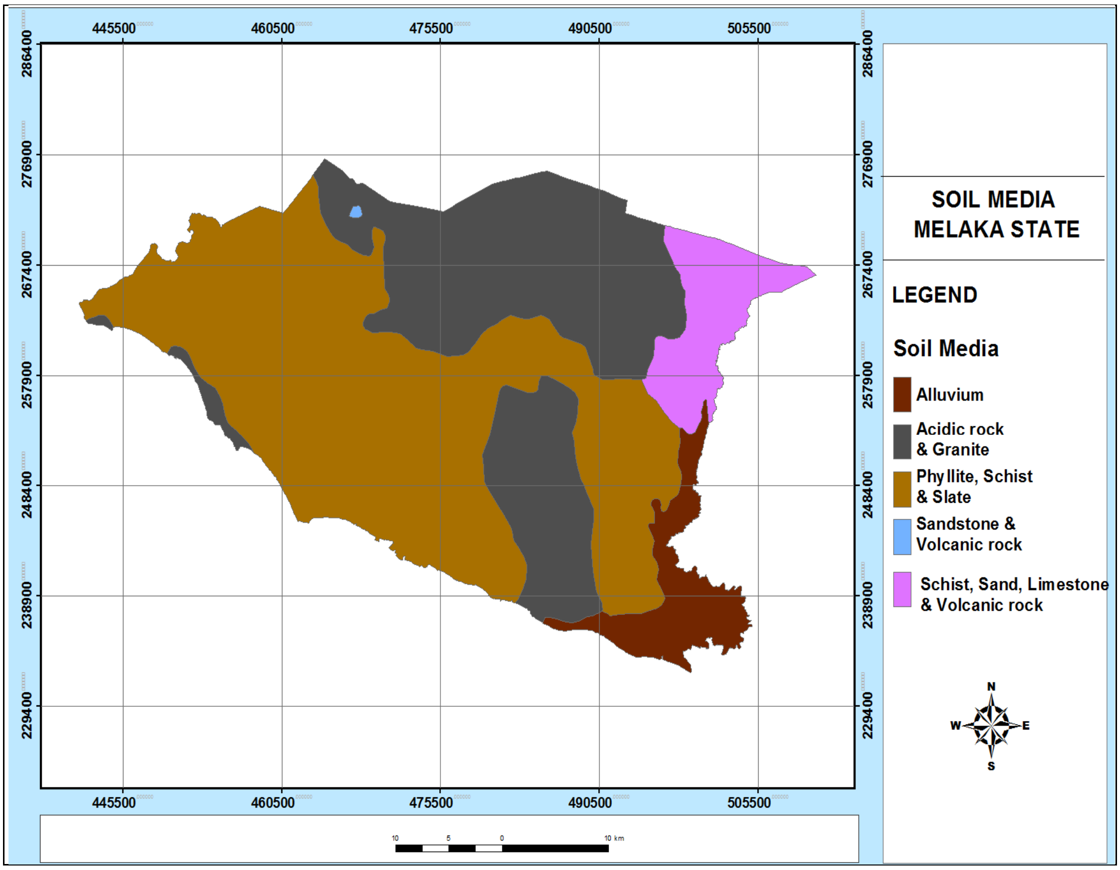

Figure 4.11: Soil media map

4.3.5 Topography

Topography is defined as the slope discrepancy of land surface. Precipitation and pollutant infiltration rate into groundwater are greatly controlled by the degree of the slope. The degree of slope dictates where the precipitation will retain or run off on the surface. On the similar manner, the contaminants will also leave its position as run off or percolate into ground or eventually reach into the groundwater table (Brady & Weil, 2004). Generally, runoff is channeled out from higher to lower elevation and make the lower area is more vulnerable. The topography in the DRASTIC method implies the slope of the ground surface in percentage and is shown in Figure 4.12. In order to compute the slope, the digital elevation model (DEM) of the Melaka catchment was used through the GIS environment. There is a readily available option in the Spatial Analyst of GIS, where it is straightforward to compute the slope of the ground surface from the grid of the DEM. The relevant slope classification is presented in Table 4.4. Topography map demonstrated that the slope range of the study area was very low mostly laid from 0-5 percent. So, it had significant threat for groundwater contamination, in which its rating values were assigned as high range between 7 and10.

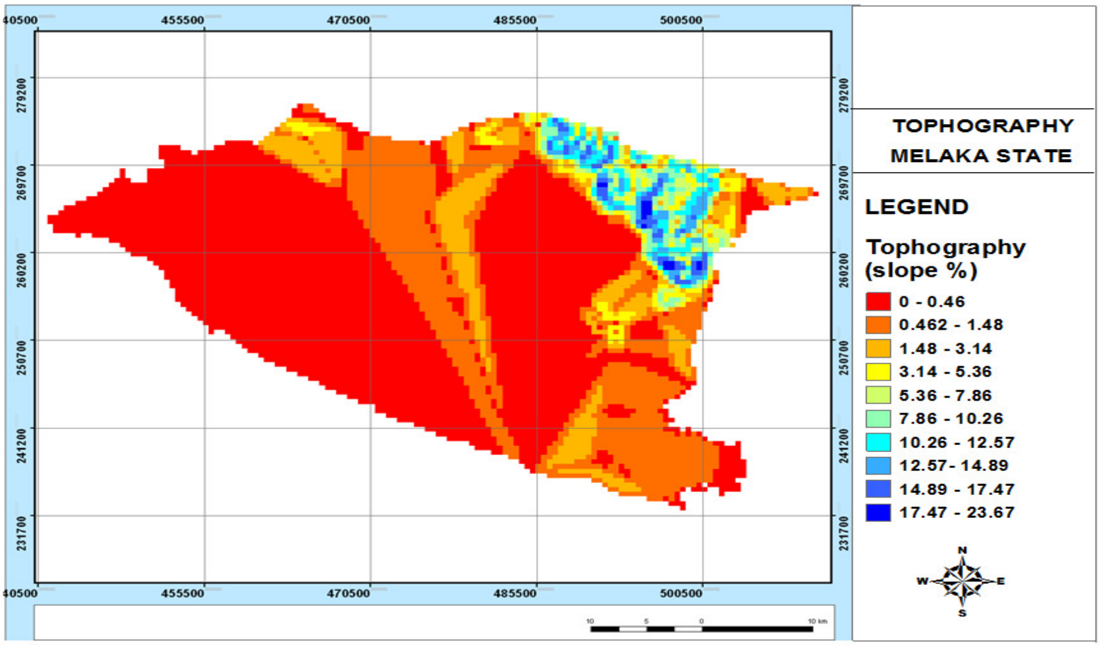

Figure 4.12: Topography map

4.3.6 Impact of Vadose Zone

Vadose zone is defined as the unsaturated layer above the groundwater table which is discontinuously saturated. The impact of vadose zone provides the first line natural defense against the contaminants to pass into the groundwater system. It controls the passage and attenuation of the contaminant into the aquifer. This zone is increased the significant travel time of the contaminants before reaching the groundwater system. The vadose zone has a significant effect to diminution groundwater pollution, because some pollutant attenuation processes occur in this layer such as biodegradation, filtration, mechanical straining, chemical reaction and dispersion (Piscopo, 2001). The impact of vadose zone map is presented in Figure 4.13 and the relevant rating ranges are shown in Table 4.4. The vadose zone formed by fine granite and gravel sand-clay mostly covered the study area and the rating values were assigned as 8 and 6, respectively because of their coarse texture formation, while another major formation of vadose governed by Granite and its assigned rating was 1 due to the insufficient opportunities for occurring some attenuation process through the media.

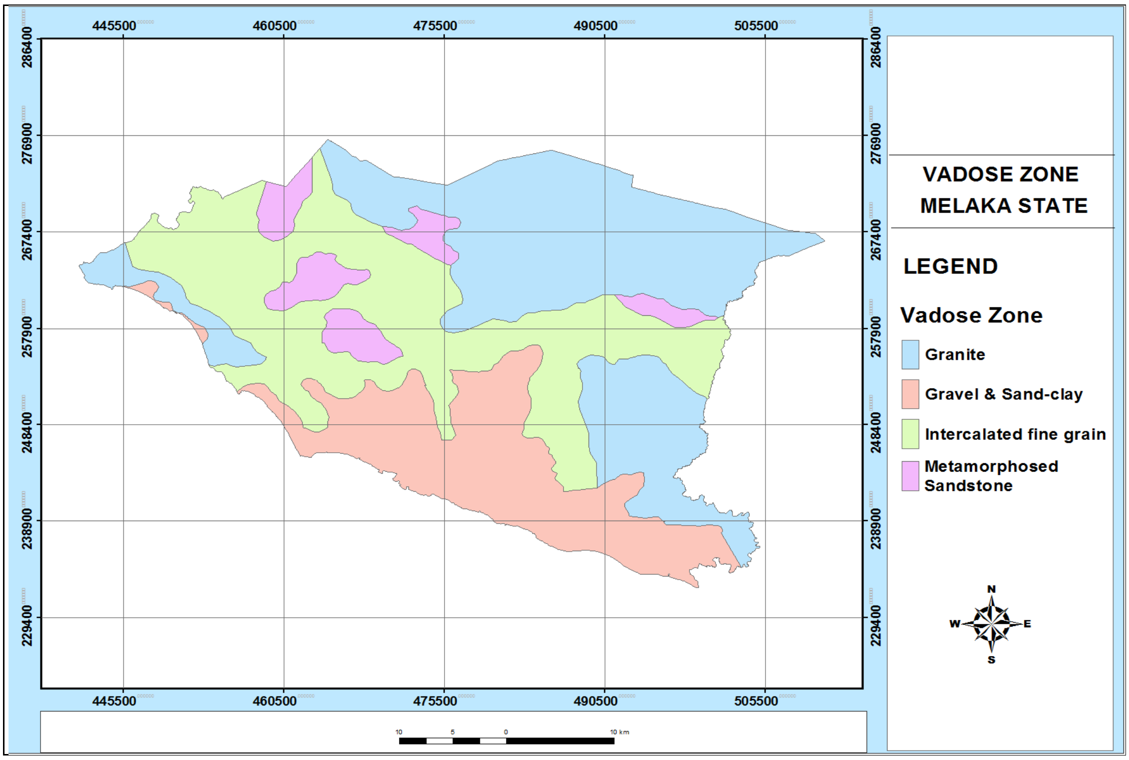

Figure 4.13: Vadose zone map

4.3.7 Hydraulic Conductivity

Hydraulic conductivity indicates the movement rate of groundwater through the saturated zone and transport contaminants into groundwater system. It represents the transfer speed of water through the aquifer of groundwater system. Contaminant percolation tendency is controlled within this zone. Only vertical conductivity was considered to assess the vulnerability, where higher rate conductivity indicates higher pollution potential. The hydraulic conductivity map (Figure 4.14) was generated from the pumping test data of 20 deep wells and improved after calibration of the mathematical model in steady state. The vertical hydraulic conductivities of the aquifer materials in the study area are commonly less than 1m/day and considered the constant rating value one (1) through the whole study area which is shown in Figure 4.14 and relevant classifications are shown in Table 4.4.

Table 4.4: DRASTIC quantitative parameters

	T x (1)	I x (5)	C x (3)
Rating	Topography (%)	Vadose zone media	Hydraulic conductivity (m/s)
10	0 - 2	Karst limestone	$> 9.5\times10^{-4}$
9	2 - 3	Basalt	$7 \times10^{-4} – 9.5\times10^{-4}$
8	3 – 4	Sand and gravel	$5\times10^{-4} – 7 \times10^{-4}$
7	4 – 5	Gravel and sand with silt and clay	$20 \times10^{-4} – 5\times10^{-4}$
6	5 – 6	Limestone, sandstone, slate	$30\times10^{-5} – 20\times10^{-4}$
5	6 – 10	Sandy silt	$20 \times10^{-5} – 30\times10^{-5}$
4	10 -12	Metamorphic/ Igneous	$15\times1^{-5} – 20\times10^{-5}$
3	12 – 16	Shale, silt, and clay	$10 \times1^{-5} – 15\times10^{-5}$
2	16 - 18	Silt/clay	$5\times10^{-5} – 10\times10^{-5}$
1	> 18	Confining layer, biotic-granite	$1.5\times10^{-7} – 5\times10^{-5}$

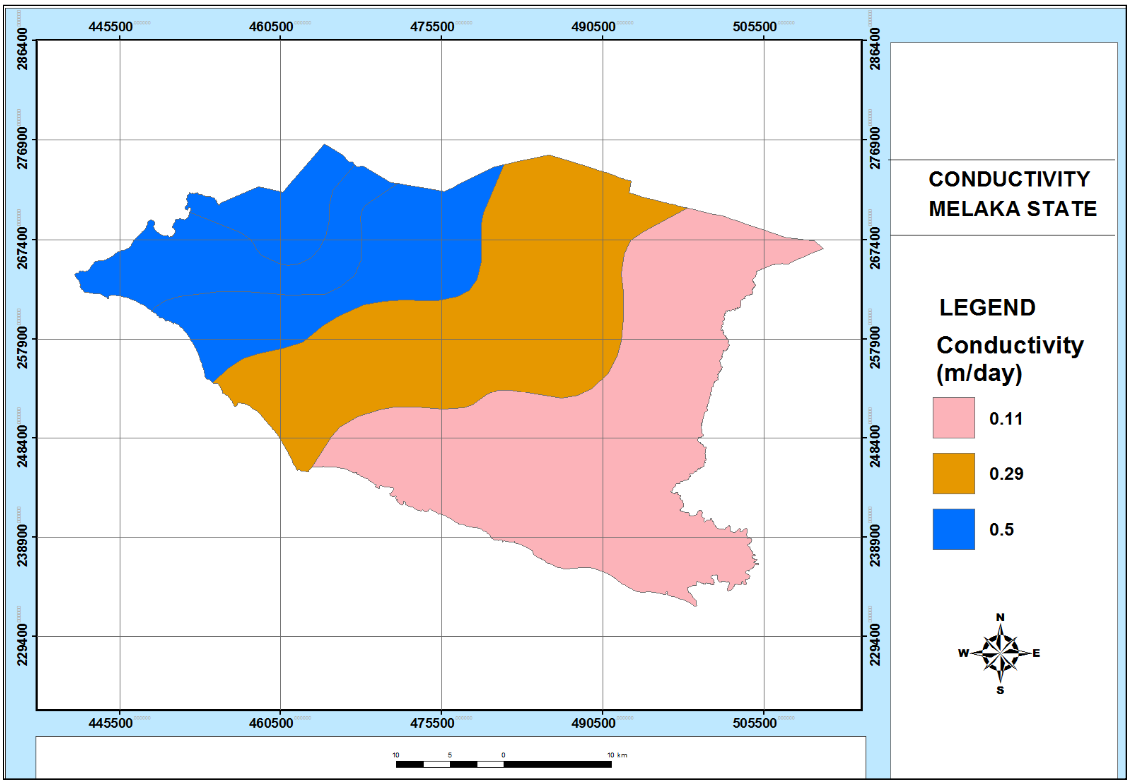

Figure 4.14: Hydraulic conductivity map

4.3.8 Final Vulnerability Map

The seven hydro-geological parameters were deemed important to generate final DRASTIC vulnerability map. The GIS coverage was all in raster format and the values for each overlay are assigned according to the pixel value of each area that resulted from multiplying the ratings with its appropriate DRASTIC weight. Combining the hydrogeological setting results in a range of numerical values termed the DRASTIC Index. Derived by combining the seven DRASTIC element index values, a range of values are developed that have been classified to represent groundwater vulnerability. These numbers are relative and have no intrinsic meaning other than in comparison with other like DRASTIC indices. The classification scheme is implemented based on the statistical grouping of DRASTIC index values. In order to maximize the difference between classes, a Natural Breaks method is chosen for identifying areas that fall within a low, medium, or high vulnerability region. The minimum and maximum range of

DRASTIC index was found as 23 and 230, respectively and classified into four classes such as very low, low, moderate and high (Aller, et al., 1987). In this study, the resulted DRASTIC index values laid between 80 and 185. Therefore, the DRASTIC index values are classified into three categories namely;- high vulnerability (>159), moderate vulnerability (120-159) and low vulnerability (80-119). The range of classifications and the affected area categorization are presented in Table 4.5. The classifications ranges are arbitrary and the corresponding categories can be varied which depend on the personal judgment of the researcher.

Table 4.5: Conventional DRASTIC index classification of the study area

DRASTIC index	DRASTIC range	% of the area
High vulnerability	> 159	27.45
Moderate vulnerability	120–159	61.53
Low vulnerability	80–119	11.02

The final DRASTIC groundwater vulnerability map (Figure 4.15) is clearly indicated that only a very small portion of the study area (North) is subjected to low vulnerability (11.02%) which is high land, and major parts of the study area shows moderate vulnerability to contamination (61.53%) is affected by agricultural and urban activities as well as found high groundwater level along the bank of Melaka Straight and its surrounding area. The area which is marked as high vulnerability (27.45%) to contamination falls in and around Melaka, Jasin and Alor Gajah Cities. These areas are threatened by high permeable and locally high recharge unconfined shallow aquifers. Wastewater is resulted from the urban and industrial activities of the Melaka, Jasin and Alor Gajah cities have significant effect to increase the high vulnerability of groundwater surrounding the city areas.

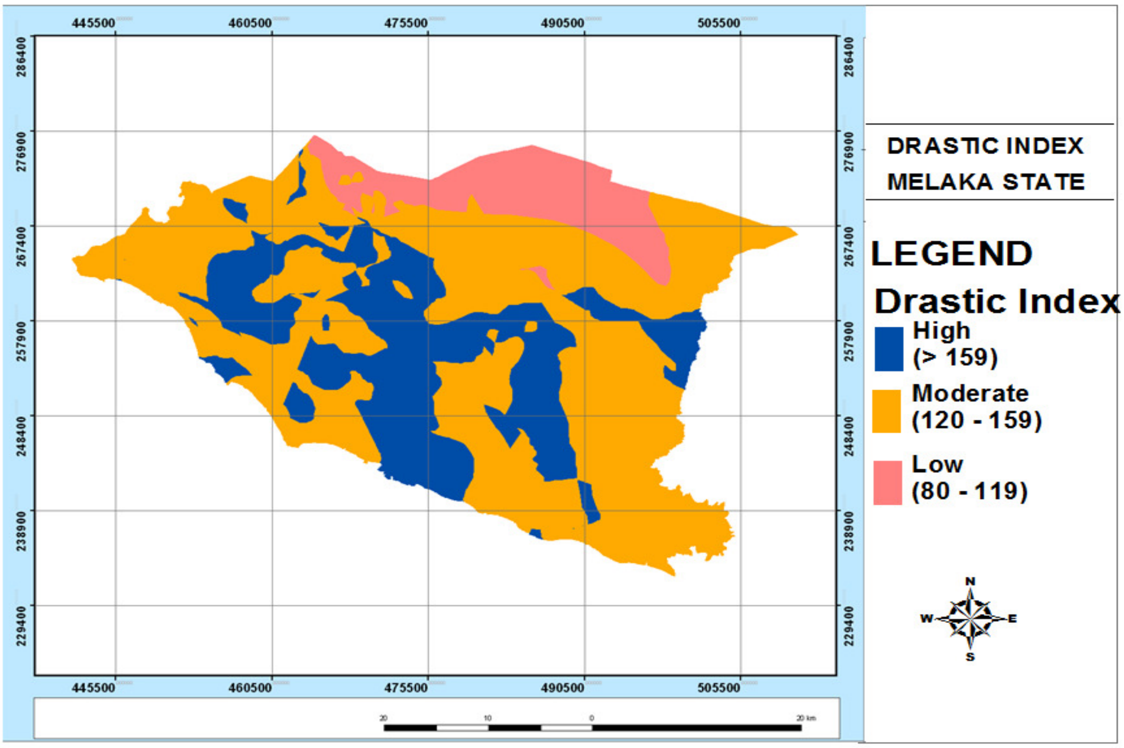

Figure 4.15: The DRASTIC aquifer vulnerability map

4.4 Final Risk Map

The risk map is generated using the modified DRASTIC method based on land use category, which indicates the area where anthropogenic activities is more liable for the groundwater vulnerability in the study area. The risk map is classified into three categories; low (100-139), moderate (140-175) and high (>175) vulnerability that is presented in Table 4.6, whereas the classification concepts are same as final vulnerability classification system.

Table 4.6: Modified DRASTIC index classification of the study area

MDI	MDI range	% of the area
High vulnerability	> 175	38.26
Moderate vulnerability	140–175	47.34
Low vulnerability	100–139	14.40

The results of the analysis show that 38.26% of the area is high vulnerability, 47.34% moderate vulnerability and 14.40% low vulnerability as presented in Figure 4.16. The risk map indicates that high vulnerability area is increased more than 11% while moderate vulnerability decreases around 14% compare to conventional DRASTIC vulnerability map. The comparison of risk map and land use map clearly indicates that the areas which are greatly affected by urban, industrial, agricultural, short term crop land, animal husbandry and horticultural activities are showed the high vulnerability of groundwater. Palm oil tree and other permanent crops are available in the moderate vulnerability zone. Therefore, it indicates the main adverse effects on the groundwater system are resulted from the agricultural, industrial and urban activities. The most hazards exist around the Melaka, Jasin and Alor Gajah cities due to the infiltration of urban and industrial waste water. Sea water intrusions also have significant effect to increase the groundwater vulnerability of coastal and its surrounding region.

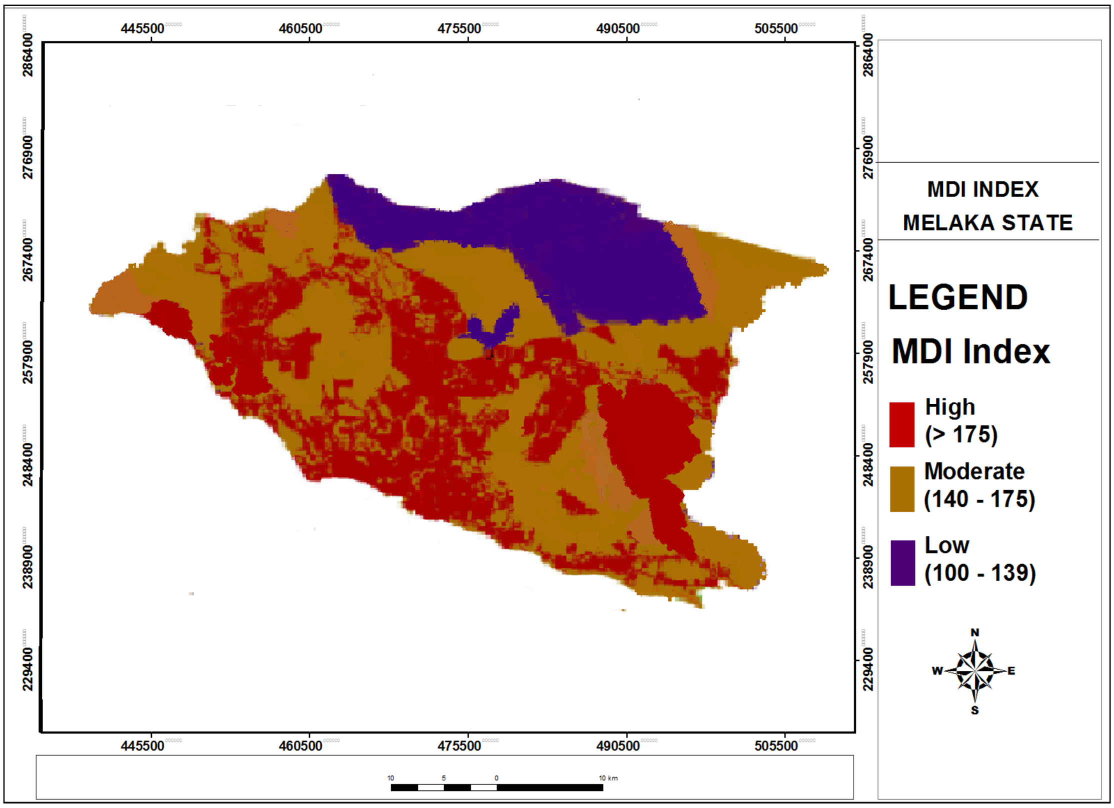

Figure 4.16: Modified DRASTIC aquifer vulnerability map

4.5 Validation of the DRASTIC Method

For the purpose of DRASTIC model validation, two groundwater quality parameters such as nitrate and chloride are used as a controlling parameter. In natural condition, nitrate is not generally present in groundwater. Usually it infiltrates from ground surface. Therefore, it is more effective indicating parameter to represent the groundwater contamination, where contaminants transport by infiltrate water from the ground surface into groundwater system. Nitrate and chloride parameter are used to develop the correlations with the values of conventional and modified DRASTIC index, respectively. Correlation is a technique for investigating the relationship between two quantitative, continuous variables. The linear correlation coefficient measures the strength and the direction of a linear relationship between two variables. The linear correlation coefficient is sometimes referred to as the Pearson product moment correlation coefficient in honor of its developer Karl Pearson (Pearson, 1900).

In this study, the correlations are established based on Pearson's correlation method and the SPSS software was used to develop the correlations. The required data such as Nitrate and Chloride concentration values as well as conventional DRASTIC index (DI) and modified DRASTIC index (MDI) values which are used to establish the correlations as shown in Table 4.7. Firstly, DI and MDI values are used to establish the correlation with Nitrate concentration values. The correlation coefficient values are found 0.772 and 0.82 for the DI and MDI which represent the strong correlations with them as shown in Tables 4.8 and 4.9. Secondly, Chloride concentration values are used to make the correlation with DI and MDI values and found the coefficient values 0.617 and 0.695, respectively which also show the good correlations between the parameters as shown in Tables 4.10 and 4.11.

Table 4.7: Correlation data for the DRASTIC method validation

Observation No.	NO_3 Concentration (mg/l)	Cl Concentration (mg/l)	DI	MDI
1	1	1	90	100
2	1	1	94	102
3	1	1	99	103
4	1	1	103	104
5	1	2	105	106
6	1	2	107	107
7	1	2	109	110
8	3	2	110	111
9	3	2	112	114
10	3	3	113	116
11	3	3	115	120
12	3	4	118	125
13	3	4	119	126
14	3	5	120	130
15	3	5	122	132
16	3	6	125	136
17	3	6	126	137
18	3	6	127	138
19	3	6	129	140
20	3	7	130	141
21	3	7	132	143
22	3	8	133	144
23	3	10	135	146
24	4	12	137	148
25	4	13	138	149
26	4	13	139	150
27	4	14	140	151
28	4	14	142	155
29	4	16	144	157
30	4	16	146	160
31	7	17	148	163
32	7	17	149	164
33	7	27	150	165
34	8	30	151	166
35	8	120	153	170
36	9	175	154	171
37	9	225	157	175
38	9	445	158	177
39	12	445	159	180
40	12	1025	161	185
41	13	1025	162	185
42	13	1750	165	190
43	13	1750	167	205
44	32	2200	173	210

Table 4.8: Correlation between Nitrate concentration and DRASTIC Index

		Nitrate	DI
Nitrate	Pearson Correlation	1	0.772**
	Sig. (2-tailed)		0.000
	N	44	44
DI	Pearson Correlation	0.772**	1
	Sig. (2-tailed)	0.000	
	N	44	44

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.9: Correlation between Nitrate concentration and Modified DRASTIC Index

		Nitrate	MDI
Nitrate	Pearson Correlation	1	0.820**
	Sig. (2-tailed)		0.000
	N	44	44
MDI	Pearson Correlation	0.820**	1
	Sig. (2-tailed)	0.000	
	N	44	44

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.10: Correlation between Chloride concentration and DRASTIC Index

		Chloride	DI
Chloride	Pearson Correlation	1	0.617**
	Sig. (2-tailed)		0.000
	N	44	44
DI	Pearson Correlation	0.617**	1
	Sig. (2-tailed)	0.000	
	N	44	44

**. Correlation is significant at the 0.01 level (2-tailed).

Table 4.11: Correlation between Chloride concentration and Modified DRASTIC Index

		Chloride	MDI
Chloride	Pearson Correlation	1	0.695**
	Sig. (2-tailed)		0.000
	N	44	44
MDI	Pearson Correlation	0.695**	1
	Sig. (2-tailed)	0.000	
	N	44	44

**. Correlation is significant at the 0.01 level (2-tailed).

The correlation coefficients are found 77% between nitrate concentrations and conventional DRASTIC index values, and 82% between nitrate concentrations and modified DRASTIC index values. Again, correlation coefficient is found 62% between chloride concentrations and conventional DRASTIC index values as well as 70 % between chloride concentrations and modified DRASTIC index values. In conclusion, Minitab's (Tables 4.9-4.12) from SPSS analysis output indicates that the strength of association between the variables is moderate to high ($r = 0.62-0.82$), and the correlation coefficient is high significantly different from zero ($P < 0.001$). All correlation coefficients are statistically significant at 99% confidence level according to Pearson's correlation method.

4.6 Groundwater Quality

Water quality is the most important issue for all living beings and different sectors of use. The chemical composition of groundwater in bedrock often varies greatly from the superficial drift deposit. The groundwater from bedrock is often more natural, more basic, more reducing, more sodium-rich and contains more of most of the minor/trace elements than drift groundwater. The 52 shallow and 14 deep boreholes groundwater quality data were collected from Mineral and Geo-science Department (Appendix G) and analyzed for major cations (Ca^{2+}, Mg^{2+}, Na^{+}, Fe^{2+}, Mn^{+2} and K^{+}) and anions (HCO_3^-, SO^{2-}_4 and Cl^-). Other physico-chemical parameters like conductivity, pH, total dissolved solids and turbidity were also measured. The different groundwater quality parameter values are presented in the form of histograms from Figures 4.17 to 4.26 for shallow and deep boreholes. The histograms represent the concentration values and its frequency of individual groundwater quality parameter. The various groundwater quality parameters of the study area are analyzed and mentioned its present state. The groundwater quality of Central Melaka is in good condition and can be used as raw water in accordance with the requirements based on the raw water quality standards by the Ministry of Health Malaysia (Appendix E). However, some places, such as Mukim Keeling, Cheng, Ayer Molek and Cage experience salty and brackish conditions as a result of seawater intrusion. The groundwater is affected by the brackish nature in the coastal region due to the seawater influence and hydrogeochemical process (Bahar & Reza, 2010). The quality of ground water in Alor Gajah district is still eligible as a source of water for residents. The quality of groundwater, particularly in the coastal areas of Kuala Linggi is still contaminated by salt water due to the intrusion of seawater. Over pumping and decreasing recharge rate causes aquifer depletion and leads to the intrusion of seawater (Moustadraf et al., 2008; Pujari & Soni, 2008; Zhou, 2009). Commonly, the coastal areas of this region are subjected to the brackish and salty conditions located both on the alluvium stone and hard rock stone.

The groundwater quality analysis indicated that turbidity, total dissolved solids, iron, chloride and cadmium values were high for both shallow and deep boreholes in few parts of the study area. The pH values of shallow boreholes indicated that around 50% of water samples were between 4-6.5 and the remaining 50% of water samples were between 6.5 and 8.2. Again, the pH values of the deep boreholes indicated that about 50% of the samples were around 5.2 and the remaining 50% were between 6.7 and 8.5. The high TDS values indicated that the groundwater was affected by the percolation of agricultural, industrial and residential runoff water. The statistical analysis of different water quality parameter values are presented in Tables 4.12 and 4.13 for shallow and deep boreholes, respectively. The statistical results indicated that Conductivity, TDS, Na, Cl and SO_4 concentration values abruptly varies for shallow aquifer as well as for deep aquifer except SO_4. On the otherhand, pH, CO_3, Cd and P values for shallow aquifer and pH, NO_3-N, Fe, K, Cd values for deep aquifer showed very close differences, in which water samples collected from different boreholes of the study area.

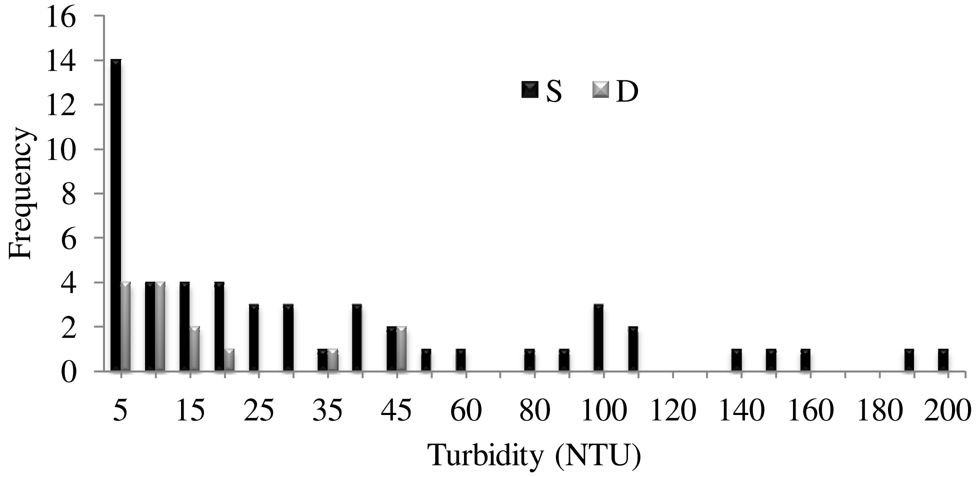

Figure 4.17: Turbidity values in shallow and deep boreholes

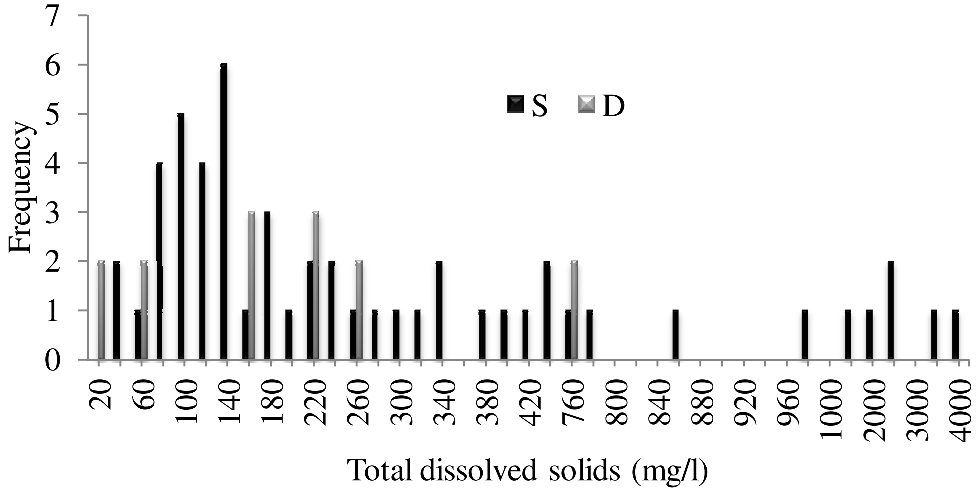

Figure 4.18: Total dissolved solids values in shallow and deep boreholes

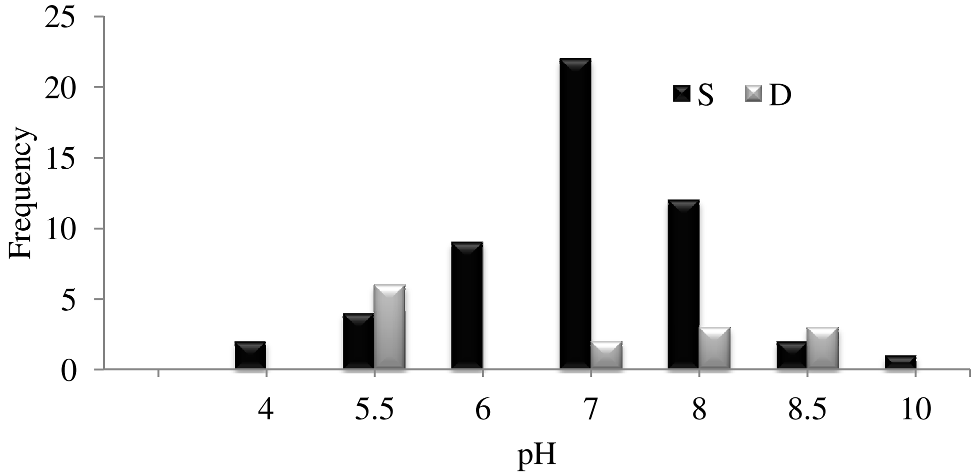

Figure 4.19: pH values in shallow and deep boreholes

S= Shallow borehole, D= Deep borehole,

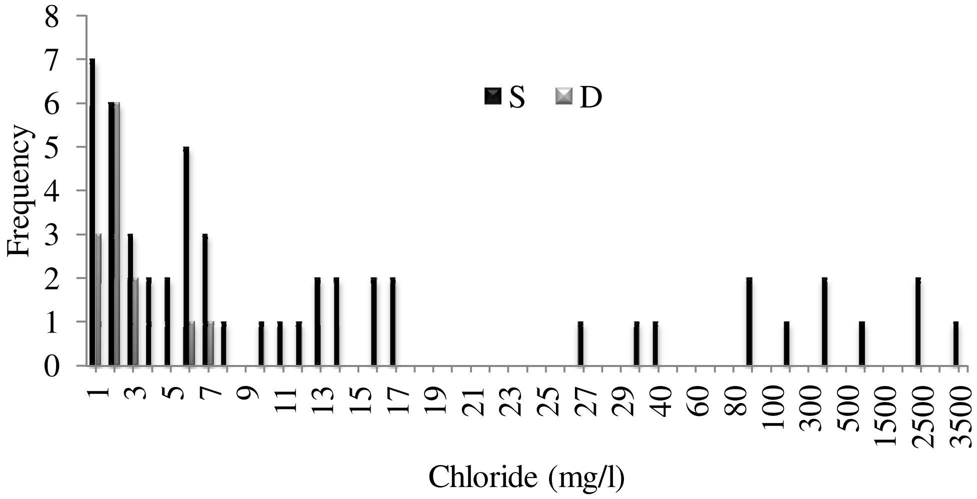

Figure 4.20: Chloride values in shallow and deep boreholes

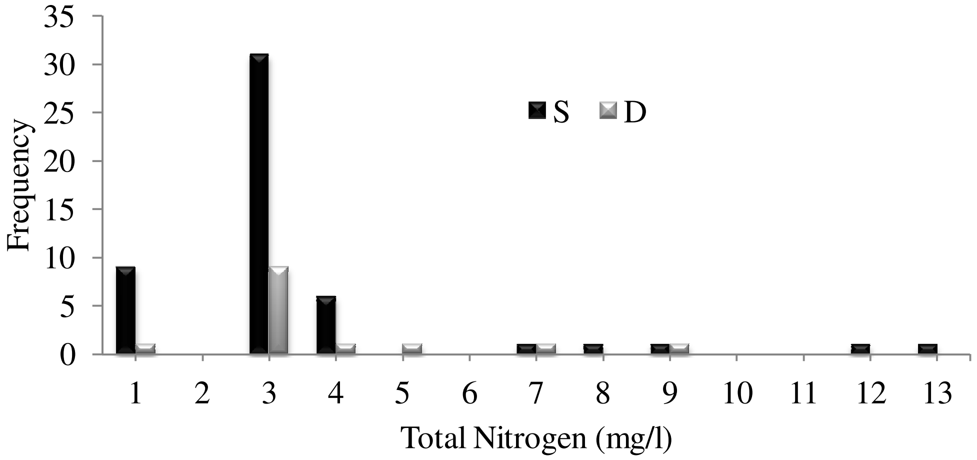

Figure 4.21: Total Nitrogen values in shallow and deep boreholes

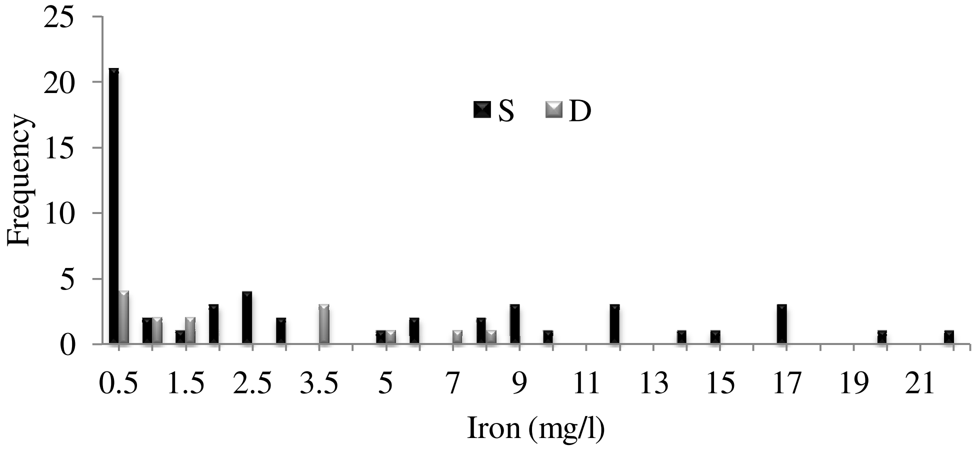

Figure 4.22: Iron values in shallow and deep boreholes

S= Shallow borehole, D= Deep borehole,

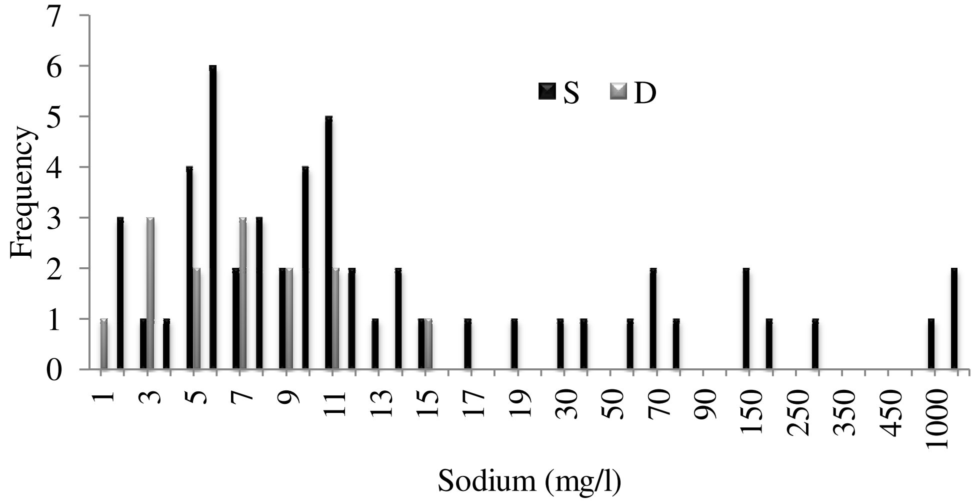

Figure 4.23: Sodium values in shallow and deep boreholes

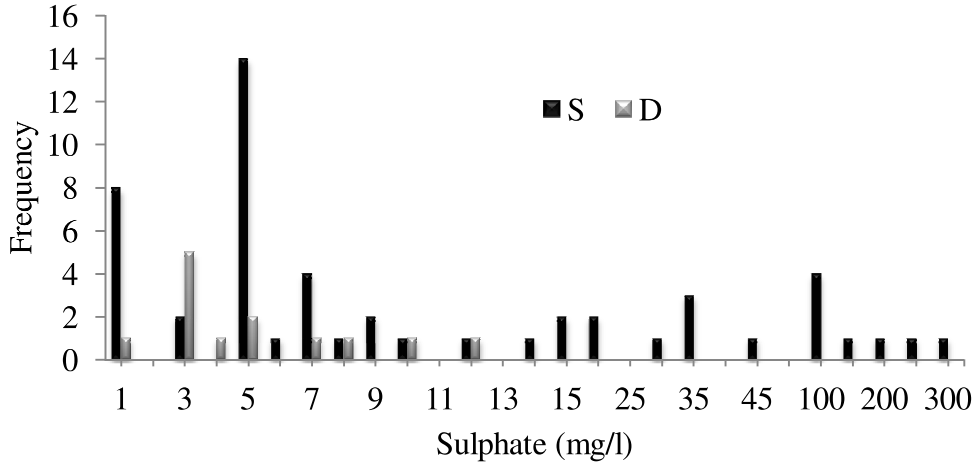

Figure 4.24: Sulphate values in shallow and deep boreholes

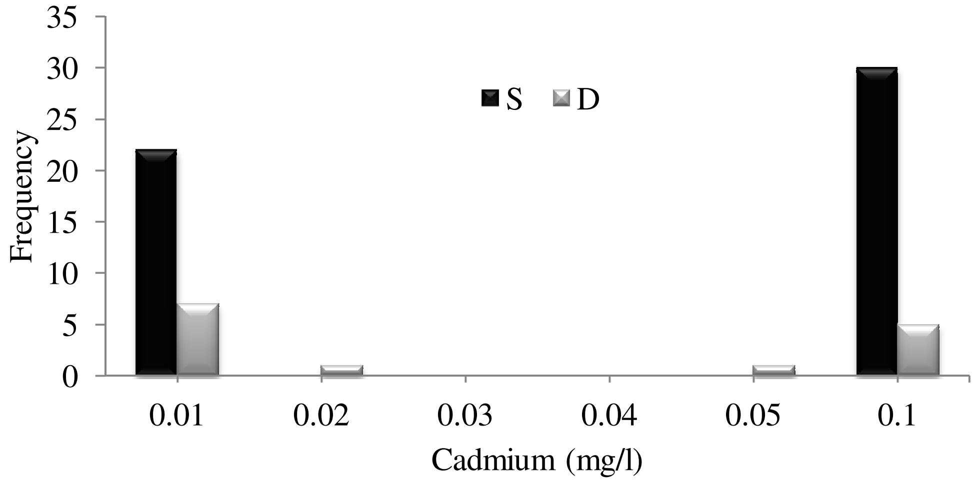

Figure 4.25: Cadmium values in shallow and deep boreholes

S= Shallow borehole, D= Deep borehole,

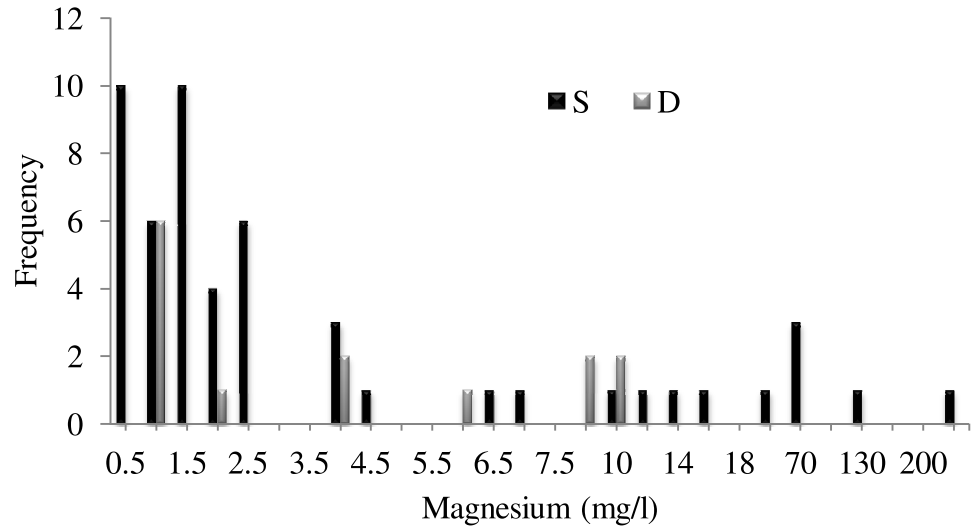

Figure 4.26: Magnesium values in shallow and deep boreholes

S= Shallow borehole, D= Deep borehole,

Table 4.12: Statistical analysis of groundwater quality parameters for shallow aquifers

Parameter	Mean	Median	Mode	Variance	Standard Deviation
Turbidity (NTU)	43.55	20.5	0.9	2838.05	53.27
pH	6.61	6.8	6.87	1.44	1.20
TDS (mgL^{-1})	575.39	182	76104128	1385412.95	1177.04
Cl (mgL^{-1})	198.08	7	1	400684.39	198.08
No_3-N (mgL^{-1})	4.89	3	3	172.99	13.45
Fe (mgL^{-1})	6.61	1.9	0	274.21	16.56
Mg (mgL^{-1})	11.58	1.65	1.3	1309.09	36.18
Na (mgL^{-1})	83.11	10	11	65539.88	256.01
So_4 (mgL^{-1})	49.75	7	5	26122.01	161.62
Ca (mgL^{-1})	22.62	8	1.7	2438.62	49.38
Hco_3 (mgL^{-1})	47.90	25	1	3040.48	55.14
Si (mgL^{-1})	19.53	17.5	21	179.98	13.42
Co_3 (mgL^{-1})	2.48	1	1	16.37	4.05
Al (mgL^{-1})	4.57	0.1	0.1	784.33	28.01
K (mgL^{-1})	7.03	3.5	3.5	184.67	13.59
Cd (mgL^{-1})	0.10	0.1	0.1	0.03	0.17
P (mgL^{-1})	0.70	0.02	0.02	5.62	2.37
Conductivity (µS/cm)	513.63	122.5	56	2316618.60	1522.04

Table 4.13: Statistical analysis of groundwater quality parameters for deep aquifers

Parameter	Mean	Median	Mode	Variance	Standard Deviation
Turbidity (NTU)	14.06	9.2	1	242.30	15.57
pH	6.66	6.7	5.2	1.86	1.36
TDS (mgL^{-1})	1210.73	196	36285480	11539996	8897.05
Cl (mgL^{-1})	74.60	2	2	79687.31	282.29
No_3-N (mgL^{-1})	3.92	3	3	9.72	3.12
Fe (mgL^{-1})	1.83	0.5	0.1,0.5	6.07	2.46
Mg (mgL^{-1})	8.74	2.4	0.1	443.69	21.06
Na (mgL^{-1})	148.6	7.4	12	194558.53	441.08
So_4 (mgL^{-1})	40.29	4	1	8788.06	40.29
Ca (mgL^{-1})	44.21	14	11	3822.74	44.21
Hco_3 (mgL^{-1})	76.72	18	5	8180.66	90.44
Si (mgL^{-1})	18	10	1	626.88	25.03
Co_3 (mgL^{-1})	6.89	1	1	395.53	19.89
Al (mgL^{-1})	20.42	0.1	0.1	3698.43	60.81
K (mgL^{-1})	3.05	1	0.01	13.88	3.73
Cd (mgL^{-1})	1.17	0.02	0.01	8.40	2.90
P (mgL^{-1})	25.49	0.025	0.02	5479.25	74.02
Conductivity (µS/cm)	355.80	55	5	870428.30	932.96

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

The research findings, various issues and discussions have been placed in the previous chapters. The methodologies, assessment and necessary discussion are placed there. This chapter summarizes the research findings and recommends for further research directions.

5.2 Summary and Conclusions

[a] The analysis of the hydraulic conductivity, transmissivity and aquifers yield results indicates that the aquifers formed by schist, sand, limestone as well as volcanic rocks are the most productive for groundwater.

[b] Groundwater potentiality is satisfactory in most places underlaid by phyllite, schist and slate. This reason may first, be because the bedrock is fractured, and second, because of the high recharge rate due to available rainfall.

[c] The productivity of the aquifer is classified by having a typical yield ranges of <3.6 m^3/h (low), 3.6-12 m^3/h (moderate) and >12 m^3/h (high). From the view of aquifer productivity, 35% of the area has low potential, 57% has moderate potential and 8% has high potential for groundwater. Most of the aquifers located on the bank of the straits of Melaka are subjected to high groundwater level.

[d] An attempt has been made to assess the aquifer vulnerability of Melaka groundwater plain employing the empirical index model called DRASTIC method. The GIS techniques have provided an efficient environment for analysis

and high capabilities in handling a large quantity of spatial data. The thematic maps of the model are constructed, classified and encoded employing various maps by GIS functions.

[e] The DRASTIC vulnerability map is classified into three categories namely;- high vulnerability (>159), moderate vulnerability (120-159) and low vulnerability (80-119). The vulnerability map shows that 27.45% of the area is high vulnerability, which is mainly due to the aquifer media of the Melaka River basin and its surrounding areas. About 61.53% of the area is categorized as moderate vulnerability, which is under threatened by high permeable as well as locally high recharge unconfined shallow aquifers, and 11.02% of the area is under the low vulnerability which is high land and located in the north.

[f] The classifications of risk map are low vulnerability (100-139), moderate vulnerability (140-175) and high vulnerability (>175). The results of the analysis show that 38.26% of the area is high vulnerability, 47.34% moderate vulnerability and 14.40% low vulnerability. Risk map shows that the high vulnerability area increases more than 11% compare to conventional DRASTIC vulnerability map, which is resulted from agricultural, urban and industrial activities. Sea water intrusions effect on the groundwater vulnerability is greatly noticed from the vulnerability and risk maps due to high groundwater level in the coastal region.

[g] The groundwater quality analysis results indicate that the quality is almost satisfactory for drinking and other purposes, however turbidity, total dissolved solids, iron, chloride and cadmium values are exceeded the limit of the drinking water quality standard in very few cases. The ranges of pH were 4 - 8.2 for shallow and 5.2 - 8.1 for deep boreholes.

[h] Groundwater along the bank of Melaka straight is subjected to brackish and salty conditions due to the intrusion of seawater. It is also affected by the percolation water resulted from the urban and agricultural activities.

[i] In conclusion, groundwater in the State of Melaka can be used for the development of the industrial and agricultural activities as well as domestic water supply in remote areas, in which some major treatments are recommended in few cases.

5.3 Implication

[a] Groundwater vulnerability, potentiality and quality maps play a prominent role to make a sustainable water resources development plans. Groundwater vulnerability and risk maps as well as productivity map can be used for groundwater protection planning, decision making and management as well as the category of environmental map.

[b] The groundwater vulnerability, risk and productivity maps can be used as a preliminary screening tool for any area to get an overall understanding of the groundwater condition.

[c] Organizations that can be benefited from the groundwater vulnerability, risk and productivity maps of the Melaka State include the Department of Groundwater Resources, Pollution Control Department, Department of Industrial Work and the Office of the Environment Policy and Planning.

[d] The results of the present study can be helped for the regulatory agencies to prioritize monitoring the problem closely and act accordingly. The respective agencies can be observed the land use pattern to groundwater contamination and can be taken the necessary actions to protect these resources. These results can be used for groundwater exploration and dumping site selection in the study area.

[e] The DRASTIC methodology is demonstrated in this study, and being generic in nature. The method can be applied in other regions in Malaysia or elsewhere with appropriate modification of the hydrogeological settings and providing adequate data are available.

5.4 Recommendations

[a] The study is carried out considering only intrinsic vulnerability. It can be developed the specific vulnerability map considering certain specific contaminants.

[b] This study is only considered the rainfall and evaporation data to calculate the net recharge. It can be considered the irrigation return flow, wastewater seepage from sewerage, infiltration from soak pits and seepage from other water networks to calculate the net recharge.

[c] Sensitivity analysis is not carried out in this study since most of the water quality parameters concentration values are not exceeded the standard water quality limit. Sensitivity analysis can be done for further study.

[d] Groundwater potentiality is assessed based only pumping test data and aquifer productivity results. It can be assessed by developing the potentiality index method based on the assign values called rating and weighting of some hydrogeological settings like as DRASTIC index.

[e] Integrated Land use planning to solve conflicts between land use and groundwater protection, as it takes, from the beginning, all relevant aspects into consideration.

[f] Awareness creation on groundwater vulnerability to pollution among the decision/policy makers and planners to give an impulse to environmental thinking and public concern.

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Appendix-A

LIST OF PUBLICATIONS

1. S.M. Shirazi, Imran Hosen, Mohammad Sholichin and Shatirah Akib (2011). Investigation of Groundwater Potential in Melaka District of Malaysia. *Advanced Materials Research,* 243-249, pp 4553-4556.

2. H.M. Imran and S.M. Shirazi (2012). Evaluation of Groundwater Contamination at Melaka Catchment in Malaysia. *Advanced Science letters*, 14, 47-53.

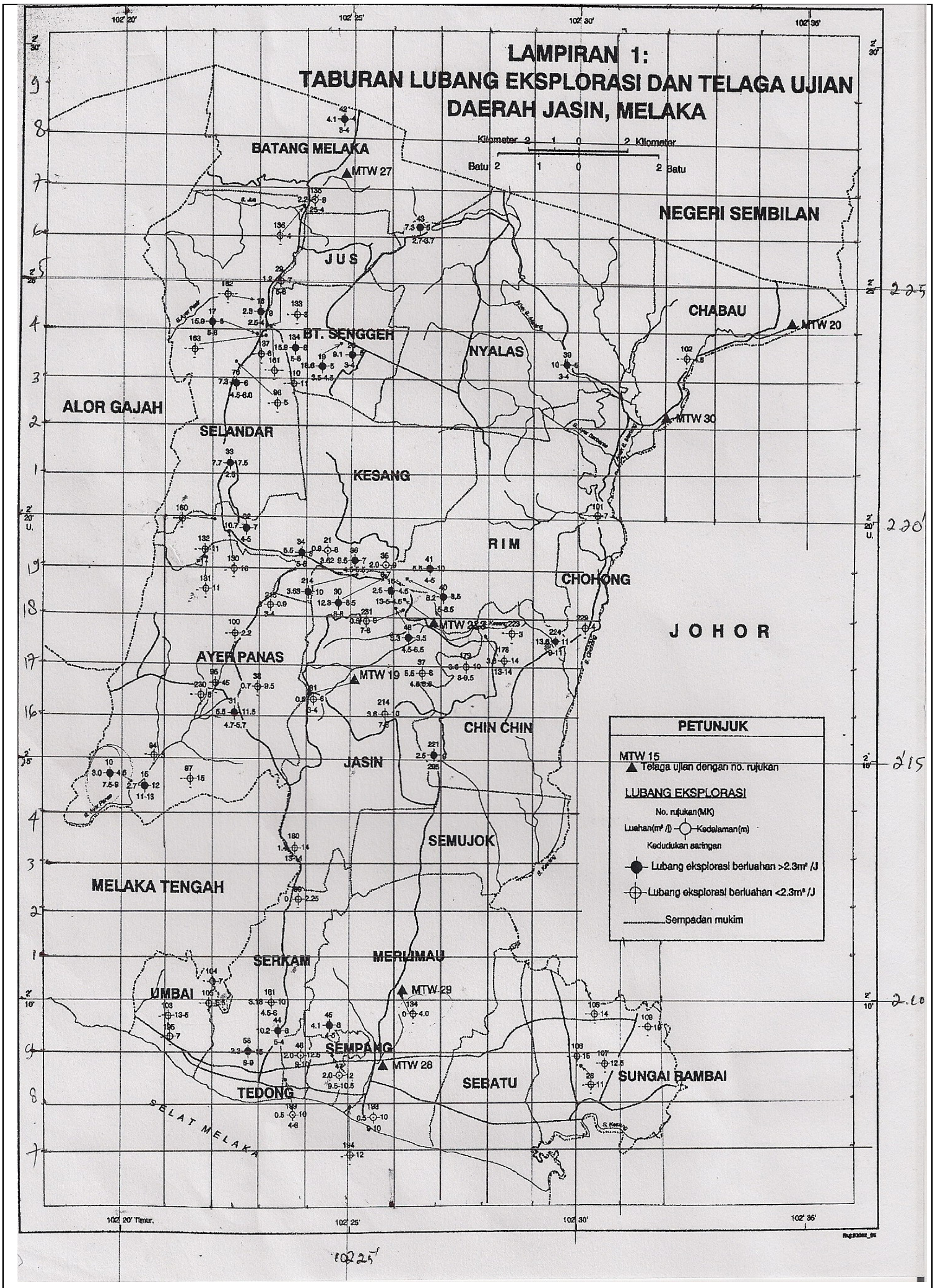
3. S.M. Shirazi and H.M. Imran and Shatirah Akib (2012). GIS-based DRASTIC Method for Groundwater Vulnerability Assessment: A Review. *Journal of Risk Research*, 1-21.

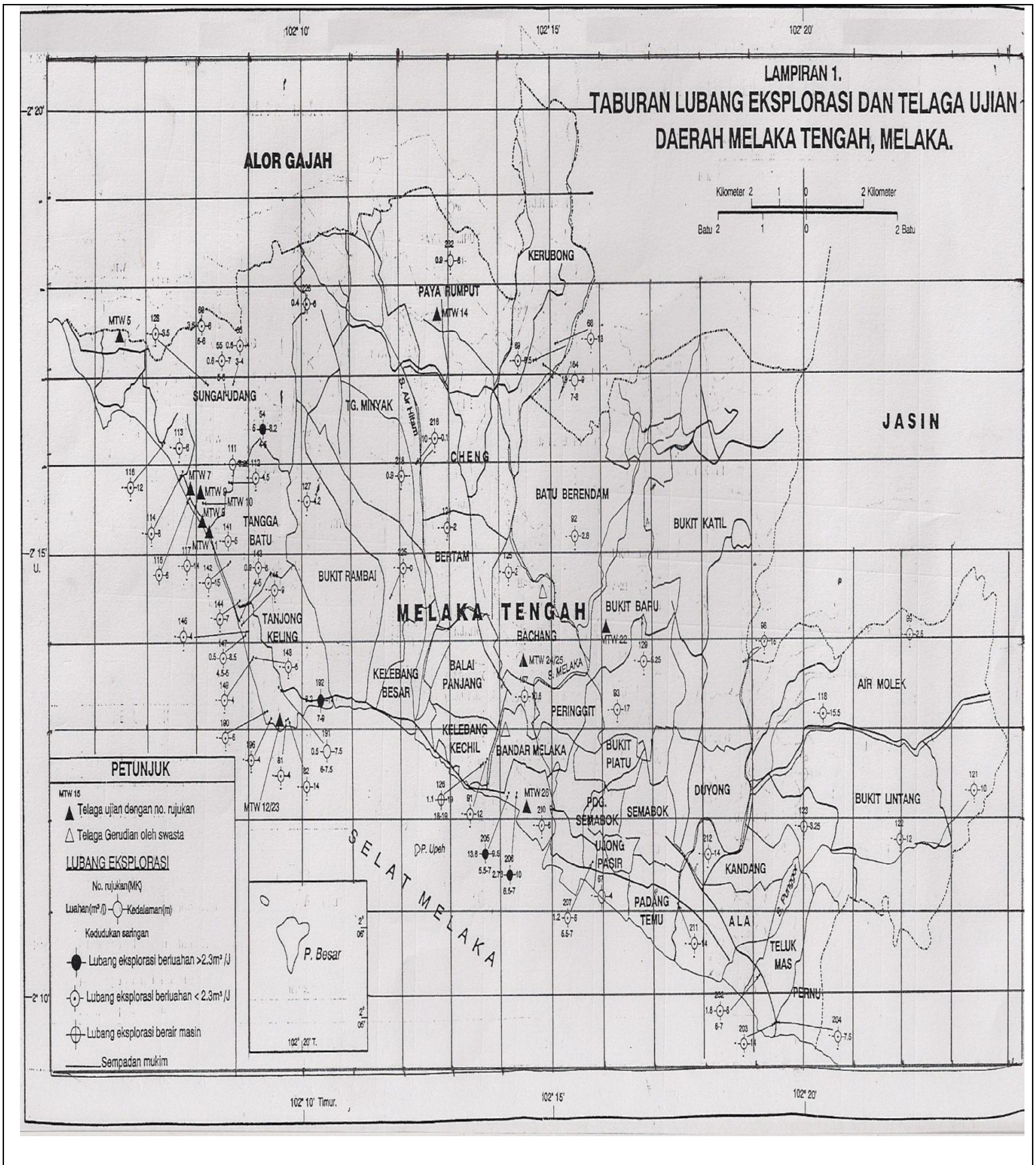
4. S.M. Shirazi, H.M. Imran, Shatirah Akib, M. Sholichin and Z.B. Harun (2012). Groundwater Vulnerability Assessment in Melaka Catchment of Malaysia Using DRASTIC and GIS Techniques. *Environmental Earth sciences*. Under Review.

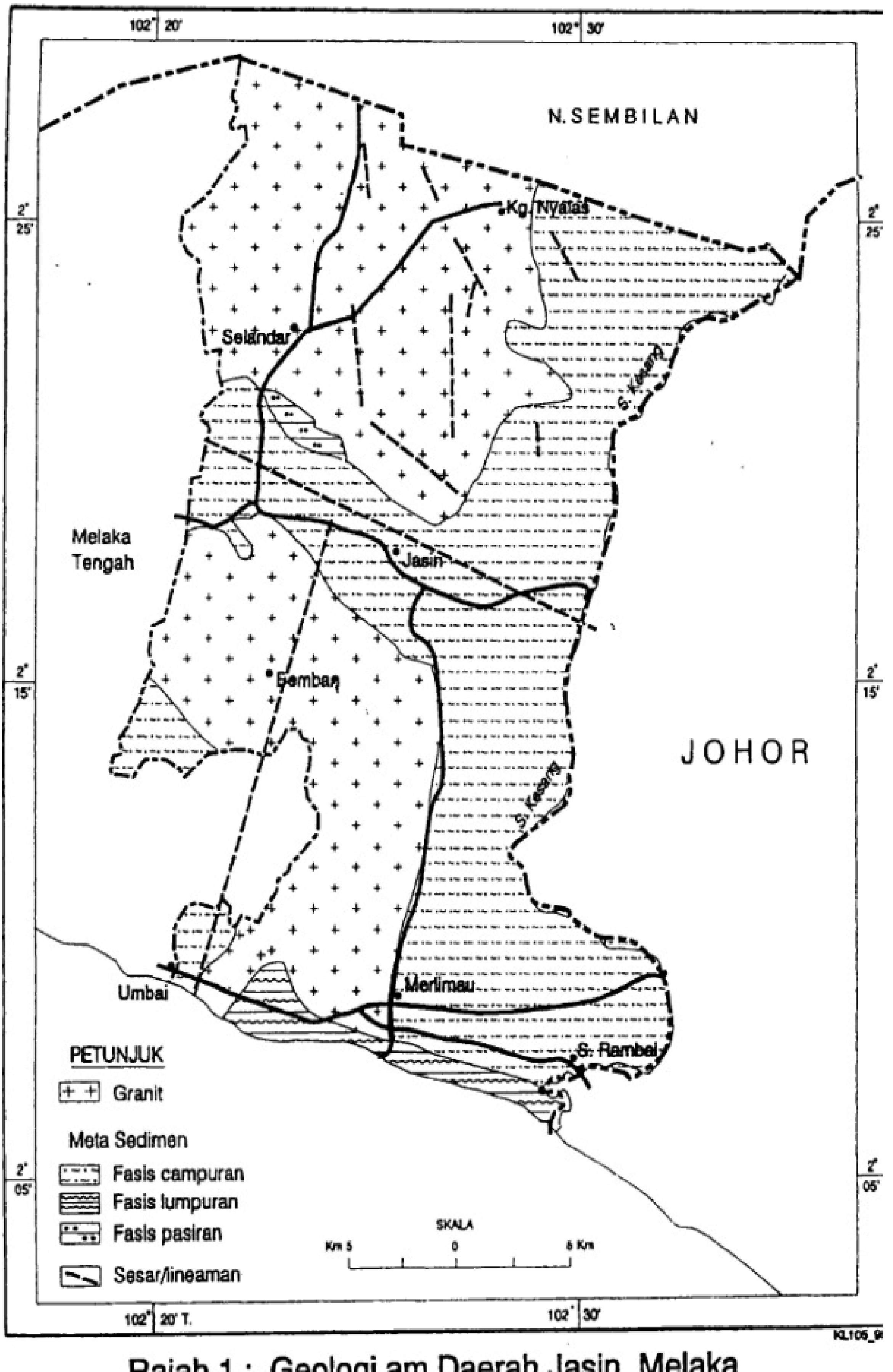
5. H.M. Imran and S.M. Shirazi (2012). Hydrogeological Investigation and Groundwater Quality Assessment of Melaka Catchment in Malaysia. Journal of Hydro-environment Research. Under Review.

Appendix - B

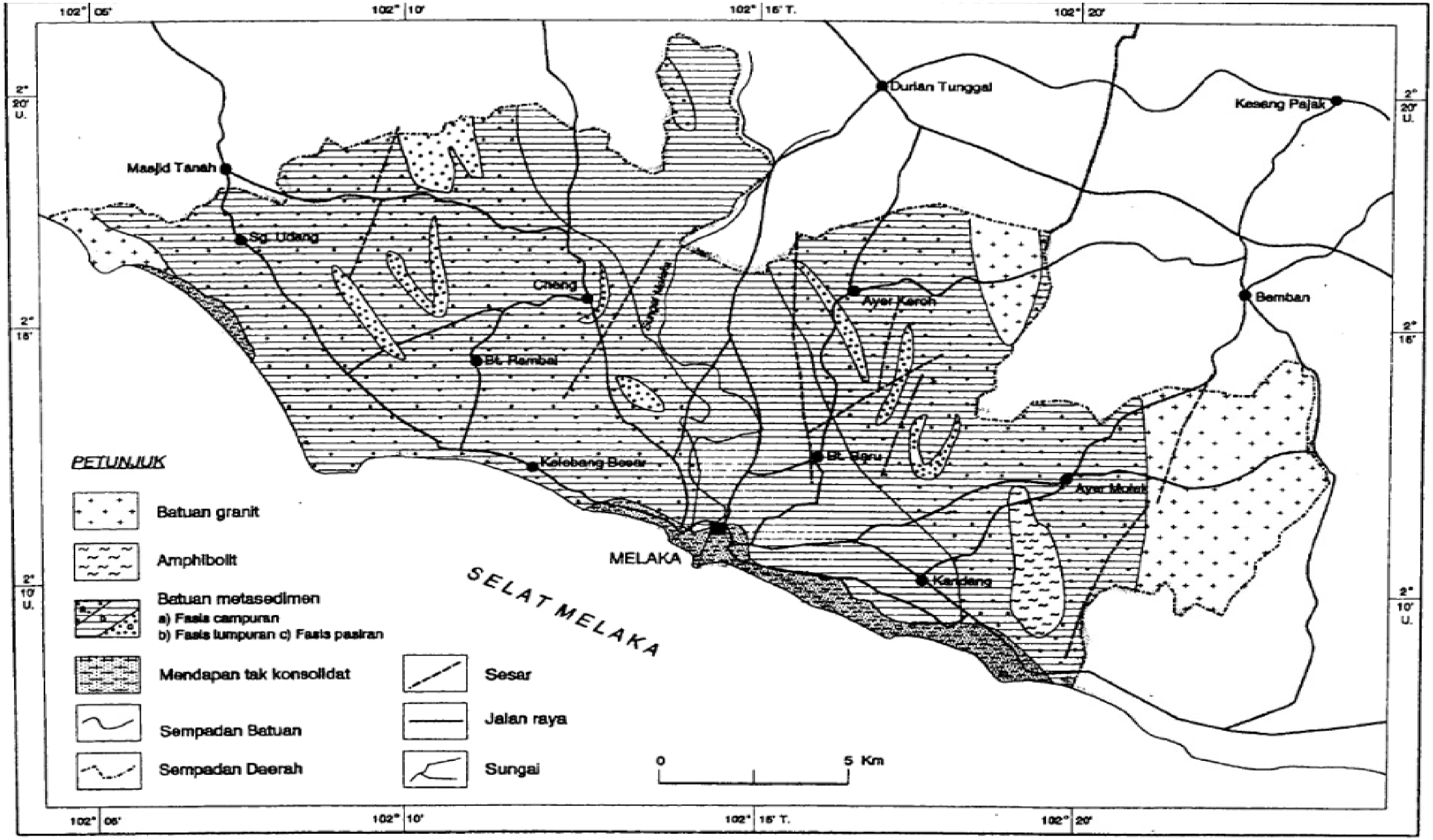
AQUIFER DISTRIBUTION AND GEOLOGY MAP OF MELAKA



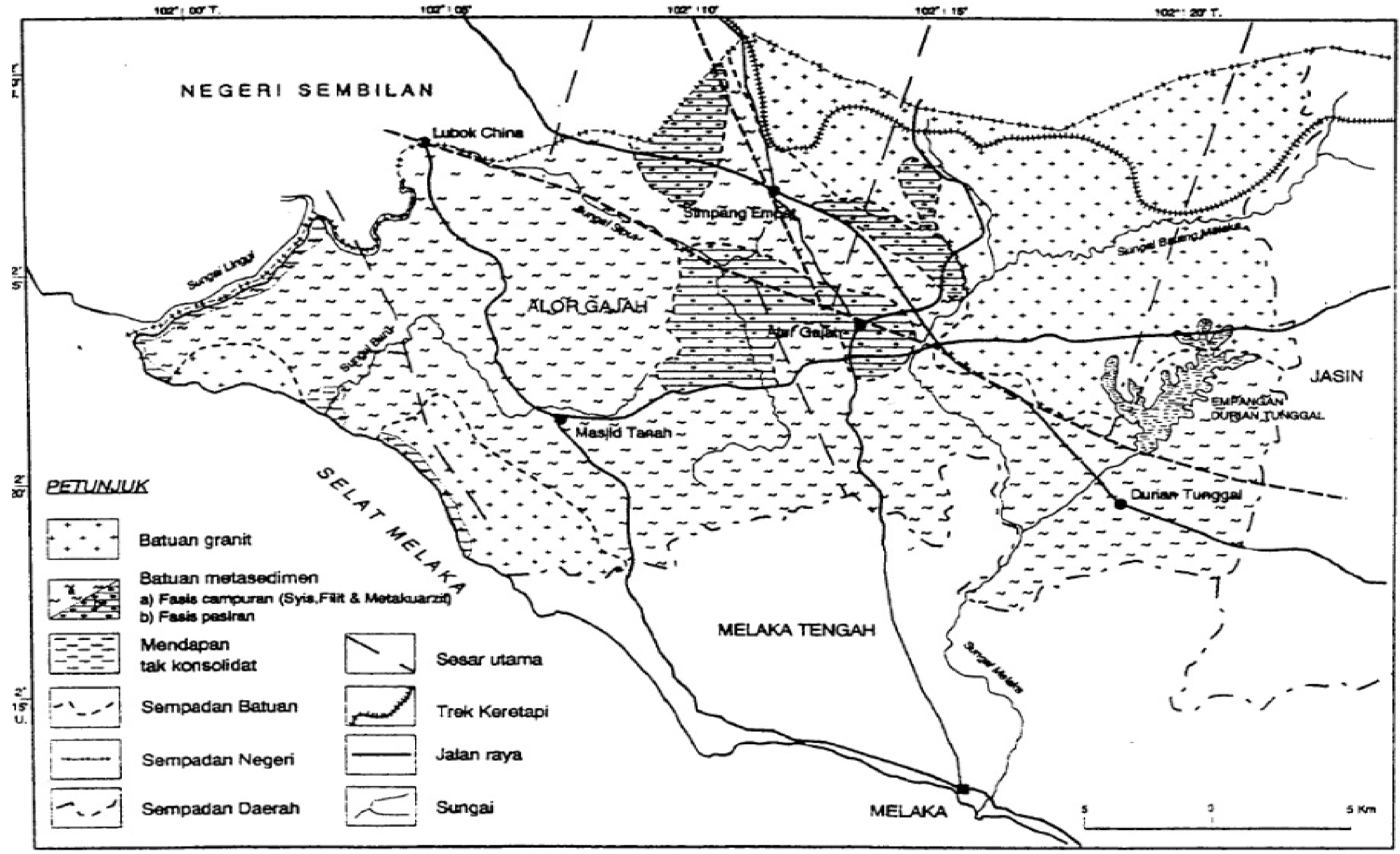

LAMPIRAN 1.
TABURAN LUBANG EKSPLORASI DAN TELAGA UJIAN
DAERAH MELAKA TENGAH, MELAKA.
Kilometer 2 1 0 2 Kilometer
Batu 2 1 0 2 Batu
102° 10'
102° 15'
102° 20'
2° 20'
2° 15' U.
2° 10'
102° 10' Timur.
ALOR GAJAH
JASIN
MELAKA TENGAH
KERUBONG
PAYA RUMPUT
MTW 14
MTW 5
SUNGAI UDANG
TG. MINYAK
S. Air Hitam
CHENG
BATU BERENDAM
BUKIT KATIL
TANGGA BATU
MTW 7
MTW 9
MTW 10
MTW 8
MTW 11
BUKIT RAMBAI
BERTAM
TANJONG KELING
BUKIT BARU
BACHANG
MTW 22
MTW 24/25
S. MELAKA
KELEBANG BESAR
BALAI PANJANG
PERINGGIT
AIR MOLEK
KELEBANG KECHIL
BANDAR MELAKA
BUKIT PIATU
DUYONG
BUKIT LINTANG
MTW 12/23
MTW 20
PDG. SEMABOK
SEMABOK
UJONG PASIR
P. Upeh
SELAT MELAKA
KANDANG
PADANG TEMU
ALA
TELUK MAS
PERNU
S. Duyong
P. Besar
2° 05'
102° 20' T.
PETUNJUK
MTW 15
▲ Telaga ujian dengan no. rujukan
△ Telaga Gerudian oleh swasta
LUBANG EKSPLORASI
No. rujukan(MK)
Luahan(m³/J) Kedalaman(m)
Kedudukan saringan
Lubang eksplorasi berluahan >2.3m³ /J
Lubang eksplorasi berluahan < 2.3m³ /J
Lubang eksplorasi berair masin
Sempadan mukim



Rajah 1 : Geologi am Daerah Jasin, Melaka



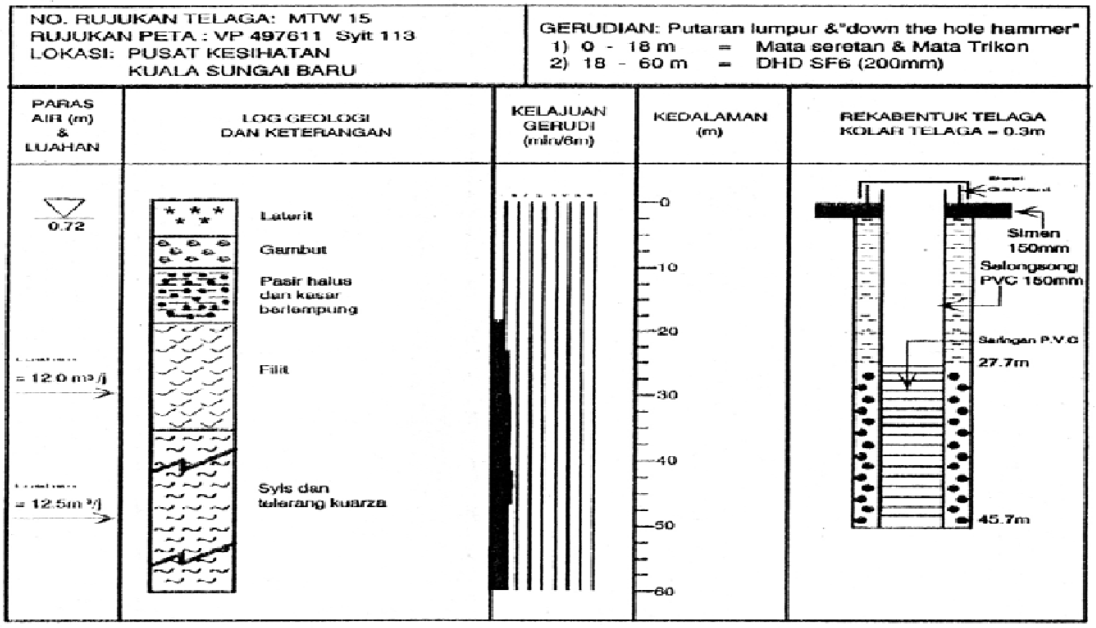
Rajah 3: Geologi am Daerah Melaka Tengah (Rishworth, 1964)

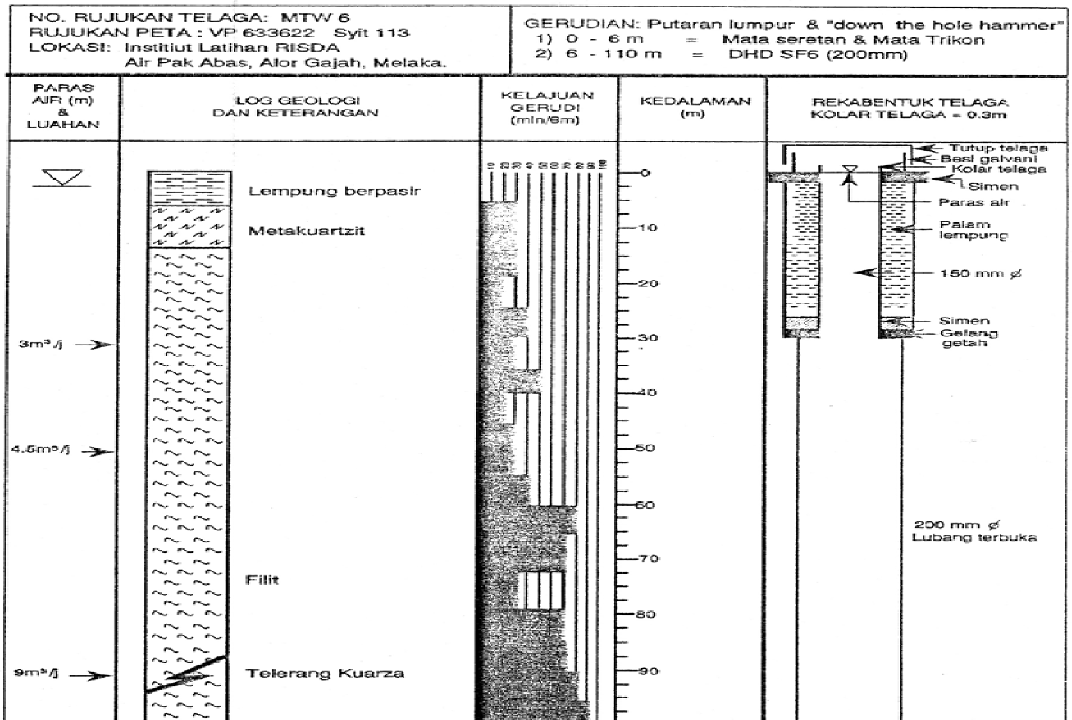


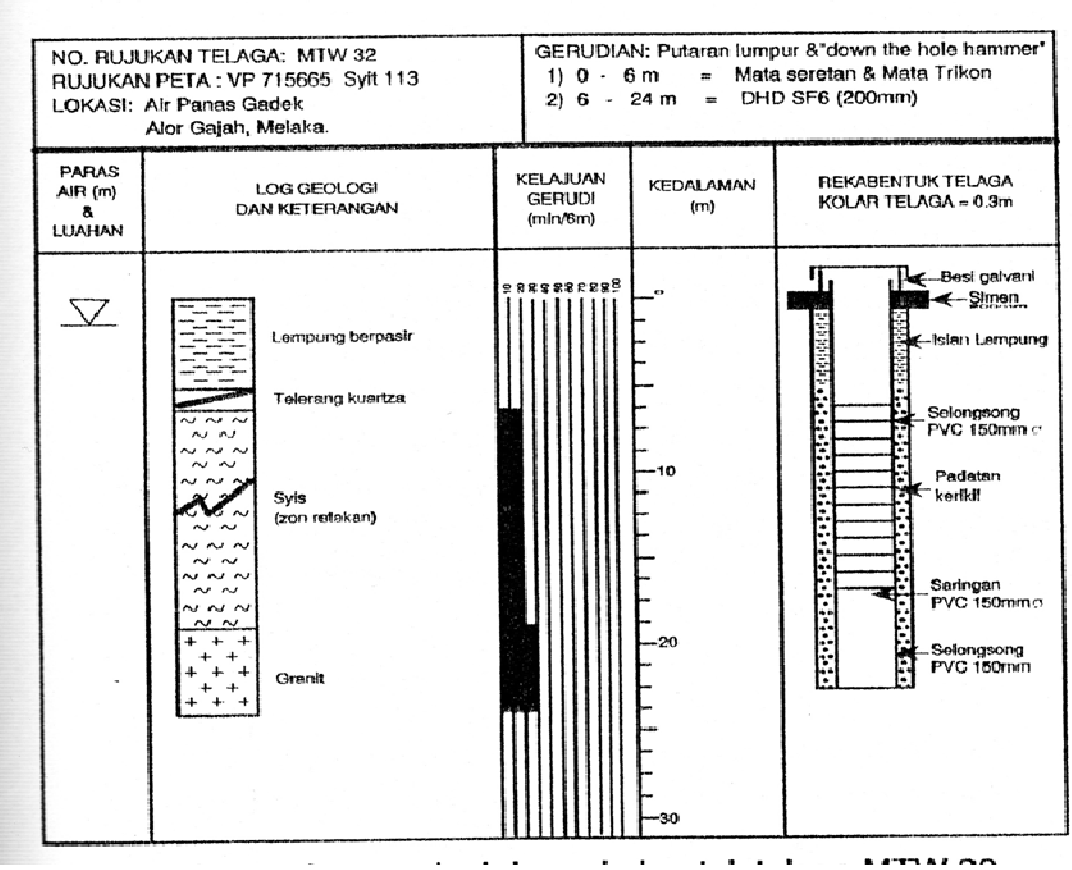
Rajah 3 : Geologi am Daerah Alor Gajah (dari Rishworth, 1964)

Appendix - C

BOREHOLES DATA OF DEEP AQUIFERS

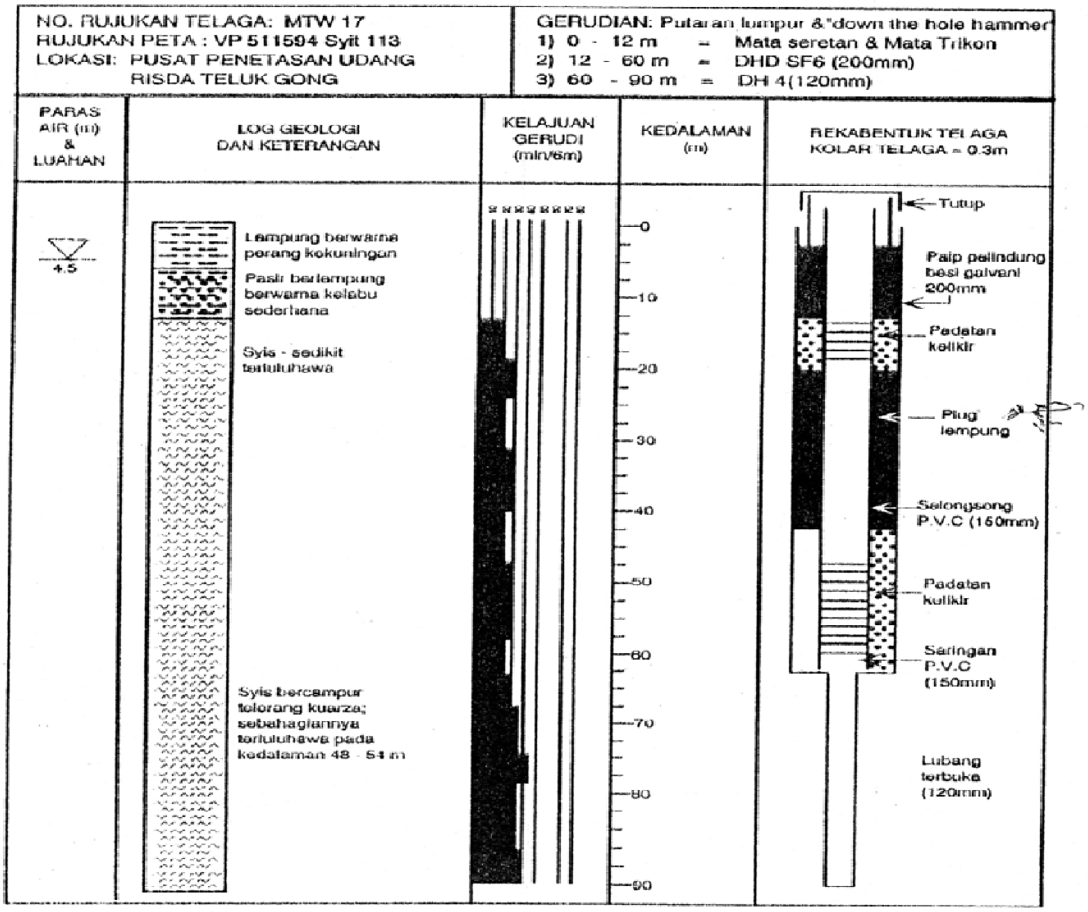






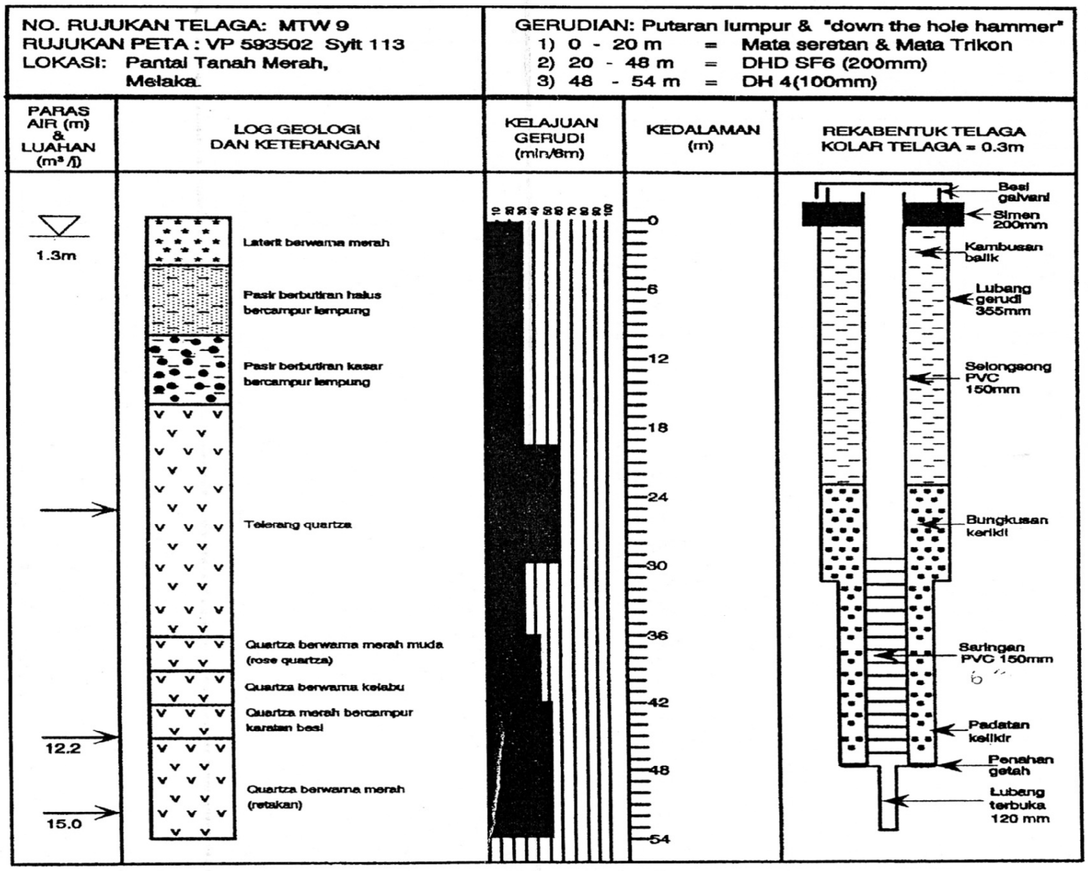
NO. RUJUKAN TELAGA: MTW 32
RUJUKAN PETA : VP 715665 Syit 113
LOKASI: Air Panas Gadek
Alor Gajah, Melaka.

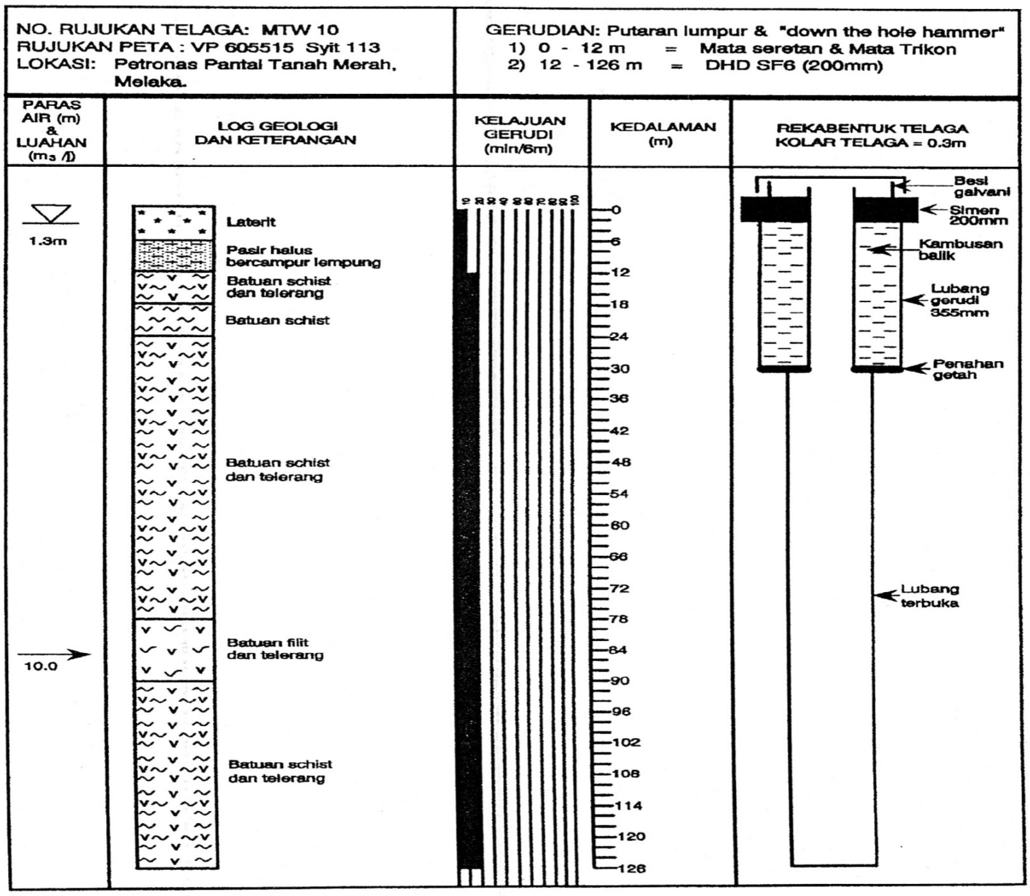
GERUDIAN: Putaran lumpur &"down the hole hammer"
1) 0 - 6 m = Mata seretan & Mata Trikon
2) 6 - 24 m = DHD SF6 (200mm)

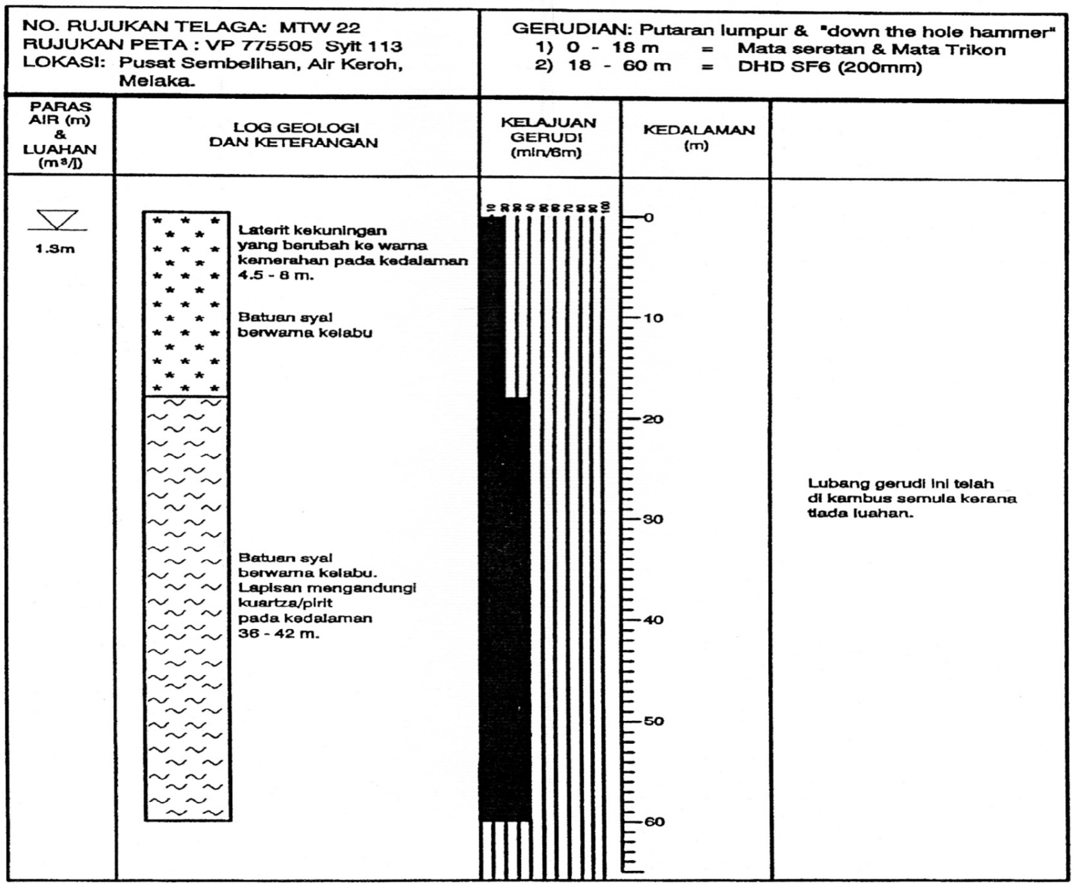


NO. RUJUKAN TELAGA: MTW 17
RUJUKAN PETA : VP 511594 Syit 113
LOKASI: PUSAT PENETASAN UDANG
RISDA TELUK GONG

GERUDIAN: Putaran lumpur &"down the hole hammer"
1) 0 - 12 m = Mata seretan & Mata Trikon
2) 12 - 60 m = DHD SF6 (200mm)
3) 60 - 90 m = DH 4(120mm)


NO. RUJUKAN TELAGA: MTW 9
RUJUKAN PETA : VP 593502 Syit 113
LOKASI: Pantai Tanah Merah, Melaka.
GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 20 m = Mata seretan & Mata Trikon
2) 20 - 48 m = DHD SF6 (200mm)
3) 48 - 54 m = DH 4(100mm)
PARAS AIR (m) & LUAHAN (m³/l)
LOG GEOLOGI DAN KETERANGAN
KELAJUAN GERUDI (min/6m)
KEDALAMAN (m)
REKABENTUK TELAGA KOLAR TELAGA = 0.3m
1.3m
12.2
15.0
Laterit berwarna merah
Pasir berbutiran halus bercampur lempung
Pasir berbutiran kasar bercampur lempung
Telerang quartza
Quartza berwarna merah muda (rose quartza)
Quartza berwarna kelabu
Quartza merah bercampur karatan besi
Quartza berwarna merah (retakan)
0
6
12
18
24
30
36
42
48
54
Besi galvani
Simen 200mm
Kambusan balik
Lubang gerudi 355mm
Selongsong PVC 150mm
Bungkusan kerikil
Saringan PVC 150mm
Padatan kelikir
Penahan getah
Lubang terbuka 120 mm


NO. RUJUKAN TELAGA: MTW 10
RUJUKAN PETA : VP 605515 Syit 113
LOKASI: Petronas Pantai Tanah Merah, Melaka.
GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 12 m = Mata seretan & Mata Trikon
2) 12 - 126 m = DHD SF6 (200mm)
PARAS AIR (m) & LUAHAN (m3/l)
LOG GEOLOGI DAN KETERANGAN
KELAJUAN GERUDI (min/6m)
KEDALAMAN (m)
REKABENTUK TELAGA KOLAR TELAGA = 0.3m
1.3m
10.0
Laterit
Pasir halus bercampur lempung
Batuan schist dan telerang
Batuan schist
Batuan schist dan telerang
Batuan filit dan telerang
Batuan schist dan telerang
0
6
12
18
24
30
36
42
48
54
60
66
72
78
84
90
96
102
108
114
120
126
Besi galvani
Simen 200mm
Kambusan balik
Lubang gerudi 355mm
Penahan getah
Lubang terbuka



NO. RUJUKAN TELAGA: MTW 22
RUJUKAN PETA : VP 775505 Syit 113
LOKASI: Pusat Sembelihan, Air Keroh,
Melaka.

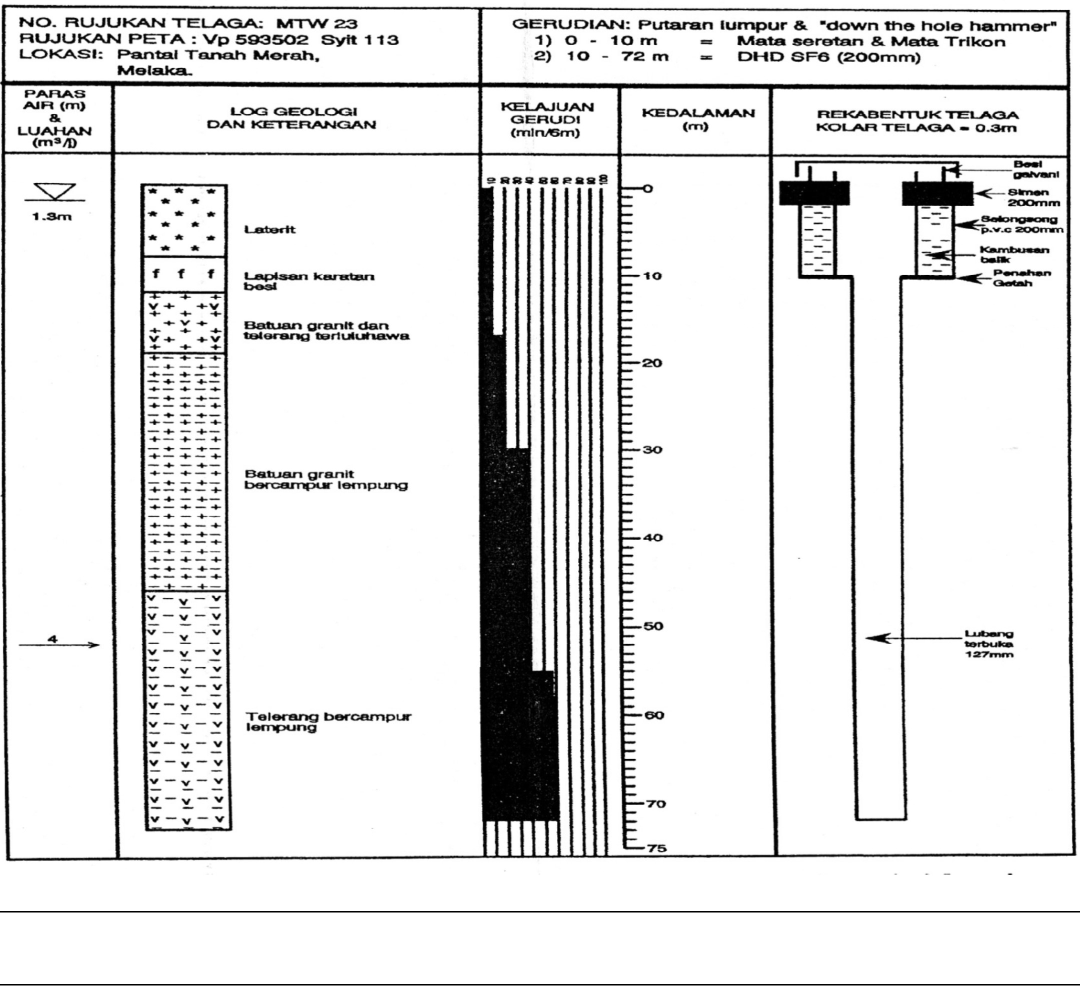
GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 18 m = Mata seretan & Mata Trikon
2) 18 - 60 m = DHD SF6 (200mm)

Laterit kekuningan yang berubah ke warna kemerahan pada kedalaman 4.5 - 8 m.

Batuan syal berwarna kelabu

Batuan syal berwarna kelabu. Lapisan mengandungi kuartza/pirit pada kedalaman 36 - 42 m.

Lubang gerudi ini telah di kambus semula kerana tiada luahan.



NO. RUJUKAN TELAGA: MTW 23
RUJUKAN PETA : Vp 593502 Syit 113
LOKASI: Pantai Tanah Merah,
Melaka.

GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 10 m = Mata seretan & Mata Trikon
2) 10 - 72 m = DHD SF6 (200mm)

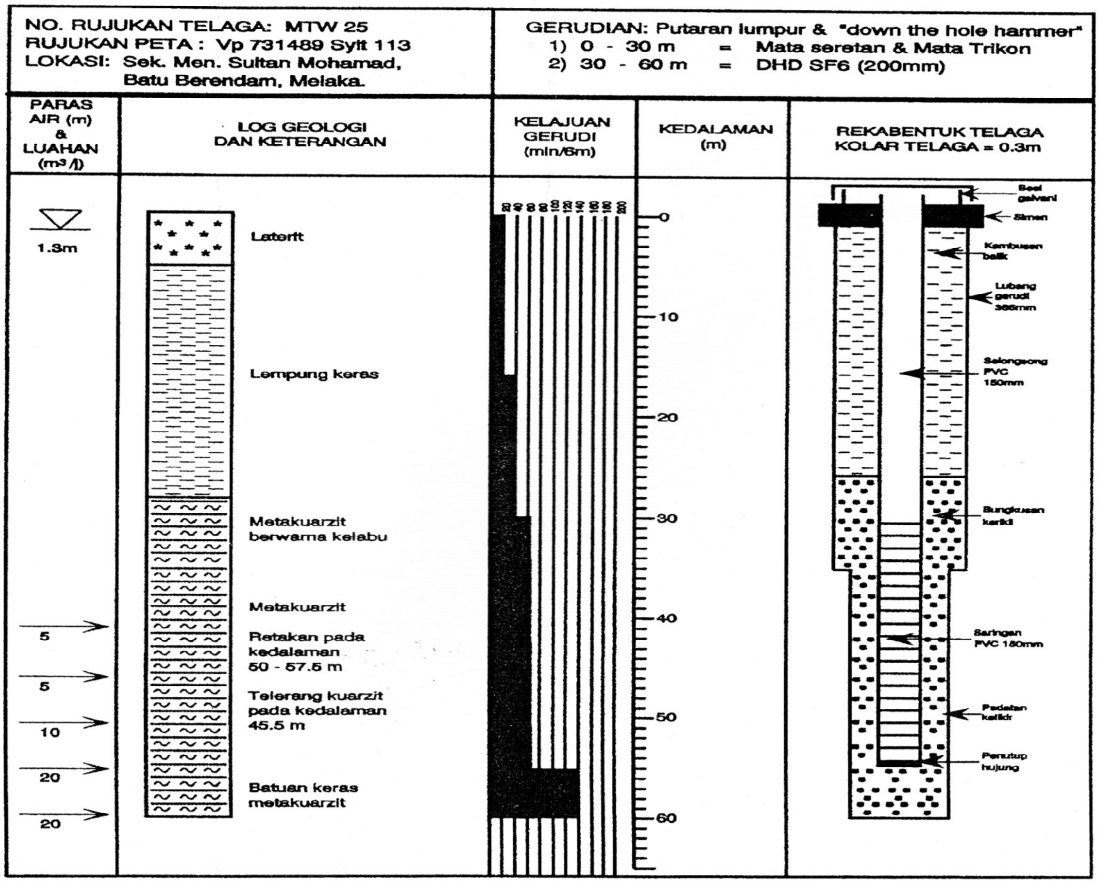
Laterit

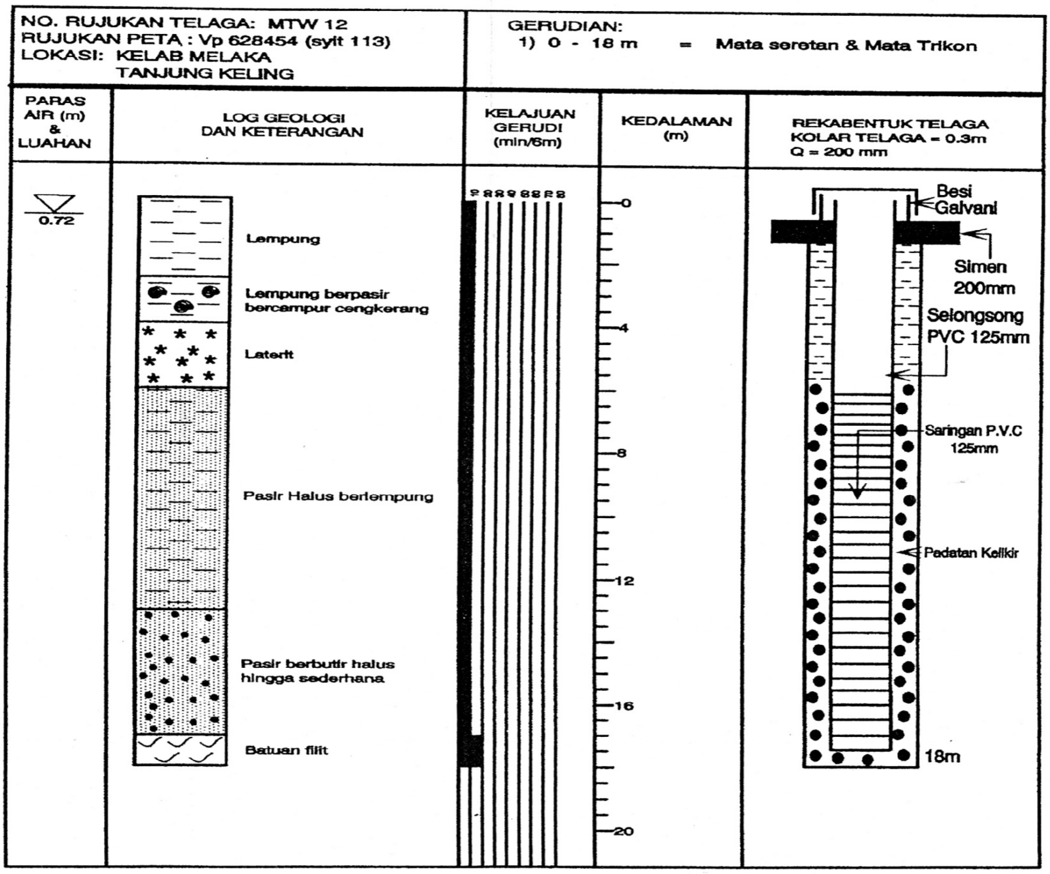
Lapisan karatan besi

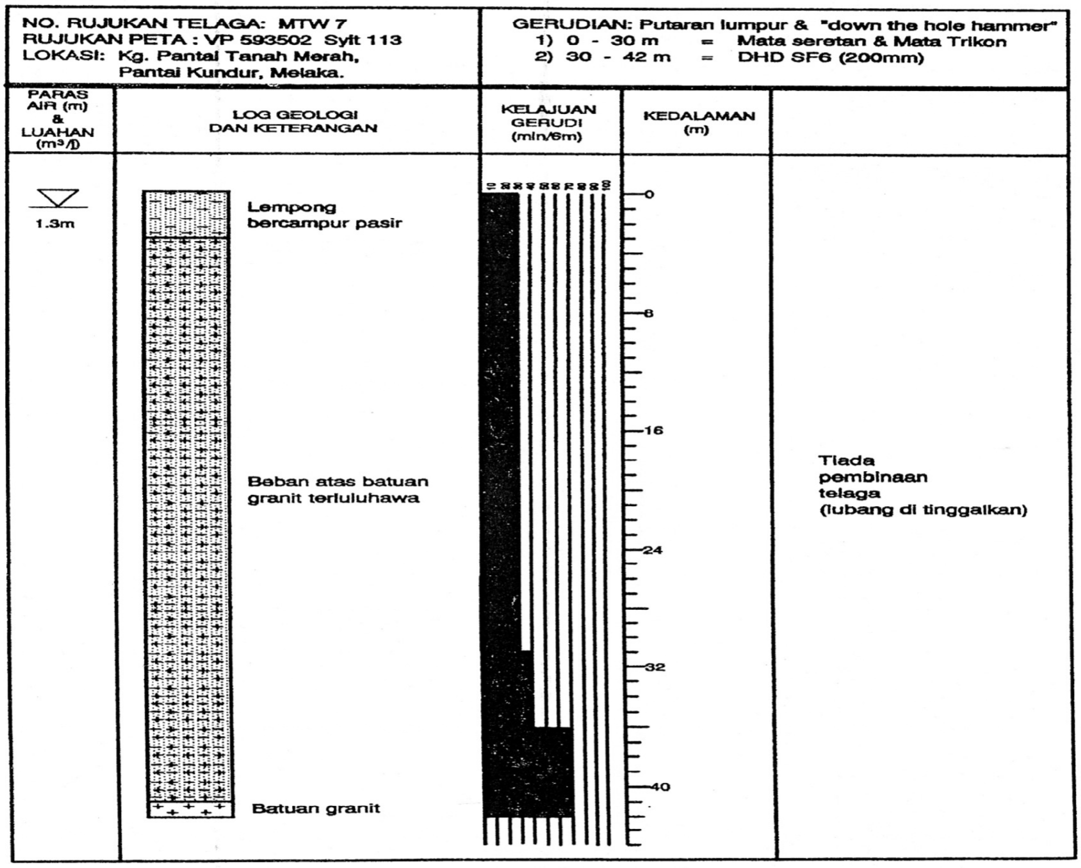
Batuan granit dan telerang terluluhawa

Batuan granit bercampur lempung

Telerang bercampur lempung

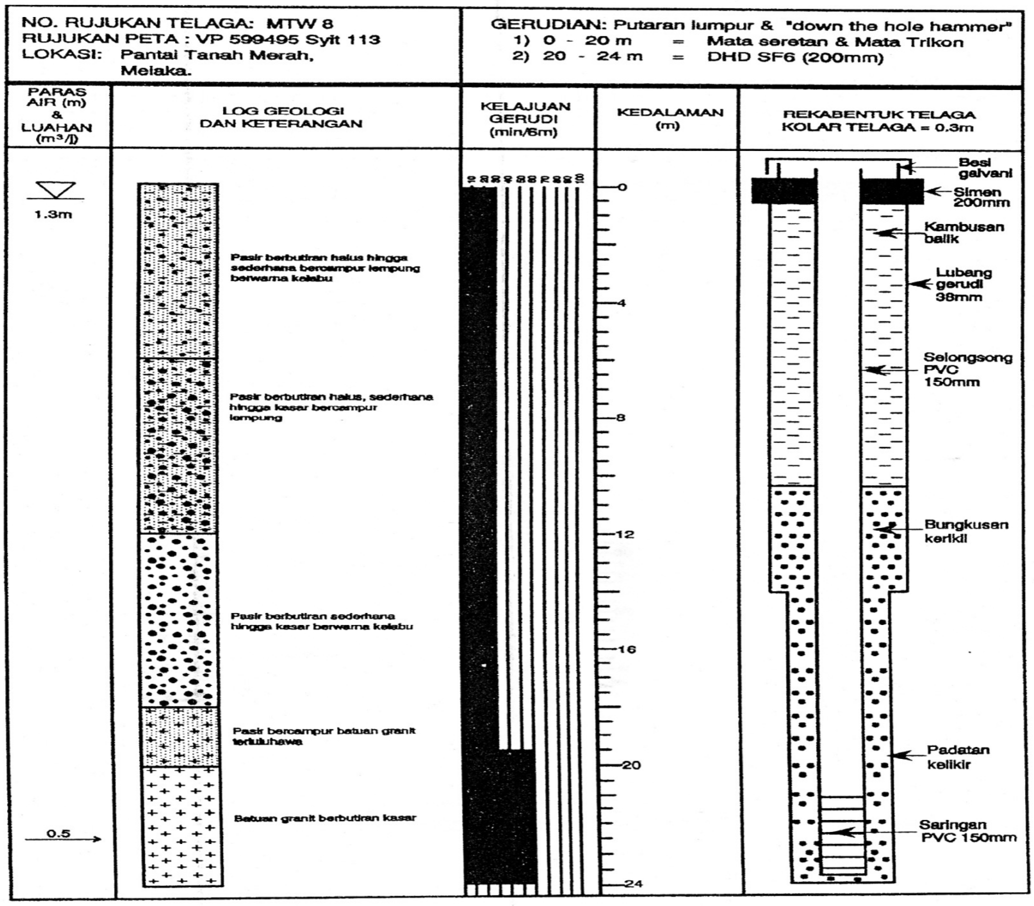

NO. RUJUKAN TELAGA: MTW 25
RUJUKAN PETA : Vp 731489 Syit 113
LOKASI: Sek. Men. Sultan Mohamad,
Batu Berendam, Melaka.
GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 30 m = Mata seretan & Mata Trikon
2) 30 - 60 m = DHD SF6 (200mm)
PARAS AIR (m) & LUAHAN (m³/j)
LOG GEOLOGI DAN KETERANGAN
KELAJUAN GERUDI (min/6m)
KEDALAMAN (m)
REKABENTUK TELAGA KOLAR TELAGA = 0.3m
1.3m
5
5
10
20
20
Laterit
Lempung keras
Metakuarzit berwarna kelabu
Metakuarzit
Retakan pada kedalaman 50 - 57.5 m
Telerang kuarzit pada kedalaman 45.5 m
Batuan keras metakuarzit
20
40
60
80
100
120
140
160
180
200
0
10
20
30
40
50
60
Besi galvani
Simen
Kambusan balik
Lubang gerudi 366mm
Selongsong PVC 150mm
Bungkusan kerikil
Saringan PVC 150mm
Padatan kelikir
Penutup hujung


NO. RUJUKAN TELAGA: MTW 12
RUJUKAN PETA : Vp 628454 (syit 113)
LOKASI: KELAB MELAKA
TANJUNG KELING
GERUDIAN:
1) 0 - 18 m = Mata seretan & Mata Trikon
PARAS AIR (m) & LUAHAN
LOG GEOLOGI DAN KETERANGAN
KELAJUAN GERUDI (min/6m)
KEDALAMAN (m)
REKABENTUK TELAGA KOLAR TELAGA = 0.3m Q = 200 mm
0.72
Lempung
Lempung berpasir bercampur cengkerang
Laterit
Pasir Halus berlempung
Pasir berbutir halus hingga sederhana
Batuan filit
10
20
30
40
50
60
70
80
0
4
8
12
16
20
Besi Galvani
Simen 200mm
Selongsong PVC 125mm
Saringan P.V.C 125mm
Padatan Kelikir
18m



NO. RUJUKAN TELAGA: MTW 7
RUJUKAN PETA : VP 593502 Syit 113
LOKASI: Kg. Pantai Tanah Merah,
Pantai Kundur, Melaka.

GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 30 m = Mata seretan & Mata Trikon
2) 30 - 42 m = DHD SF6 (200mm)

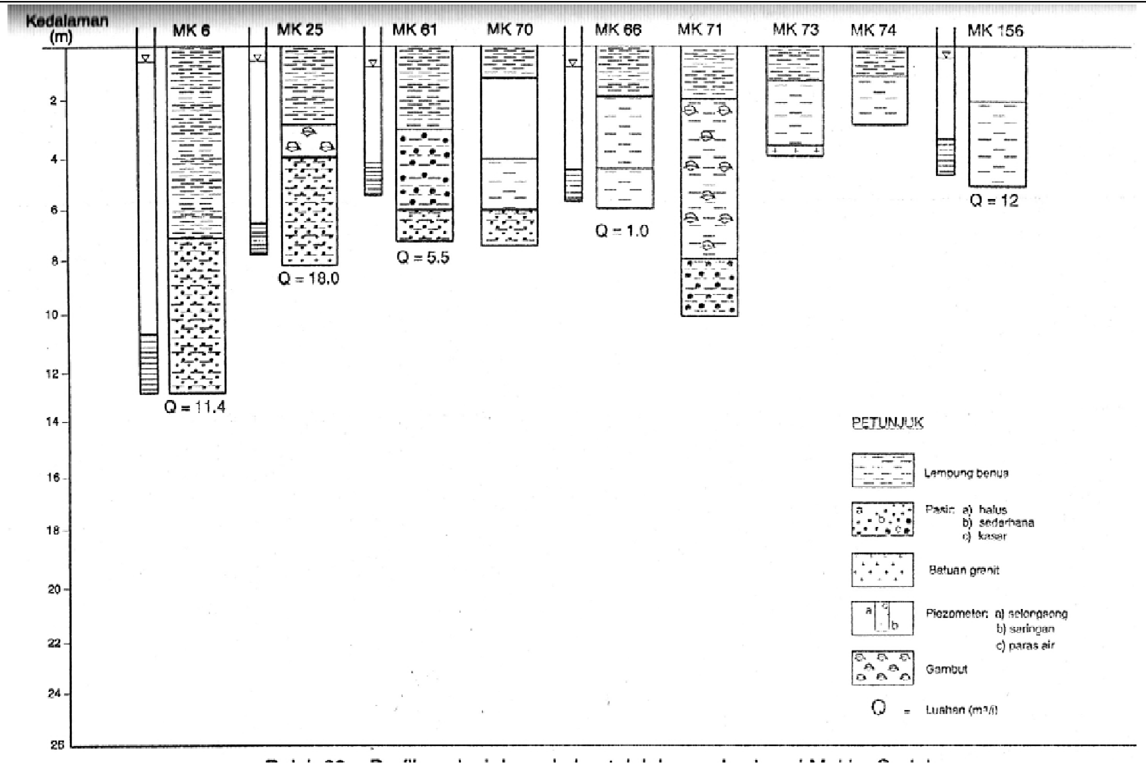


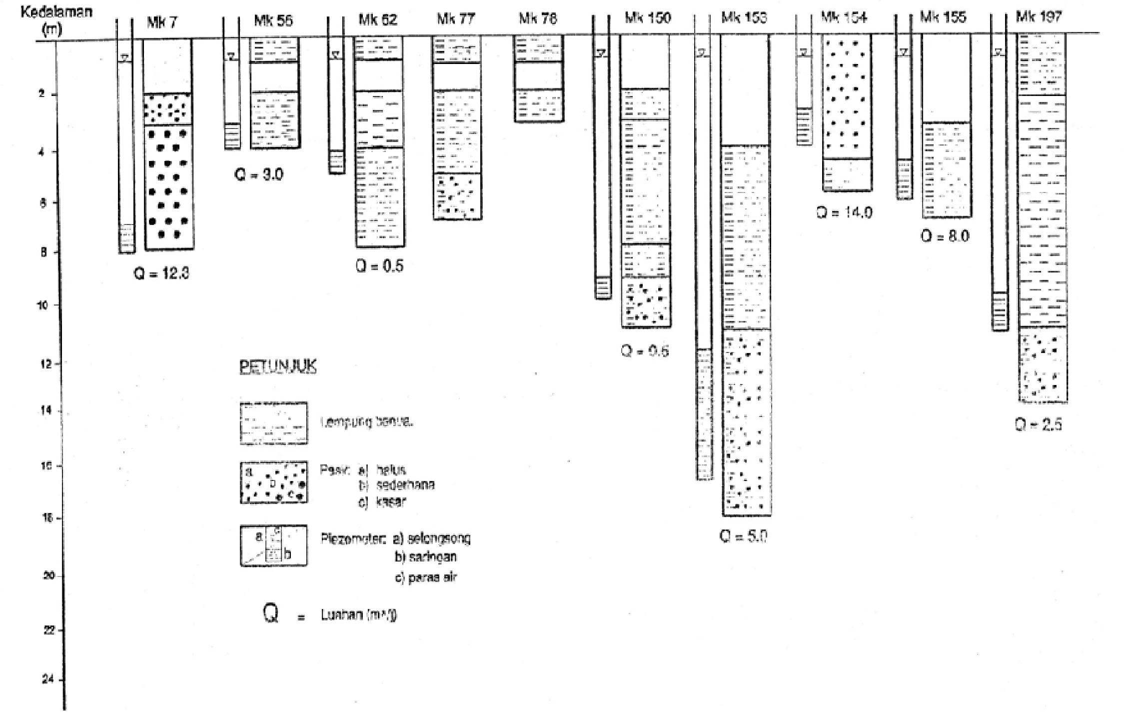
NO. RUJUKAN TELAGA: MTW 8
RUJUKAN PETA : VP 599495 Syit 113
LOKASI: Pantai Tanah Merah,
Melaka.

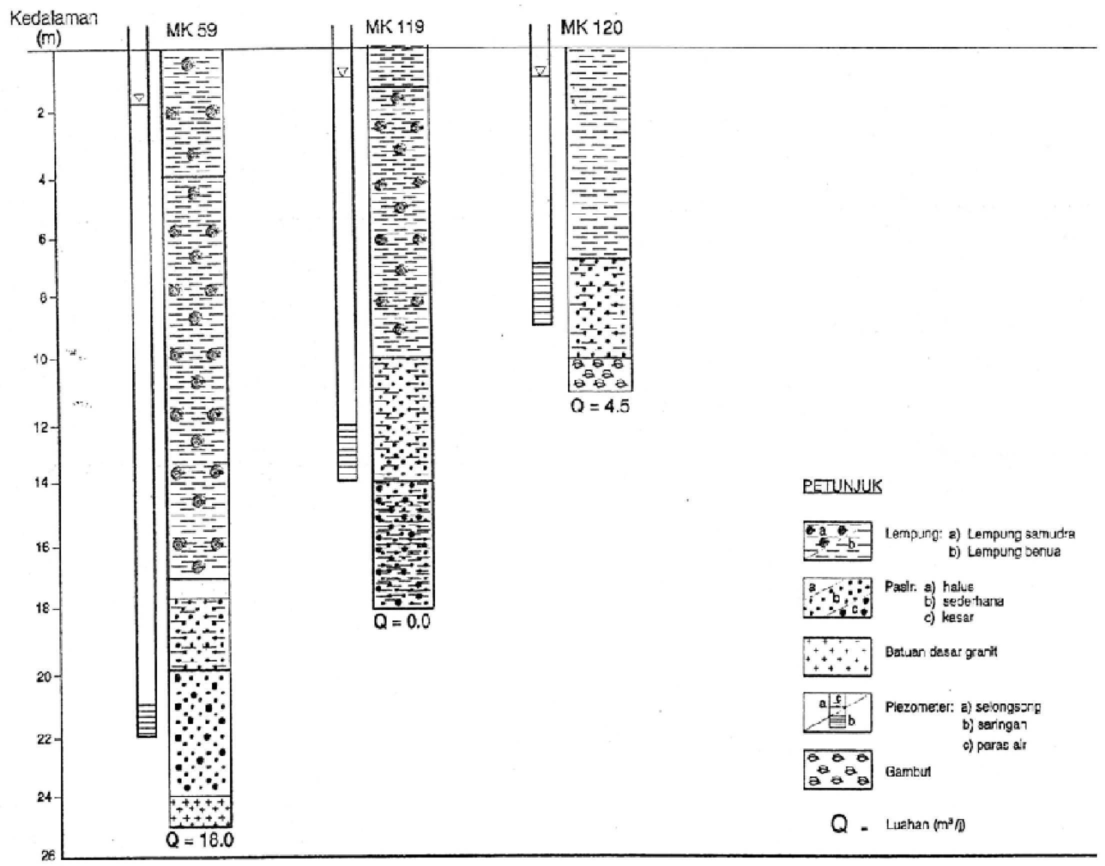
GERUDIAN: Putaran lumpur & "down the hole hammer"
1) 0 - 20 m = Mata seretan & Mata Trikon
2) 20 - 24 m = DHD SF6 (200mm)

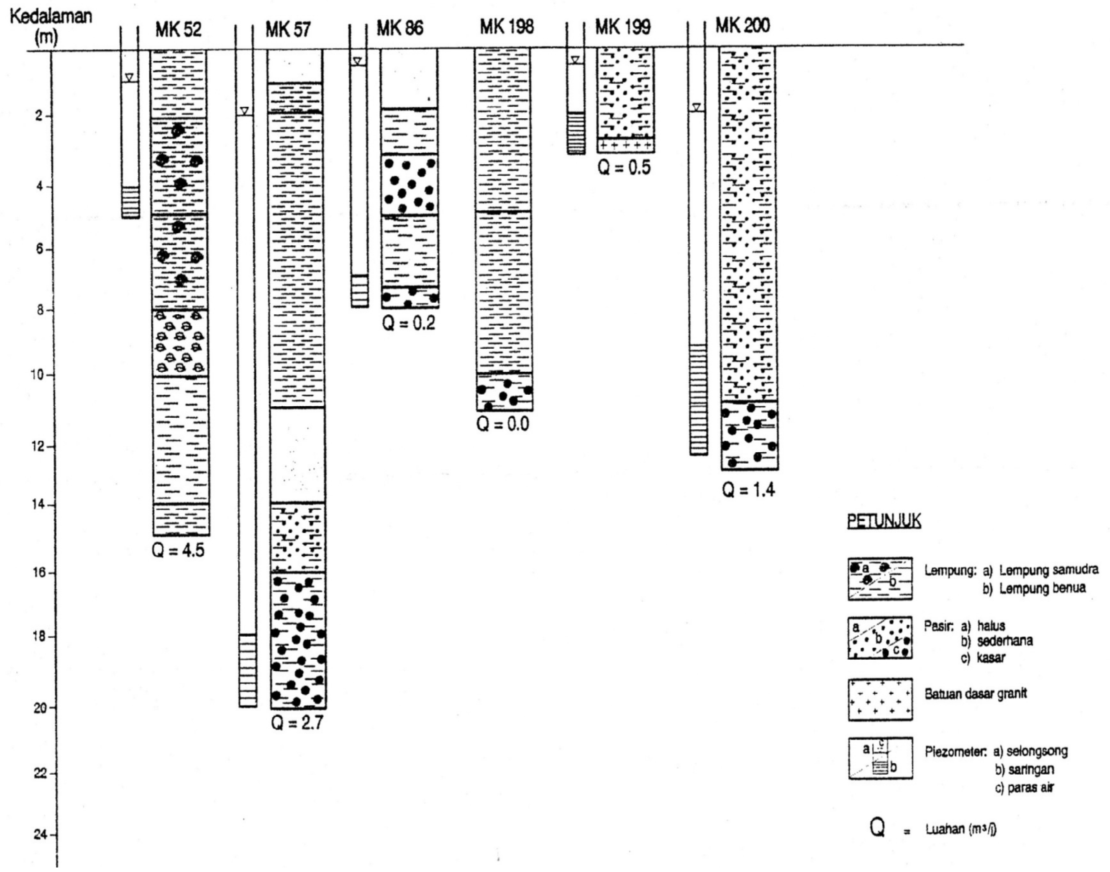
Appendix – D

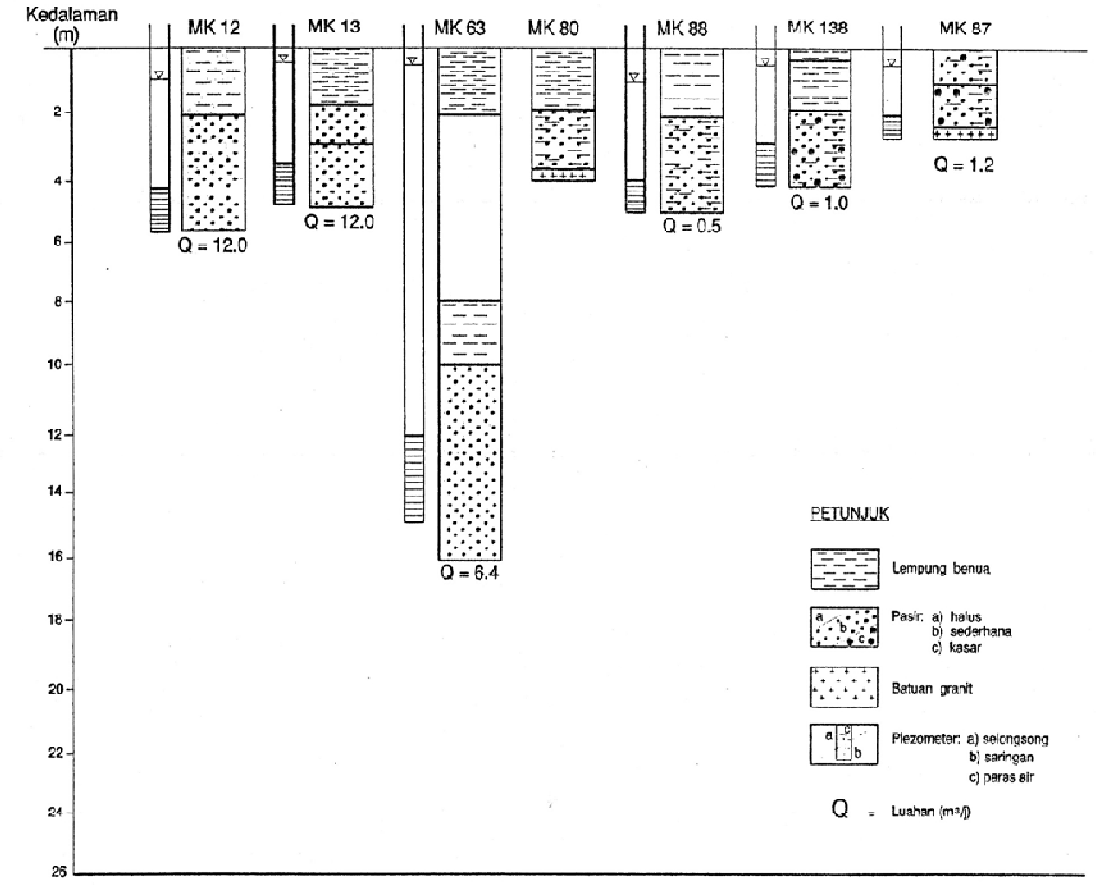
BOREHOLES DATA OF SHALLOW AQUIFERS

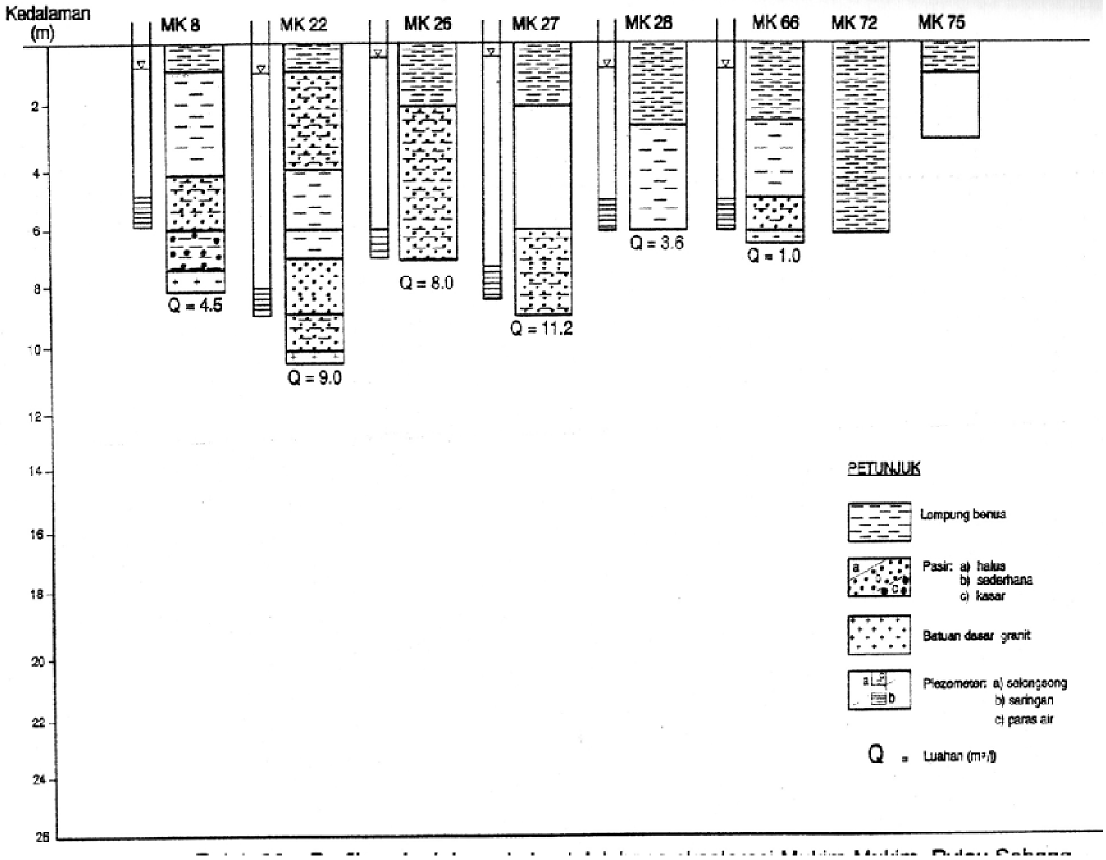


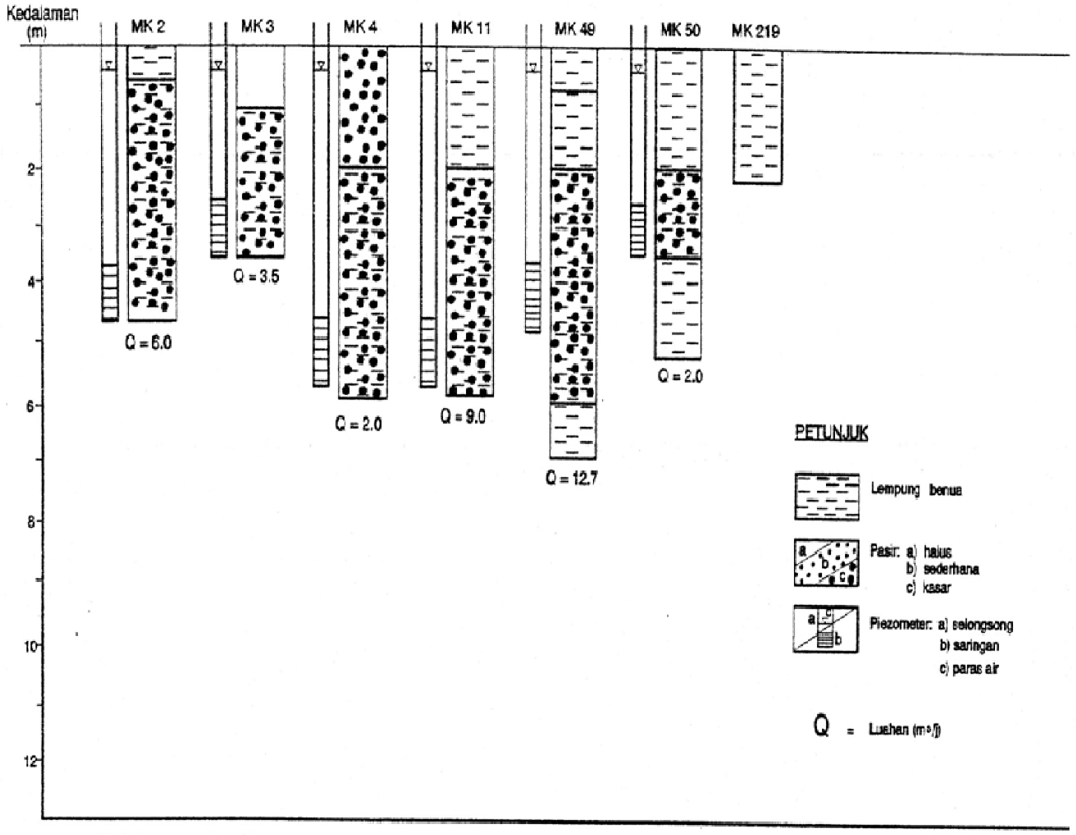


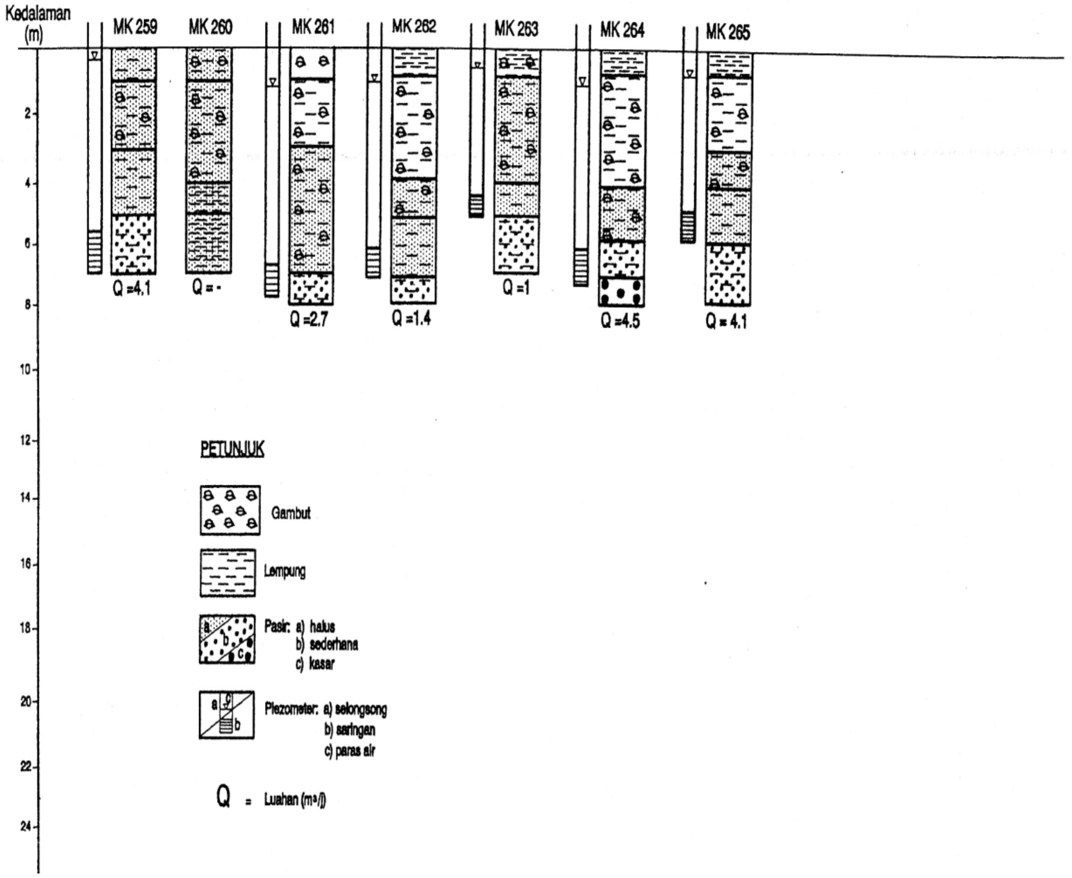

Kedalaman (m)
MK 59
MK 119
MK 120
2
4
6
8
10
12
14
16
18
20
22
24
26
Q = 18.0
Q = 0.0
Q = 4.5
PETUNJUK
Lempung: a) Lempung samudra
b) Lempung benua
Pasir: a) halus
b) sederhana
c) kasar
Batuan dasar granit
Piezometer: a) selongsong
b) saringan
c) paras air
Gambut
Q = Luahan (m³/j)

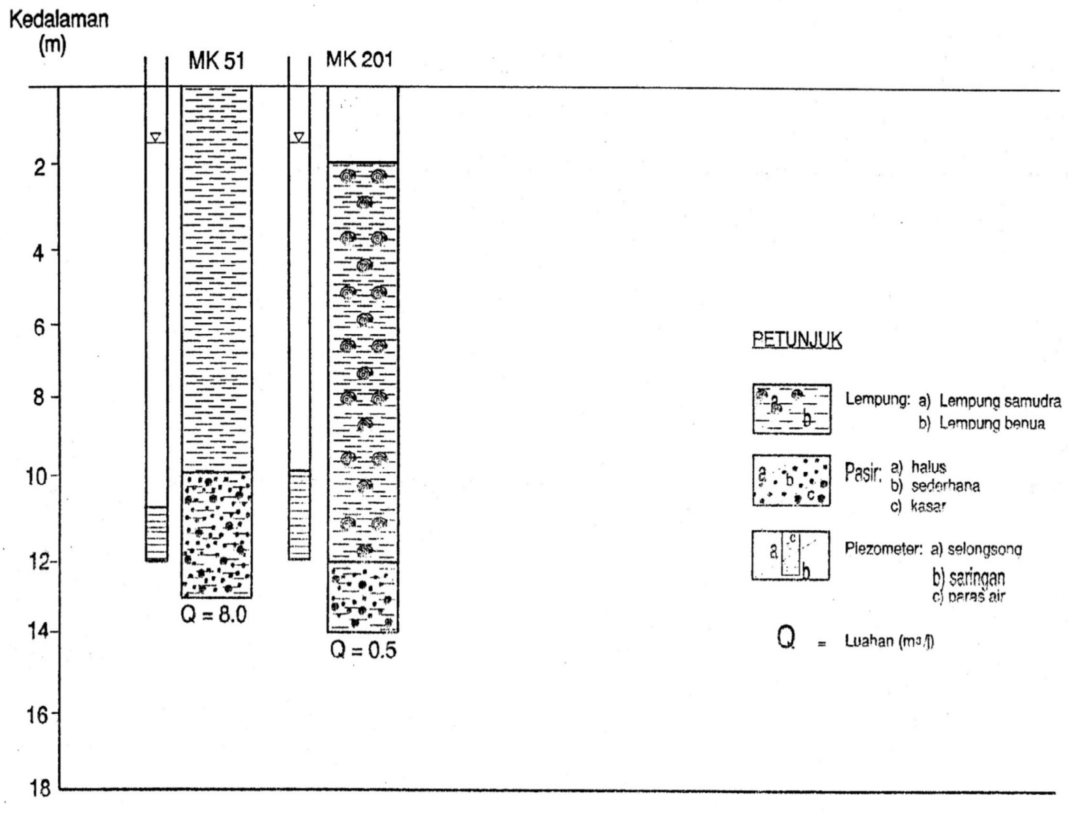

Kedalaman (m)
MK 52
MK 57
MK 86
MK 198
MK 199
MK 200
2
4
6
8
10
12
14
16
18
20
22
24
Q = 4.5
Q = 2.7
Q = 0.2
Q = 0.0
Q = 0.5
Q = 1.4
PETUNJUK
Lempung: a) Lempung samudra
b) Lempung benua
Pasir: a) halus
b) sederhana
c) kasar
Batuan dasar granit
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)

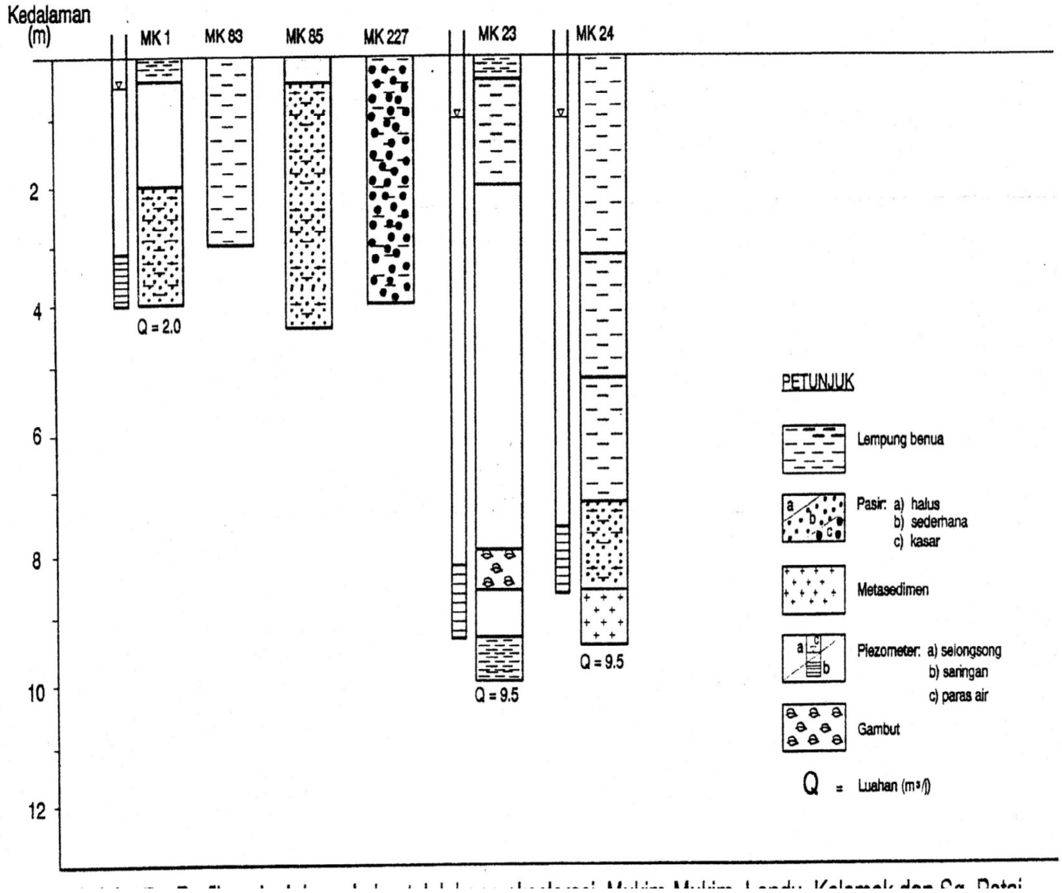

Kedalaman (m)
MK 12
MK 13
MK 63
MK 80
MK 88
MK 138
MK 87
2
4
6
8
10
12
14
16
18
20
22
24
26
Q = 12.0
Q = 12.0
Q = 6.4
Q = 0.5
Q = 1.0
Q = 1.2
PETUNJUK
Lempung benua
Pasir: a) halus
b) sederhana
c) kasar
Batuan granit
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)

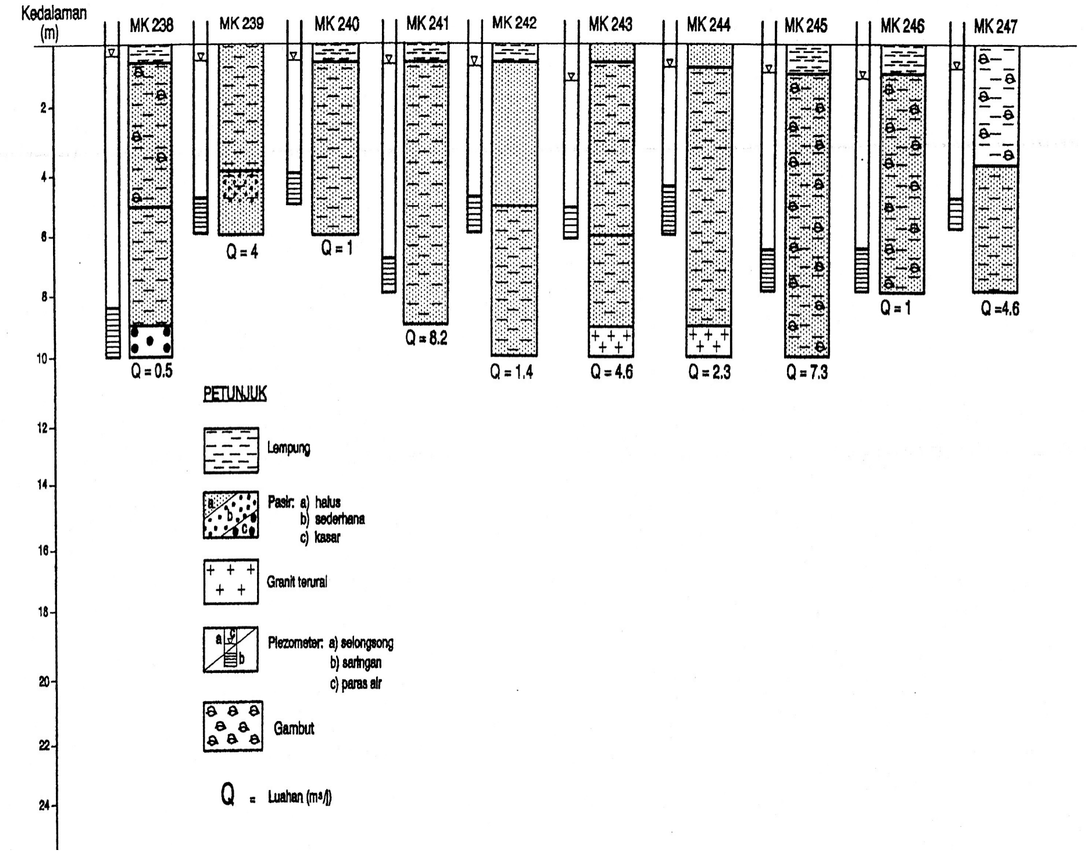

Kedalaman (m)
MK 8
MK 22
MK 26
MK 27
MK 28
MK 66
MK 72
MK 75
2
4
6
8
10
12
14
16
18
20
22
24
26
Q = 4.5
Q = 9.0
Q = 8.0
Q = 11.2
Q = 3.6
Q = 1.0
PETUNJUK
Lempung benua
Pasir: a) halus
b) sederhana
c) kasar
Batuan dasar granit
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)


Kedalaman (m)
2
4
6
8
10
12
MK 2
MK 3
MK 4
MK 11
MK 49
MK 50
MK 219
Q = 6.0
Q = 3.5
Q = 2.0
Q = 9.0
Q = 12.7
Q = 2.0
PETUNJUK
Lempung benua
Pasir: a) halus
b) sederhana
c) kasar
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)


Kedalaman (m)
2
4
6
8
10
12
14
16
18
20
22
24
MK 259
MK 260
MK 261
MK 262
MK 263
MK 264
MK 265
Q =4.1
Q = -
Q =2.7
Q =1.4
Q =1
Q =4.5
Q = 4.1
PETUNJUK
Gambut
Lempung
Pasir: a) halus
b) sederhana
c) kasar
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)


Kedalaman (m)
MK 51
MK 201
2
4
6
8
10
12
14
16
18
Q = 8.0
Q = 0.5
PETUNJUK
a
b
Lempung: a) Lempung samudra
b) Lempung benua
a
b
c
Pasir: a) halus
b) sederhana
c) kasar
a
b
c
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)


Kedalaman (m)
MK 1
MK 83
MK 85
MK 227
MK 23
MK 24
2
4
6
8
10
12
Q = 2.0
Q = 9.5
Q = 9.5
PETUNJUK
Lempung benua
a
b
c
Pasir: a) halus
b) sederhana
c) kasar
Metasedimen
a
b
c
Piezometer: a) selongsong
b) saringan
c) paras air
Gambut
Q = Luahan (m³/j)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MK 238
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MK 241
MK 242
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MK 247
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4
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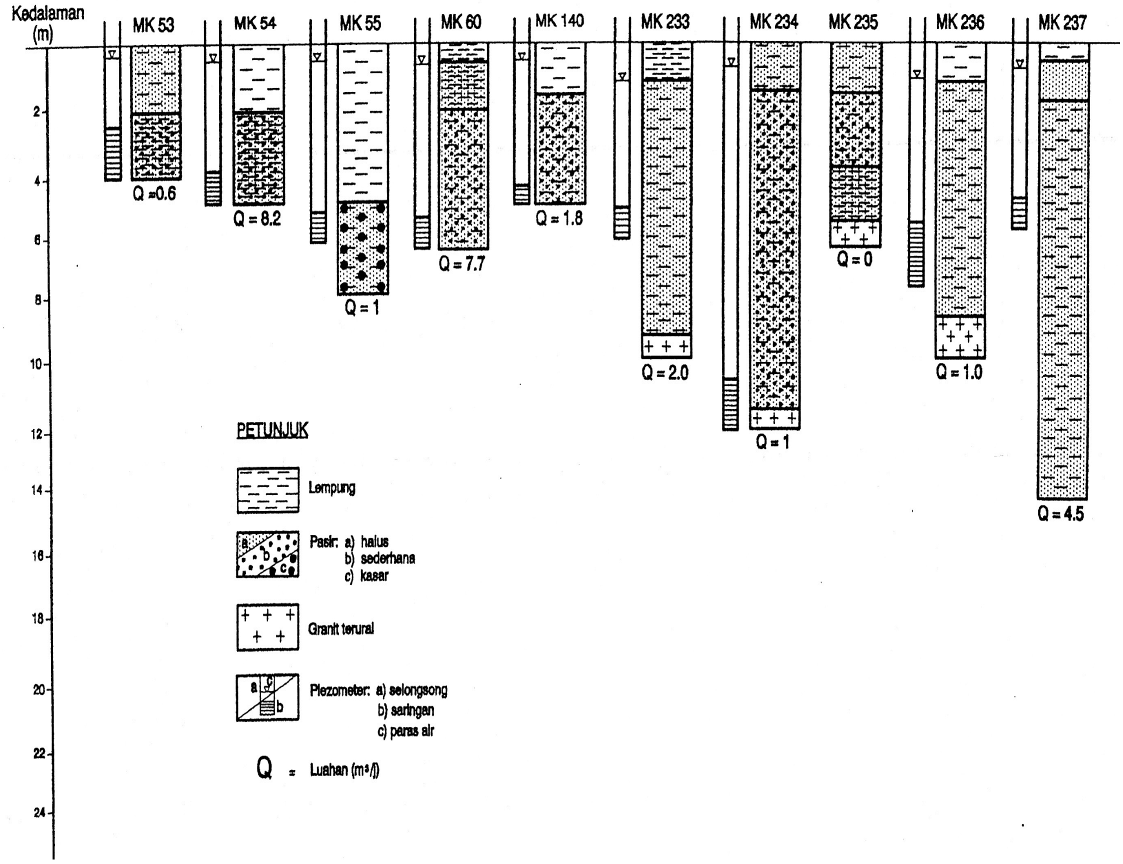
8
10
12
14
16
18
20
22
24
Q = 0.5
Q = 4
Q = 1
Q = 8.2
Q = 1.4
Q = 4.6
Q = 2.3
Q = 7.3
Q = 1
Q = 4.6
PETUNJUK
Lempung
Pasir: a) halus
b) sederhana
c) kasar
Granit terurai
Piezometer: a) selongsong
b) saringan
c) paras air
Gambut
Q = Luahan (m³/j)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MK 55
MK 60
MK 140
MK 233
MK 234
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4
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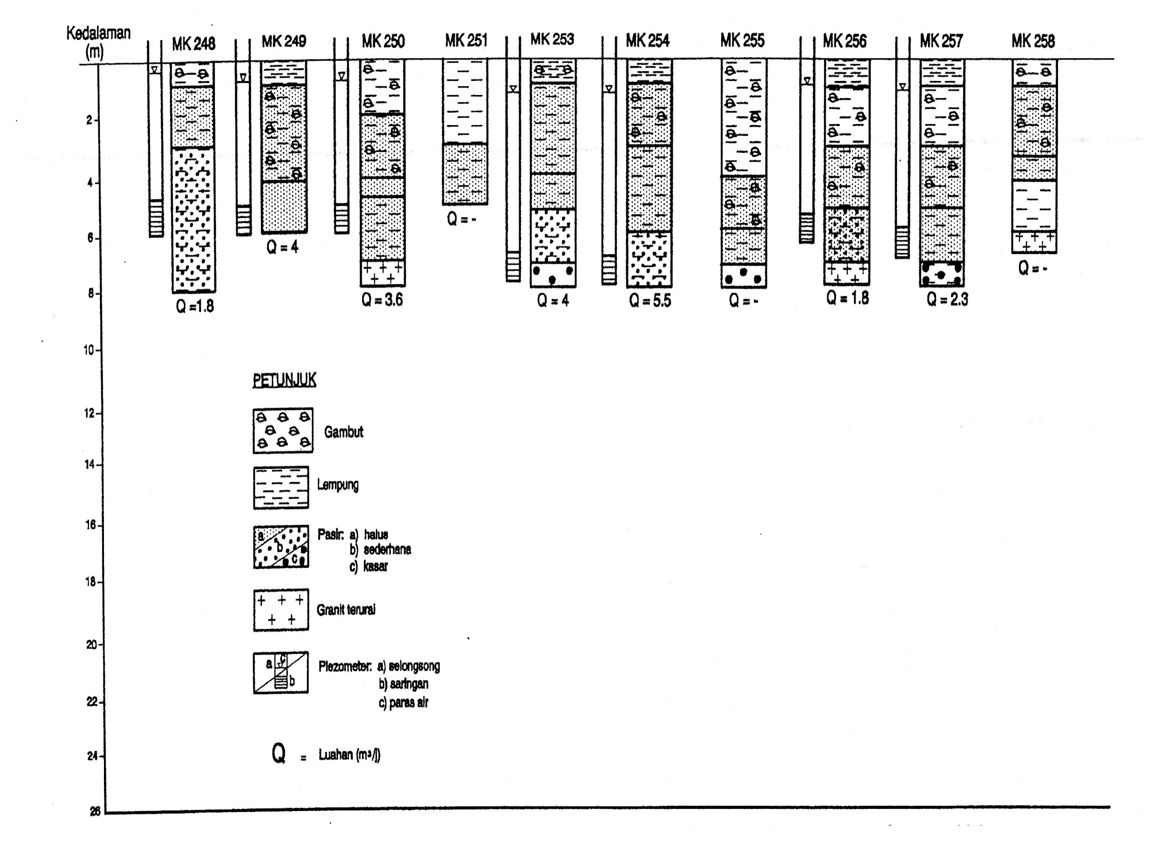
8
10
12
14
16
18
20
22
24
Q = 0.6
Q = 8.2
Q = 1
Q = 7.7
Q = 1.8
Q = 2.0
Q = 1
Q = 0
Q = 1.0
Q = 4.5
PETUNJUK
Lempung
Pasir: a) halus
b) sederhana
c) kasar
Granit terurai
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/j)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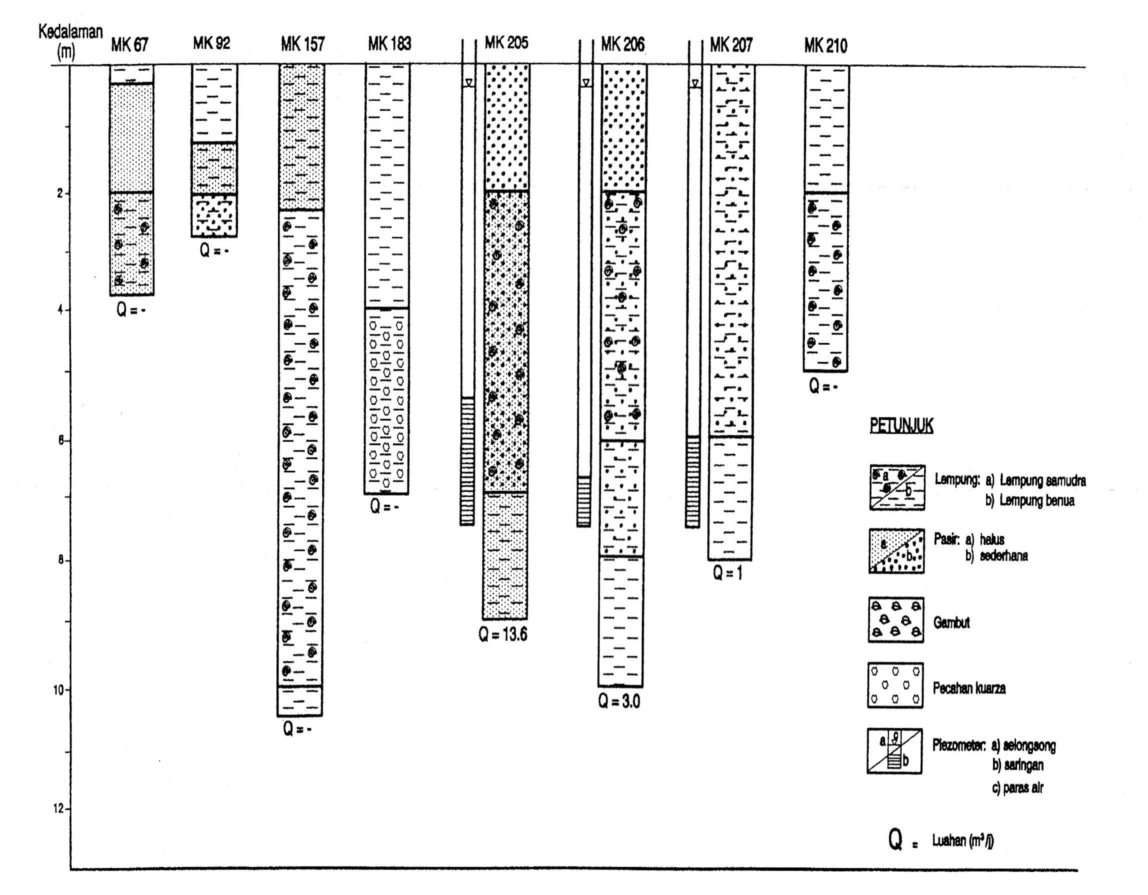
12
14
16
18
20
22
24
26
Q = 1.8
Q = 4
Q = 3.6
Q = -
Q = 4
Q = 5.5
Q = -
Q = 1.8
Q = 2.3
Q = -
PETUNJUK
Gambut
Lempung
Pasir: a) halus
b) sederhana
c) kasar
Granit terurai
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/l)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MK 157
MK 183
MK 205
MK 206
MK 207
MK 210
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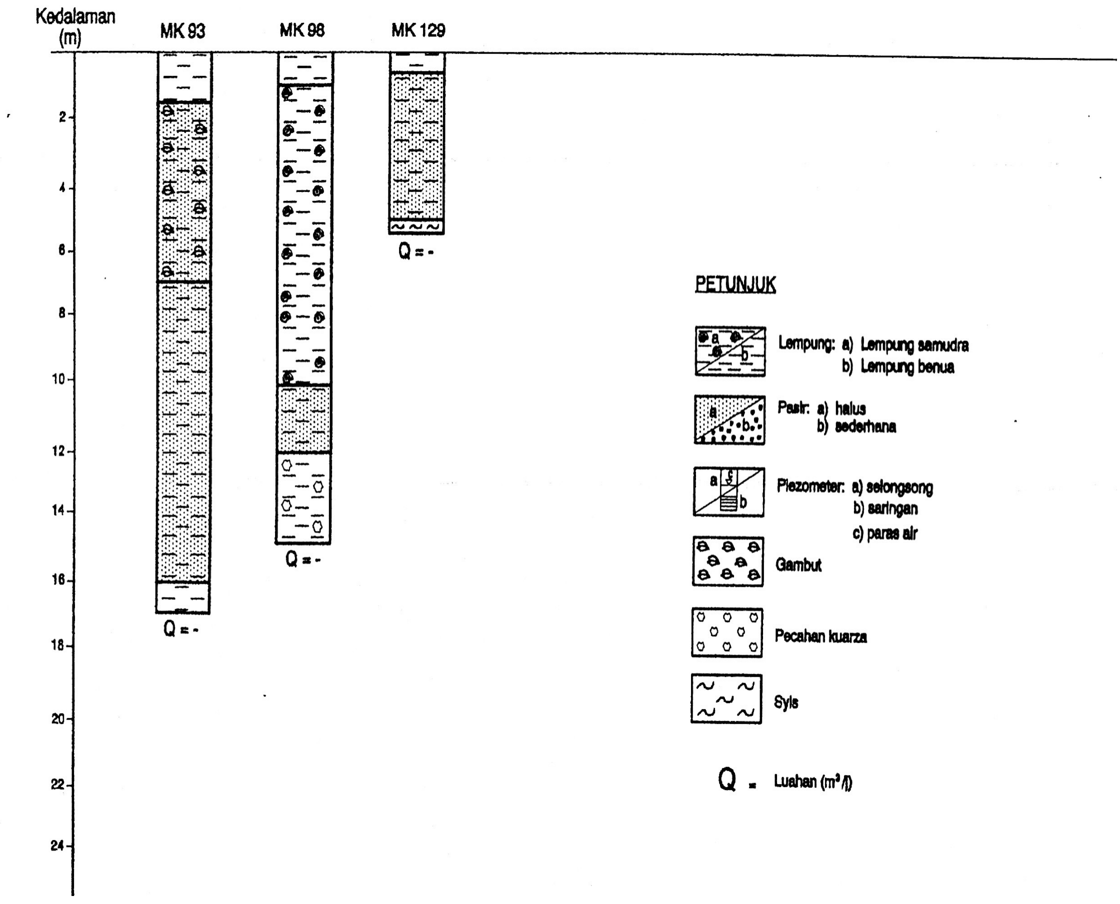
6
8
10
12
Q = -
Q = -
Q = -
Q = -
Q = 13.6
Q = 3.0
Q = 1
Q = -
PETUNJUK
Lempung: a) Lempung samudra
b) Lempung benua
Pasir: a) halus
b) sederhana
Gambut
Pecahan kuarza
Piezometer: a) selongsong
b) saringan
c) paras air
Q = Luahan (m³/l)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MK 98
MK 129
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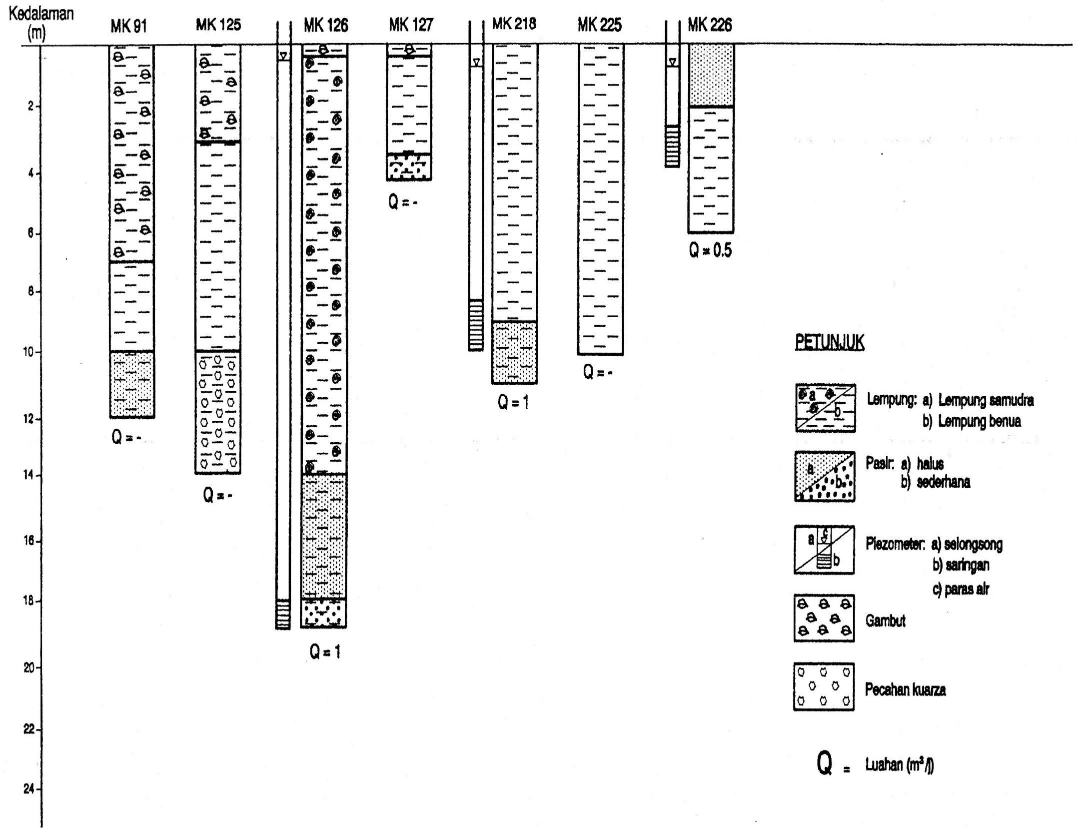
8
10
12
14
16
18
20
22
24
Q = -
Q = -
Q = -
PETUNJUK
Lempung: a) Lempung samudra
b) Lempung benua
Pasir: a) halus
b) sederhana
Piezometer: a) selongsong
b) saringan
c) paras air
Gambut
Pecahan kuarza
Syis
Q = Luahan (m³/l)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8
10
12
14
16
18
20
22
24
Q = -
Q = -
Q = 1
Q = -
Q = 1
Q = -
Q = 0.5
PETUNJUK
Lempung: a) Lempung samudra
b) Lempung benua
Pasir: a) halus
b) sederhana
Piezometer: a) selongsong
b) saringan
c) paras air
Gambut
Pecahan kuarza
Q = Luahan (m³/l)

Appendix – E

DRINKING WATER QUALITY STANDARD – MALAYSIA, 1992

Table 1: Drinking Water Quality Standard - Malaysia, 1992

Parameter				
Parameter	**Short Name**	**Group**	**Raw Water**	**Treated Water**
Turbidity	NTU	Physical	100	5
Color	TCU		300(Hazen)	15
pH	pH		5.5-9	6.5-9
Total Dissolved Solids	TDS	Inorganic	1500	1000
Chloride	Cl		250	250
Ammonia	NH_4-N		0.5	0.5
Nitrate	No_3-N		10	10
Iron	Fe		1	0.3
Fluoride	Fl		1.5	0.9
Total Nitrogen	NO_3		1	-
Violence			500	500
Manganese	Mn	Element Effects	0.2	-
Copper	Cu		1	1
Mercury	Hg		0.001	0.001
Cadmium	Cd		0.005	0.005
Arsenic	As		0.05	0.05
Cyanide	Cn		0.1	0.1
Lead	Pb		0.1	0.05
Chromium	Cr		0.05	0.05
Zink	Zn		5	5
Sodium	Na		200	200
Sulfate	SO_4		400	400
Selenium	Se		0.01	0.01
Silver	Ag		0.05	0.05
Magnesium	Mg		150	150
Oil Mineral	MykMin		0.3	0.3
Phenol	C_6H_5OH		0.002	0.002

Appendix – F

SHALLOW AND DEEP BOREHOLES PROFILE IN MELAKA

Table 1: The Number of Shallow Boreholes in Alor Gajah District

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
1	MK 1	Kg Lendu	4.00	2.00	Granite
2	MK 2	Kg Pantai Belimbing	4.80	6.00	Phyllite
3	MK 3	Kg Melaka Pindah	3.60	3.50	Schist
4	MK 4	Tabika Kemas, Blimbing Dalam	6.20	2.00	Phyllite
5	MK 5	Kg Air Pasir	6.20	4.00	Granite
6	MK 6	Loji Air Gadek	13.00	11.40	Granite
7	MK 7	Kg Padang Kemunting	8.00	12.30	Granite
8	MK 8	Kg Pulau Sedang	7.50	4.50	Granite
9	MK 9	Kg Air Limau	4.00	1.00	Granite
10	MK 10	Kg Tehel Solok	9.50	2.00	Phyllite
11	MK 11	Kg Pantai Belimbing	6.10	9.00	Phyllite
12	MK 12	Kg Sungai Siput	5.50	12.00	Phyllite
13	MK 13	Kg Berisau	4.30	12.00	Phyllite
14	MK 14	Kg Air Pak Abas	4.50	5.00	Phyllite
15	MK 22	Pulau Sebang	10.00	9.00	Granite
16	MK 23	Ladang Liang Guat	10.00	9.50	Granite
17	MK 24	Kg Dalong	9.00	9.50	Granite
18	MK 25	Ladang Liang Guat	8.50	18.00	Granite
19	MK 26	Pulau Sebang	7.00	8.00	Granite
20	MK 27	Kg Padang Sebang	9.00	11.20	Granite
21	MK 28	Tg Rimau	6.50	3.60	Granite
22	MK 49	Solok Duku	7.00	12.70	Schist
23	MK 50	Solok Duku	6.00	2.00	Schist
24	MK 51	Kg Air Molek	12.50	8.00	Phyllite
25	MK 52	Telok Gong	15.00	4.50	Schist
26	MK 56	Padang Kemunting	4.00	3.00	Granite
27	MK 57	Kg Tengah	20.00	2.70	Schist
28	MK 59	Kg Nelayan Kuala Linggi	25.00	18.00	Granite
29	MK 61	Ladang Liang Guat	7.00	5.50	Granite
30	MK 62	Tanjung Bidara	8.00	0.50	Granite

Table 1: The Number of Shallow Boreholes in Alor Gajah District (continue)

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
31	MK 63	Pekan Lubak Cina	16.00	6.40	Phyllite
32	MK 64	Solok Air Batu	6.50	0.90	Phyllite
33	MK 65	Solok Mek Selama	2.00	0.00	Granite
34	MK 66	Loji Air Gadek	5.70	0.90	Granite
35	MK 68	Rumah Pam Durian Tunggal	13.00	0.00	Schist
36	MK 69	Rumah Pam Durian Tunggal	8.50	0.00	Granite
37	MK 70	Kg Gadek	7.50	0.00	Granite
38	MK 71	Kg Gadek	10.00	0.00	Granite
39	MK 72	Kg Tanjung Rimau	6.50	0.00	Granite
40	MK 73	Ladang Liang Guat	4.00	0.00	Granite
41	MK 74	Ladang Liang Guat	3.00	0.00	Granite
42	MK 75	Kg Kemuning	4.00	0.00	Granite
43	MK 77	Air Hitam Ulu	6.50	0.00	Granite
44	MK 78	Kg Lodang	3.00	0.00	Schist
45	MK 79	Kg Paya Rumput	4.00	0.00	Schist
46	MK 80	Solok Air Limau Nipis	3.50	0.00	Schist
47	MK 83	Ulu Lendu	3.00	0.00	Schist
48	MK 84	Felda Hutan fercha	8.00	0.60	Granite
49	MK 85	Kg Sungai Petai	4.60	0.00	Phyllite
50	MK 86	Kg Telok Gong	8.00	0.20	Granite
51	MK 87	Kg Solok Ubai	3.10	1.20	Granite
52	MK 88	Kg Sg Jernih	4.20	0.50	Granite
53	MK 89	Pekan Rembia	5.20	2.50	Phyllite
54	MK 90	Kg Tengah, Durian Tunggal	8.00	0.00	Schist
55	MK 119	Kampung Tanjung Dahan	18.00	0.00	Granite
56	MK 120	Kampung Tanjung Dahan	11.00	4.50	Schist
57	MK 138	Sg Buloh	4.00	1.00	Granite
58	MK 139	Kg Durian Daun	3.00	0.00	Phyllite
59	MK 150	Pasir Gempor	11.00	0.50	Granite
60	MK 152	Solok Mangga	7.00	0.00	Granite

Table 1: The Number of Shallow Boreholes in Alor Gajah District (continue)

No.	**Code Number**	**Location**	**Depth (m)**	**Discharge cu.m/hour**	**Main Stone**
61	MK 153	Solok Mangga	18.00	2.70	Granite
62	MK 154	Padang Kemunting	5.00	14.00	Granite
63	MK 155	Kg Hailan	6.00	8.00	Granite
64	MK 156	Jalan Kolam Air	10.00	12.00	Granite
65	MK 197	Pengkalan Balak	14.00	2.50	Granite
66	MK 198	Kuala Sg Baru	11.00	0.00	Schist
67	MK 199	Kg Telok Belanga	3.00	0.50	Granite
68	MK 200	Kg Telok Gong	13.00	1.40	Granite
69	MK 201	Sungai Tuang	14.00	0.50	Phyllite
70	MK 219	Kampung Pancor	3.00	0.00	Phyllite
71	MK 220	Masjid Durian Tunggal	6.00	0.50	Phyllite
72	MK 227	Kg Air Manggis	4.00	0.00	Granite
73	MK 232	Kg Paya Rumput	6.00	0.50	Granite

Table 2: The Number of Deep Boreholes in Alor Gajah District

No.	**Code Number**	**Location**	**Depth (m)**	**Discharge cu.m/hour**	**Main Stone**
1		Pusat pertaian Sungai Udang	113	6	Phyllite/ Schist
2		Ladang sg. Baru, Mukim Masjid tanah	76	0	Phyllite
3		Ladang pegoh, Mukim Pengoh	68	9	Phyllite
4		Ladang Bertam, Mkm Durian Tunggal	76	6	Phyllite
5		Ladang Home, Mkm Kuala Sg Baru	77	8	Quartz
6		Kilang Sinma, Sg Baru Ilir	200	5	Schist
7		MARDEC Durian, Mkm Durian Tunggal	900	10	Phyllite

Table 3: The Number of Shallow Boreholes in Melaka Tengah District

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
1	MK 53	Kg Paya Rumput Jaya, Sg Udang	4.00	0.60	Granite
2	MK 54	Kg Paya Rumput Jaya, Sg Udang	5.00	8.20	Granite
3	MK 55	Kg Paya Rumput Jaya, Sg Udang	7.00	0.60	Granite
4	MK 60	Pusat Latihan Pertanian, Sg Udang	6.00	7.70	Granite
5	MK 67	Balai Polis Bandar Hilir	4.00	0.00	Schist
6	MK 81	Kelab Melaka, Tanjong Keling	4.00	0.00	Schist
7	MK 82	Kelab Melaka, Tanjong Keling	14.00	0.00	Schist
8	MK 91	Pusat Pertanian, Pulau Gadong	12.00	0.00	Metasediment
9	MK 92	Sekolah Munshi Abdullah, Air Keroh	2.80	0.00	Metasediment
10	MK 93	Kg Bt Baru Dalam	17.00	0.00	Metasediment
11	MK 111	Tangga Batu	5.25	0.00	Metasediment
12	MK 112	Tangga Batu	4.50	0.00	Metasediment
13	MK 113	Kg Tanah Merah	6.00	0.00	Metasediment
14	MK 114	Kg Tanah Merah	8.00	0.00	Metasediment
15	MK 115	Kg Tanah Merah	6.00	0.00	Metasediment
16	MK 116	Kg Batu Punggung, Pantai Kundur	10.00	0.00	Metasediment
17	MK 117	Pantai Tanah Merah, Pantai Kundur	14.00	0.00	Metasediment
18	MK 118	Kg Tambak Paya, Air Keroh	15.50	0.00	Metasediment
19	MK 121	Kg Paya Redan, Tiang Dua	10.00	0.70	Metasediment
20	MK 122	Kg Bukit Nibong, Tiang Dua	12.00	0.00	Metasediment
21	MK 123	Solok Hj. Madzuki, Bukit Lintang	3.25	0.00	Metasediment
22	MK 124	Pulau Gadong	2.00	0.00	Metasediment
23	MK 125	Kg Bertam Malim	2.00	0.00	Metasediment
24	MK 126	Permatang Kelebang	19.00	1.00	Metasediment
25	MK 127	Taman Bukit Rambai	4.25	0.00	Metasediment
26	MK 128	Surau sg Udang	3.50	0.00	Metasediment
27	MK 129	Kg Bukit Beruang	5.25	0.00	Metasediment
28	MK 141	Pantai Kundur	5.00	0.00	Schist

Table 3: The Number of Shallow Boreholes in Melaka Tengah District (continue)

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
31	MK 144	Bt 10, Kg Pantai Kundor	7.00	0.00	Schist
32	MK 145	Pantai Rombang	9.00	0.00	Schist
33	MK 146	Pantai Rombang	4.00	0.00	Schist
34	MK 147	Kg Pantai Kundor	8.50	0.50	Schist
35	MK 148	Pengkalan Perigi	5.00	0.00	Schist
36	MK 149	Pengkalan Perigi	4.00	0.00	Schist
37	MK 157	Sek Men Tun Tuah Bachang	10.50	0.00	Metasediment
38	MK 158	Kg Pantai Tanah Merah	9.00	1.00	Granite
39	MK 159	Kg Pantai Tanah Merah	9.00	1.00	Granite
40	MK 160	Masjid Jamek Kg Pernu	8.00	2.00	Metasediment
41	MK 98	Pengkalan Badak	15.00	0.00	Granite
42	MK 183	Pengkalan Rama	7.00	0.00	Metasediment
43	MK 184	Kg Pantai Rombang	9.00	1.50	Schist
44	MK 185	Kg Pantai Rombang	6.00	0.00	Schist
45	MK 186	Kg Pantai Rombang	8.00	2.00	Schist
46	MK 187	Kg Sg Lereh	11.00	0.50	Schist
47	MK 190	Kg Tanjung Keling	6.00	0.00	Metasediment
48	MK 191	Tanjung Keling	7.50	8.00	Metasediment
49	MK 192	Sg Lerek, Tg Keling	14.00	0.00	Metasediment
50	MK 196	Kg Nelayan Tg Keling	4.00	2.00	Metasediment
51	MK 202	Kg Telok Mas	8.00	0.00	Metasediment
52	MK 203	Kg Telok Mas	14.00	0.00	Metasediment
53	MK 204	Kg Ketapang Pernu	7.50	13.50	Metasediment
54	MK 205	Kg Solok Tengkera	9.50	2.50	Metasediment
55	MK 206	Jalan Tengkera	10.00	1.00	Metasediment
56	MK 207	Kg Ujong Pasir	8.00	0.00	Metasediment
57	MK 208	Pulau Dodol	2.50	0.00	Granite
58	MK 209	Pulau Dodol	2.00	0.00	Granite
59	MK 210	Kg Bukit Cina	5.00	0.00	Metasediment
60	MK 211	Padang Temu, Sg Duyong	14.00	0.00	Metasediment
61	MK 212	Masjid Bt Lima, Kandang	14.00	0.00	Metasediment
62	MK 216	Jalan Tanjung Minyak, Rembia	10.00	0.00	Metasediment

Table 3: The Number of Shallow Boreholes in Melaka Tengah District (continue)

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
64	MK 225	Bukit Rambai	10.00	0.00	Metasediment
65	MK 226	Tanjong Minyak	6.00	0.50	Metasediment
66	MK 233	Kem Terendak, Sg Udang	10.00	2.00	Granite
67	MK 234	Kem Terendak, Sg Udang	11.00	1.00	Granite
68	MK 235	Kem Terendak, Sg Udang	7.00	0.00	Granite
69	MK 236	Kem Terendak	10.00	1.00	Granite
70	MK 237	Kem Terendak	13.00	4.50	Granite
71	MK 238	Kem Terendak	10.00	0.50	Granite
72	MK 239	Kem Terendak	6.00	4.00	Granite
73	MK 240	Kem Terendak	6.00	1.00	Granite
74	MK 241	Kem Terendak	10.00	1.00	Granite
75	MK 242	Kem Terendak	10.00	4.50	Granite
76	MK 243	Kem Terendak	10.00	2.00	Granite
77	MK 244	Kem Terendak	10.00	7.00	Granite
78	MK 245	Kg Baru Pantai Kundor	8.00	1.00	Schist
79	MK 246	Kem Terendak	8.00	4.50	Granite
80	MK 247	Kem Terendak	8.00	2.00	Granite
81	MK 248	Kem Terendak	6.00	4.00	Granite
82	MK 249	Kem Terendak	8.00	3.50	Granite
83	MK 250	Kem Terendak	7.00	0.00	Granite
84	MK 251	Kem Terendak	3.00	0.00	Granite
85	MK 252	Kem Terendak	7.50	4.00	Granite
86	MK 253	Kem Terendak	7.50	5.50	Granite
87	MK 254	Kem Terendak	6.00	0.00	Granite
88	MK 255	Kem Terendak	7.50	2.00	Granite
89	MK 256	Kem Terendak	8.00	2.00	Granite
90	MK 257	Kem Terendak	6.50	0.00	Granite
91	MK 258	Kem Terendak	7.00	4.00	Granite
92	MK 259	Kem Terendak	9.00	8.00	Granite
93	MK 260	Kem Terendak	6.50	0.00	Granite

Table 3: The Number of Shallow Boreholes in Melaka Tengah District (continue)

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
94	MK 261	Kem Terendak	7.50	2.50	Granite
95	MK 262	Kem Terendak	8.00	1.50	Granite
96	MK 263	Kem Terendak	6.50	1.00	Granite
97	MK 264	Kem Terendak	7.50	4.50	Granite
98	MK 265	Kem Terendak	7.50	4.00	Granite
99	MK 106	Parit Perawas Sg Rambai	15.50	0.00	Schist
100	MK 107	Kg Cap Tangan	12.50	0.00	Schist
101	MK 108	Parit Penghulu Benting	14.00	0.00	Schist
102	MK 109	Kg Tasik Teluk Gong	19.50	0.00	Schist

Table 4: The Number of Deep Boreholes in Melaka Tengah District

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
1	-	Ladang Getah Lee, kerubong	75.00	5.00	Schist
2	-	Taman Aggrerik, kelebang	20.00	5.00	Aluvium
3	-	Hospital Besar Melaka	20.00	5.00	Schist
4	-	Klinik Bukit Baru	30.00	4.00	Schist
5	-	Kilang Kertas Seng Kong	100	18	Schist

Table 5: The Number of Shallow Boreholes in Jasin District

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
1	MK 10	Solok Tehel	9.50	2.00	Shale
2	MK 15	Pekan tehel	13.00	2.70	Shale
3	MK 16	Ulu Jasin	4.50	2.50	Shale
4	MK 17	Batu 21 jalan Selandar	6.00	16.00	Shale
5	MK 18	Batu 24 Ja;an Selandar	9.00	2.20	Shale
6	MK 19	Bukit Senggeh	5.00	18.50	Schist
7	MK 20	Anak Air keroh, Selandar	5.00	9.00	Schist
8	MK 21	Kg Tengah, Selandar	6.00	7.00	Schist
9	MK 29	Pulau selendar	7.00	1.00	Schist
10	MK 30	Pekan Jasin	8.50	12.30	Schist
11	MK 31	Lubok Kesau, Benban	11.50	5.50	Schist
12	MK 32	Kesang pajak	9.00	10.70	Schist
13	MK 33	Solok Pondok, Keempas	7.50	7.70	Schist
14	MK 34	Kesang Tua	8.00	5.50	Schist
15	MK 35	Sek Iskandar Syah	8.00	2.00	Schist
16	MK 36	Kg Kelubi	7.00	9.60	Schist
17	MK 37	Solok Gapam	8.00	5.50	Granite
18	MK 38	Km 14. Jln Jasin Bemban	9.50	0.70	Schist
19	MK 39	Km 7, Jasin Nyala	5.00	10.00	Schist
20	MK 40	Kg Rim	8.80	8.20	Schist
21	MK 41	Gong Bangkong	10.00	5.50	Schist
22	MK 42	Kg Tengah, Btg Melaka	4.00	4.00	Schist
23	MK 43	Solok Ulu Gapis	5.00	7.30	Schist
24	MK 44	Tedong Darat	8.00	10.30	Schist
25	MK 45	Tedong Darat	8.50	4.10	Schist
26	MK 46	Paya Rayong	12.50	2.00	Schist
27	MK 47	Seberang darat, Merlimau	12.00	2.00	Schist
28	MK 48	Ulu Jasin	5.50	3.30	Schist
29	MK 58	Serkam darat	15.00	2.30	Schist
30	MK 94	Solok Serompong	3.00	0.00	Granite

Table 5: The Number of Shallow Boreholes in Jasin District (continue)

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
31	MK 95	Ulu Duyung	4.50	0.00	Schist
32	MK 96	Selandar	5.00	0.00	Schist
33	MK 97	Paya Kundang	15.00	0.00	Granite
34	MK 99	Bukit Kajang	2.25	0.00	Granite
35	MK 100	Air Panas	2.25	0.00	Granite
36	MK 101	Cabau	7.00	0.00	Granite
37	MK 102	Asahan	4.50	0.00	Granite
38	MK 104	Paya Tanjung	7.00	0.00	Granite
39	MK 106	Parit Perawas	15.50	0.00	Laterite
40	MK 108	Parit Penghulu	14.00	0.00	Laterite
41	MK 109	Telok Gong	19.50	0.00	Schist
42	MK 110	Air Kangkong	110.00	0.00	Granite
43	MK 130	Kesang	11.00	0.00	Laterite
44	MK 133	Batu 21 Kesang	8.00	0.00	Laterite
45	MK 134	Heifer's Park	4.00	0.00	Laterite
46	MK 135	Batu 15 Merlimau	9.00	1.80	Granite
47	MK 136	Batu Melaka	4.00	0.00	Laterite
48	MK 161	Solok Pasal	10.00	0.00	Schist
49	MK 178	Kg Kumpai, Cenderah	14.00	4.00	Granite
50	MK 179	Kg Nelayan, Tg Keling	4.00	0.00	Schist
51	MK 180	Air Molek	14.00	1.40	Schist
52	MK 181	Solok Minyak barat	10.00	3.00	Schist
53	MK 193	Permatang Pasir	10.00	0.50	Schist
54	MK 76	Kg Tengah, Selandar	6.00	0.00	Schist
55	MK 213	Simpang Jasin_Bemban	6.00	0.00	Granite
56	MK 214	Air Barok	10.00	3.60	Granite
57	MK 215	Felda kemendor	8.00	1.00	Granite
58	MK 221	Felda Lembah Kesang	9.00	2.00	Granite
59	MK 223	Surau Cincin	3.50	0.00	Granite
60	MK 224	Simpang Kumpai	11.00	13.60	Granite
61	MK 229	Simpang Cincin/Tangkak	6.00	0.00	Granite
62	MK 230	Risda Sg Duyung	6.00	0.50	Granite
63	MK 231	Blai Islam	9.00	0.50	Granite

Table 6: The Number of Deep Boreholes in Jasin District

No.	Code Number	Location	Depth (m)	Discharge cu.m/hour	Main Stone
1	TMW 2	MRSM, Jasin	65.00	4.00	Shale
2	TMW 3	I.K.M, Jasin	54.00	15.60	Shale
3	TMW 19	Bemban	200.00	1.00	Granite
4	TMW 20	Asahan	170.00	15.00	Shale
5	TMW 27	Btg Melaka	150.00	3.00	Granite
6	TMW 28	Klinik Merlimau	52.00	1.00	Granite
7	TMW 29	JHP Merlimau	48.00	1.50	Granite
8	TMW 30	Chabau	30.00	6.00	Schist

Appendix – G

GROUNDWATER QUALITY DATA OF MELAKA

Table 1: Water Quality Data in Shallow Boreholes – Alor Gajah District

Parameters	**MK-120**	**KSB-Ib)**	**MK-52**	**MK-57**	**MK-200**
Turbidity	3.5	0.9	0.9	150	38
Color	5	5	5	5	5
pH	8	5.2	7.4	7	3.7
TDS	6760	1936	222	2456	1038
Chloride (Cl)	3230	2220	40	980	16
Ammonia (NH_4-N)	1.8	0.65	0.88	0.06	0.08
Nitrate (NO_3-N)	9	96	12	<3	<3
Iron (Fe)	16.9	2.6	8.5	<0.1	6
Fluoride (F)	<0.5	4.1	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	0.006	<0.005	<0.005	0.007
Copper	<0.1	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	232	116	9.9	62	1.1
Manganese (Mn)	8.3	2.4	<0.1	<0.1	0.4
Zink (Zn)	<0.1	<0.1	0.1	<0.1	0.4
Sodium (Na)	1480	1015	37	575	11
Sulfate(So_4)	450	210	70	73	28
Calcium(Ca)	220	147	4.2	36	4.6
Bicarbonate(Hco_3)	127	23	35	260	<1
Silica(Si)	13	13	16	14	5.1
Carbonate(Co_3)	5	<1	<1	3	<1
Aluminum(Al)	0.1	0.2	<0.1	<0.1	0.3
Potassium(K)	88	38	4.2	35	1.7
Cadmium(Cd)	<0.1	<0.01	<0.1	<0.1	<0.01
Phosphorus(P)	<0.02	0	<0.02	<0.02	0.03
Conductivity	10,200	2850	310	3670	144
Sodium nibs	16.61	15.2	2.25	13.47	1.20

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 1: Water Quality Data in Shallow Boreholes – Alor Gajah District (continue)

Parameters	**MK-51**	**MK-12**	**MK-14**	**MK-7**	**MK-56**
Turbidity	0.9	135	30	11	0
Color	5	5	5	5	5
pH	8	7.6	5.9	5	6.6
TDS	852	416	92	94	76
Chloride (Cl)	385	27	6	14	6
Ammonia (NH_4-N)	0.72	0.02	0.02	0.06	0.02
Nitrate (NO_3-N)	4	<3	<13	<3	<3
Iron (Fe)	8.8	2.4	0.4	2.1	0.1
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	<0.005	<0.005	<0.005	<0.005
Copper	<0.1	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	15	3.6	0.8	0.5	0.5
Manganese (Mn)	0.2	0.3	<0.1	<0.1	<0.1
Zink (Zn)	0.4	<0.1	0.1	<0.1	<0.1
Sodium (Na)	272	28	7.5	13	6.2
Sulfate(So_4)	125	<5	<5	15	31
Calcium(Ca)	21	5	1.3	1.7	0.8
Bicarbonate(Hco_3)	93	62	1	<1	<1
Silica(Si)	14	28	18	5.3	21
Carbonate(Co_3)	4	<1	<1	<1	<1
Aluminum(Al)	<0.1	<0.1	<0.1	<0.1	<0.1
Potassium(K)	10	10	1.3	3.5	<0.5
Cadmium(Cd)	<0.1	<0.1	<0.1	<0.1	<0.1
Phosphorus(P)	<0.02	<0.02	0.02	<0.02	<0.02
Conductivity	1,504	210	56	108	171
Sodium nibs	11.08	2.33	1.28	2.25	1.30

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 1: Water Quality Data in Shallow Boreholes – Alor Gajah District (continue)

Parameters	**MK-154**	**MK-155**	**MK-197**	**MK-8**	**MK-22**
Turbidity	9	14	24	185	148
Color	5	70	5	5	5
pH	4.5	6.8	5.6	6.6	6.5
TDS	128	104	306	328	164
Chloride (Cl)	17	13	7	12	8
Ammonia (NH_4-N)	0.4	0.64	0.02	0.24	0.24
Nitrate (NO_3-N)	<3	3	<3	<3	3
Iron (Fe)	4.4	1.9	1.3	16.2	2.4
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	<0.005	<0.005	<0.005	<0.005
Copper	<0.1	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	1.3	1.8	0.8	2.1	3.9
Manganese (Mn)	<0.1	<0.1	0.2	0.3	0.5
Zink (Zn)	<0.1	<0.1	<0.1	<0.1	0.2
Sodium (Na)	19	10	5.3	14	14
Sulfate(So_4)	35	15	<3	<0.5	<0.5
Calcium(Ca)	7.8	2.2	2.2	16	7.8
Bicarbonate(Hco_3)	10	10	20	66	68
Silica(Si)	3.2	5.3	15	21	21
Carbonate(Co_3)	<1	<1	<1	<1	<1
Aluminum(Al)	0.1	0.6	<0.1	<1	0.2
Potassium(K)	4.3	8.6	2.7	3.5	5.1
Cadmium(Cd)	<0.1	<0.1	<0.01	<0.1	<0.1
Phosphorus(P)	0.05	0.05	0.18	0.05	0.02
Conductivity	161	117	56	177	144
Sodium nibs	161	1.21	0.78	0.87	1.02

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 1: Water Quality Data in Shallow Boreholes – Alor Gajah District (continue)

Parameters	MK-26	MK-63	MK-9	MK-6	MK-25
Turbidity	18	80	200	96	11
Color	5	5	5	5	5
pH	6.5	9.7	5.4	6.4	5.9
TDS	86	388	366	128	54
Chloride (Cl)	<1	84	6	2	2
Ammonia (NH_4-N)	0.96	0.02	0.1	0.2	0.28
Nitrate (NO_3-N)	<3	<3	<3	<3	<3
Iron (Fe)	2.4	14.3	21.7	0.3	0.4
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	<0.025	<0.005	<0.005	<0.005
Copper	<0.1	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	2.1	21	1.3	1.3	1.0
Manganese (Mn)	0.4	0.1	<0.1	<0.1	<0.1
Zink (Zn)	<0.1	0.1	<0.1	<0.1	<0.1
Sodium (Na)	5.5	59	4.1	4.7	4.2
Sulfate(So_4)	<0.5	<5	7	<0.5	8
Calcium(Ca)	12	15	3.3	2.2	1.7
Bicarbonate(Hco_3)	106	140	7	22	5
Silica(Si)	14	18	10	12	11
Carbonate(Co_3)	<1	24	<1	<1	<1
Aluminum(Al)	<1	<0.1	<0.1	<0.1	<0.1
Potassium(K)	3.1	7.9	<0.5	4	2
Cadmium(Cd)	<0.1	<0.1	<0.1	<0.1	<0.1
Phosphorus(P)	0.03	0.76	<0.02	0.03	0.03
Conductivity	110	523	59	56	45
Sodium nibs	0.35	2.31	0.47	0.62	0.63

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 1: Water Quality Data in Shallow Boreholes – Alor Gajah District (continue)

Parameters	**MK-156**	**MK-72**	**MK-23**	**MK-24**	**MK-5**
Turbidity	155	22	52	2.7	30
Color	5	5	5	5	5
pH	8.0	5.2	6.5	5.8	7.4
TDS	132	254	140	36	240
Chloride (Cl)	3	6	<1	<1	1
Ammonia (NH_4-N)	1.4	0.04	0.44	0.32	0.02
Nitrate (NO_3-N)	<3	<1	<3	<3	<0.3
Iron (Fe)	17	0.1	0.7	2.6	11.1
Fluoride (F)	1	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	0.017	<0.005	<0.005	<0.005
Copper	<0.1	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	1.3	0.3	2.4	0.8	1.8
Manganese (Mn)	0.3	<0.3	0.2	<0.1	0.1
Zink (Zn)	<0.1	<0.1	<0.1	<0.1	<0.1
Sodium (Na)	15	62	10	1.4	7.7
Sulfate(So_4)	<5	7	<0.5	<0.5	<5
Calcium(Ca)	13	4.1	12	1.7	13
Bicarbonate(Hco_3)	90	150	76	10	67
Silica(Si)	23	53	28	11	31
Carbonate(Co_3)	<1	6	<1	<1	<1
Aluminum(Al)	<0.1	<0.1	<0.1	<0.1	<0.1
Potassium(K)	3.5	3.3	1.6	0.3	3.4
Cadmium(Cd)	<0.1	<0.01	<0.1	<0.1	<0.1
Phosphorus(P)	0.03	14	0.03	0.02	0.77
Conductivity	138	311	124	26	129
Sodium nibs	1.06	8.11	0.69	0.22	0.55

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 1: Water Quality Data in Shallow Boreholes – Alor Gajah District (continue)

Parameters	**MK-2**	**MK-3**	**MK-4**	**MK-49**	**MK-50**
Turbidity	95	45	110	1.3	1.3
Color	5	5	5	5	5
pH	6.5	5.9	4	7.9	7.9
TDS	322	278	214	114	188
Chloride (Cl)	2	14	17	1	<1
Ammonia (NH_4-N)	0.16	0.06	0.04	0.24	0.04
Nitrate (NO_3-N)	<3	4	8	4	4
Iron (Fe)	13.5	1.7	9.9	8.7	0.6
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	<0.005	<0.005	<0.005	<0.005
Copper	<0.1	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	19	0.8	<0.5	3.6	2.3
Manganese (Mn)	1.2	0.2	<0.1	0.2	<0.1
Zink (Zn)	<0.1	<0.1	<0.1	<0.1	<0.1
Sodium (Na)	8.6	10	12	7.2	11
Sulfate(So_4)	73	9	6	<5	<5
Calcium(Ca)	15	2.5	1.7	16	8
Bicarbonate(Hco_3)	54	11	<1	76	61
Silica(Si)	38	21	10	42	68
Carbonate(Co_3)	<1	<1	<1	6	4
Aluminum(Al)	<0.1	<0.1	<0.1	<0.1	<0.1
Potassium(K)	2	5.8	2.3	2.5	5.3
Cadmium(Cd)	<0.1	<0.1	<0.1	<0.1	<0.1
Phosphorus(P)	<0.02	<0.02	<0.02	<0.02	<0.02
Conductivity	281	97	152	120	111
Sodium nibs	0.36	1.41	2.15	0.41	0.88

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 2: Water Quality Data in Deep Boreholes – Alor Gajah District

Parameters	**MTW-15**	**MTW-4**	**MTW-18**	**MTW-31**	**MTW-21**
Turbidity	8.1	11	10	9.2	0.9
Color	5	5	5	5	5
pH	5.2	5.2	5.2	5.2	5.2
TDS	2720	54	80	28	196
Chloride (Cl)	1095	2	2	1	7
Ammonia (NH_4-N)	0.08	0.28	<0.02	0.08	196
Nitrate (NO_3-N)	9	<3	4	<3	7
Iron (Fe)	4.1	0.4	0.3	3.1	<0.02
Fluoride (F)	0.8	<0.5	<0.5	<0.5	5
Arsenic (As)	0.021	<0.005	<0.005	<0.005	1.3
Copper	<0.1	<0.1	<0.1	<0.1	<0.5
Magnesium (Mg)	81	1.0	3.6	1.4	<0.005
Manganese (Mn)	1.9	<0.1	0.3	<0.5	<0.1
Zink (Zn)	<0.1	<0.1	<0.1	<0.1	3.4
Sodium (Na)	445	4.2	2.5	6.7	0.3
Sulfate(So_4)	204	8	4	7	4
Calcium(Ca)	200	1.7	1.3	0.2	15
Bicarbonate(Hco_3)	49	5	5	5	<3
Silica(Si)	26	11	<0.1	11	16
Carbonate(Co_3)	0.9	<1	<1	<1	78
Aluminum(Al)	0.2	<0.1	<0.1	<0.1	52
Potassium(K)	12	2	0.8	0.7	<1
Cadmium(Cd)	<0.01	<0.1	<0.01	<0.01	0.1
Phosphorus(P)	<0.02	0.03	<0.02	0	<0.01
Conductivity	3,700	45	55	31	<162
Sodium nibs	6.71	0.63	0.2	1.17	0.89

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 3: Water Quality Data in Shallow Boreholes – Melaka Tengah District

Parameters	**MK-143**	**MK-192**	**MK- 241**	**MK-254**	**MK-126**
Turbidity	36	31	5.6	4.3	7450
Color	5	4	5	5	5
pH	7	6.8	4.6	6.9	3.5
TDS	64	756	90	76	4732
Chloride (Cl)	7	90	10	5	<0.005
Ammonia (NH_4-N)	0.08	0.02	0.02	0.02	0.1
Nitrate (NO_3-N)	4	<3	7	<3	0.12
Iron (Fe)	7.9	5.3	7.9	<0.1	116.5
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	4.1
Arsenic (As)	<0.005	<0.005	<0.005	<0.005	<0.1
Copper	0.5	<0.1	<0.1	<0.1	<0.1
Magnesium (Mg)	0.5	14	0.6	0.5	<0.02
Manganese (Mn)	0.1	0.3	<0.1	<0.1	0.2
Zink (Zn)	<0.1	<0.1	<0.1	<0.1	176
Sodium (Na)	5.2	70	7.5	4.5	128
Sulfate(So_4)	45	90	<5	<5	1080
Calcium(Ca)	1.7	31	1.6	1.6	25
Bicarbonate(Hco_3)	5	1.18	5	20	<1
Silica(Si)	4.3	22	9.6	17	<1
Carbonate(Co_3)	<1	<1	<1	<1	2410
Aluminum(Al)	0.4	<0.1	<0.1	<0.1	200
Potassium(K)	4	19	3.3	3.5	4
Cadmium(Cd)	<0.01	<0.01	<0.01	<0.01	<0.5
Phosphorus(P)	<0.5	<0.5	<0.5	<0.5	4.2
Conductivity	56	665	68	44	15.1
Sodium nibs	4.9	14.7	7.1	4.3	5

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 3: Water Quality Data in Shallow Boreholes – Melaka Tengah District (continue)

Parameters	**MK-126**	**MK-205**	**MK-202**
Turbidity	3.5	14	41
Color	5	70	5
pH	4.2	6.8	7.1
TDS	4732	104	284
Chloride (Cl)	2410	13	5
Ammonia (NH_4-N)	0.12	0.64	0.2
Nitrate (NO_3-N)	4	3	<3
Iron (Fe)	116.5	1.9	1.1
Fluoride (F)	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	<0.005	<0.005
Copper	<0.1	<0.1	<0.1
Magnesium (Mg)	128	1.8	2
Manganese (Mn)	4.1	0.1	0.1
Zink (Zn)	0.2	<0.1	<0.1
Sodium (Na)	1080	10	11
Sulfate(So_4)	200	14	9
Calcium(Ca)	176	2.2	2.4
Bicarbonate(Hco_3)	<1	10	35
Silica(Si)	-	-	-
Carbonate(Co_3)	<1	<1	<1
Aluminum(Al)	0.1	0.6	<1
Potassium(K)	25	8.6	2.2
Cadmium(Cd)	<0.5	<0.5	<0.5
Phosphorus(P)	0.02	0.05	0.02
Conductivity	7450	117	78
Sodium nibs	15.1	1.2	1.27

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 4: Water Quality Data in Deep Boreholes – Melaka Tengah District

Parameters	**MTW-14**	**MTW-25**	**MTW-12**	**MTW-9**	**MTW-10**
Turbidity	*8.1*	*<1*	*50*	*33*	*14*
Color	*5*	*5*	*5*	*5*	*5*
pH	*8.2*	*8.4*	*6.7*	*5.2*	*8*
TDS	*268*	*240*	*26040*	*32*	*242*
Chloride (Cl)	*0.7*	*3*	*13250*	*6*	*3*
Ammonia (NH_4-N)	*<0.04*	*0.08*	*1.1*	*0.2*	*0.02*
Nitrate (NO_3-N)	*7*	*<3*	*100*	*<3*	*<3*
Iron (Fe)	*1*	*1*	*12*	*0.4*	*3.5*
Fluoride (F)	*<0.5*	*<0.5*	-	*<0.5*	*<0.5*
Arsenic (As)	*<0.005*	*<0.005*	*<0.05*	*<0.005*	*<0.005*
Copper	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*<0.1*
Magnesium (Mg)	*5.7*	*23*	*859*	*0.4*	*7.6*
Manganese (Mn)	*0.2*	*0.1*	*<0.1*	*0.1*	*0.2*
Zink (Zn)	*<0.1*	*<0.1*	*<0.1*	*<0.1*	*0.2*
Sodium (Na)	*12*	*<3*	*6700*	*4.1*	*11*
Sulfate(So_4)	*12*	*<3*	*1690*	*<3*	*10*
Calcium(Ca)	*62*	*30*	*323*	*0.4*	*35*
Bicarbonate(Hco_3)	*188*	*226*	*110*	*11*	*153*
Silica(Si)	*1*	*3*	*4.9*	*14*	*18*
Carbonate(Co_3)	*5*	*<1*	*<1*	*<1*	*10*
Aluminum(Al)	*0.7*	*1*	*<0.2*	*<0.01*	*0.1*
Potassium(K)	*1*	*1*	*235*	*1.8*	*6.5*
Cadmium(Cd)	*8.2*	*8.4*	*<0.01*	*<0.01*	*<0.01*
Phosphorus(P)	*0.02*	*0.02*	*<0.5*	*<0.02*	*0.05*
Conductivity	*145*	*333*	*388000*	*38*	*274*

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 5: Water Quality Data in Shallow Boreholes – Jasin District

Parameters	**MK-19**	**MK-20**	**MK-30**	**MK-31**	**MK-32**
Turbidity	5.7	4.7	37	18	27
Color	5	5	5	5	5
pH	7	8.2	7	5.9	7.9
TDS	84	148	176	168	122
Chloride (Cl)	6	4	16	7	2
Ammonia (NH_4-N)	0.12	0.02	0.12	0.02	0.12
Nitrate (NO_3-N)	<3	<3	<3	<3	<3
Iron (Fe)	-	-	-	-	-
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	-	-	-	<0.005	<0.005
Copper	-	-	-	-	-
Magnesium (Mg)	1.3	1.0	1.8	1.3	2
Manganese (Mn)	-	-	-	-	-
Zink (Zn)	-	-	-	-	-
Sodium (Na)	8.4	9.6	11	6.7	5.9
Sulfate(So_4)	7	<5	20	<5	<5
Calcium(Ca)	3.3	21	18	14	29
Bicarbonate(Hco_3)	27	79	45	15	56
Silica(Si)	23	44	18	14	29
Carbonate(Co_3)	<1	7	<1	<1	<1
Aluminum(Al)	<0.1	<0.1	<0.1	<0.1	<0.1
Potassium(K)	3.7	3.7	4.5	1.8	3.8
Cadmium(Cd)	<0.1	-	-	-	-
Phosphorus(P)	-	0.02	0.02	-	-
Conductivity	70	143	119	55	101
Sodium nibs	-	-	-	-	-

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 5: Water Quality Data in Shallow Boreholes – Jasin District (continue)

Parameters	**MK-41**	**MK-42**	**MK-43**	**MK-44**	**MK-46**
Turbidity	85	17	19	8.9	4.6
Color	5	5	5	5	5
pH	6.8	8.5	6.7	7.9	6.8
TDS	110	124	80	204	422
Chloride (Cl)	1	11	2	30	157
Ammonia (NH_4-N)	-	-	-	-	-
Nitrate (NO_3-N)	-	-	-	-	-
Iron (Fe)	-	-	-	-	-
Fluoride (F)	-	-	-	-	-
Arsenic (As)	<0.005	-	-	-	-
Copper	-	-	-	-	-
Magnesium (Mg)	1.3	2.3	1.3	2.5	11
Manganese (Mn)	-	-	-	-	-
Zink (Zn)	-	-	-	-	-
Sodium (Na)	5.5	12	5.3	2.7	71
Sulfate(So_4)	10	<5	-	-	12
Calcium(Ca)	22	15	-	-	24
Bicarbonate(Hco_3)	16	27	2.7	-	44
Silica(Si)	22	15	-	-	32
Carbonate(Co_3)	-	8	-	-	-
Aluminum(Al)	<0.1	<0.1	<0.1	-	-
Potassium(K)	3.2	5.1	3.1	5.8	-
Cadmium(Cd)	-	-	-	-	-
Phosphorus(P)	-	-	-	-	-
Conductivity	70	121	59	231	613
Sodium nibs	-	-	-	-	-

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 5: Water Quality Data in Shallow Boreholes – Jasin District (continue)

Parameters	MK-47	MK-48	MK-214	MK-221	MK-224
Turbidity	93	<1	25	109	4.6
Color	5	5	5	5	5
pH	6.8	6.3	7	7	7.2
TDS	976	32	780	436	2040
Chloride (Cl)	389	3	4	3	2
Ammonia (NH_4-N)	-	-	0.06	0.2	0.44
Nitrate (NO_3-N)	-	-	<3	<3	<3
Iron (Fe)	-	-	12	12	<0.1
Fluoride (F)	-	-	<0.5	<0.5	<0.5
Arsenic (As)	-	-	-	-	-
Copper	-	-	-	-	-
Magnesium (Mg)	31	1.5	4.4	6.4	6.9
Manganese (Mn)	-	-	<0.1	<0.2	<0.1
Zink (Zn)	-	-	<0.1	0.1	<0.1
Sodium (Na)	193	3.4	17	11	11
Sulfate(So_4)	35	<5	7	19	<3
Calcium(Ca)	31	0.8	26	14	40
Bicarbonate(Hco_3)	93	6	128	76	188
Silica(Si)	21	10	24	34	28
Carbonate(Co_3)	-	-	<1	<1	<1
Aluminum(Al)	-	1.1	0.1	<1	<0.1
Potassium(K)	20	-	2.5	3.3	1.6
Cadmium(Cd)	-	-	<0.01	<0.01	<0.01
Phosphorus(P)	-	-	<0.02	<0.02	<0.02
Conductivity	1404	35	224	158	295
Sodium nibs	-	-	-	-	-

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity

Table 6: Water Quality Data in Deep Boreholes – Jasin District

Parameters	MTW-2	MTW-3	MTW-20	MTW-27	MTW-30
Turbidity	19	42	2.6	<1	<1
Color	5	5	5	5	5
pH	8.1	7.1	8	8	6.2
TDS	478	182	168	256	232
Chloride (Cl)	2	2	2	2	1
Ammonia (NH_4-N)	<0.02	0.12	<0.02	<0.02	<0.08
Nitrate (NO_3-N)	<3	<3	<3	<3	<3
Iron (Fe)	3.2	7.3	6.6	1.1	<0.1
Fluoride (F)	<0.5	<0.5	<0.5	<0.5	<0.5
Arsenic (As)	<0.005	<0.005	<0.005	<0.005	<0.3
Copper	-	-	-	-	-
Magnesium (Mg)	8.6	7.3	7.2	8.3	3.4
Manganese (Mn)	0.1	0.2	0.3	0.7	-
Zink (Zn)	<0.01	<0.01	1.2	0.4	<0.1
Sodium (Na)	7.3	7.4	12	16	3.6
Sulfate(So_4)	<5	<5	<3	1	3
Calcium(Ca)	43	11	14	42	55
Bicarbonate(Hco_3)	-	94	112	193	234
Silica(Si)	-	52	61	77	-
Carbonate(Co_3)	<1	<1	<1	<1	2
Aluminum(Al)	0.1	<0.1	<0.1	<0.1	0.1
Potassium(K)	9	7.2	3.9	5.1	3
Cadmium(Cd)	<0.1	-	<0.01	<0.01	<0.01
Phosphorus(P)	<0.02	<0.02	0.06	<0.02	-
Conductivity	306	156	179	299	348
Sodium nibs	-	-	-	-	-

Note: all parameter as concentration (mg/l), exclude pH, Turbidity and Conductivity