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Groundwater quality assessment using remote sensing and related datasets

NORAINI SURIP

Pusat Remote Sensing Negara (MACRES)
13 Jalan Tun Ismail, 50480 Kuala Lumpur

Abstract: The study was carried out in Selangor and Kuala Lumpur for developing a model to assess groundwater quality using remotely sensed, borehole and ancillary datasets. Remote sensing data were useful in extracting groundwater contamination sources due to specific land usage such as agricultural activities and urbanization. They were also useful in generating digital elevation model (DEM) and extracting geological features including lineaments and faults, which influenced the movement of contamination sources to the aquifer. Borehole data providing relevant subsurface geological information such as aquifer media, vadose zone media, hydraulic conductivity and groundwater level. These information together with population census data formed the basis in formulating the suitable model to access the groundwater quality. The model was used to generate the groundwater contamination risk map. Urban and highly populated area having shallow limestone aquifer identified as having the highest risk of groundwater contamination. On the contrary, groundwater located within forested mountainous aquifer was identified as having the lowest risk of contamination. Future groundwater quality was also modelled using predicted landuse changes and population density increased for the year 2010, 2020 and 2030.

Abstrak: Kajian untuk pemodelan penilaian kualiti air tanah telah dijalankan di Selangor dan Kuala Lumpur dengan menggunakan data remote sensing, data lubang gerudi dan data sedia ada. Data remote sensing telah digunakan untuk mengenalpasti punca pencemaran dari pengguaan tanah yang spesifik seperti aktiviti pertanian dan perbandaran. Data ini juga telah digunakan untuk membina DEM dan mengenalpasti fitur-fitur geologi seperti lineaments dan sesar yang diketahui boleh mempengaruhi pergerakan punca pencemaran ke dalam akuifer. Data lubang gerudi memberikan informasi geologi bawah permukaan seperti medium akuifer, zon vados, konduktiviti dan aras air tanah. Semua informasi ini berserta data kepadatan penduduk telah digunakan sebagai asas untuk menghasilkan model penilaian air tanah. Model tersebut seterusnya telah digunakan untuk menyediakan peta risiko pencemaran air tanah. Adalah didapati kawasan perbandaran yang berkepadatan penduduk dan mempunyai akuifer batu kapur yang cetek mempunyai risiko pencemaran air tanah yang tinggi. Sebaliknya, air tanah yang terletak di kawasan hutan tanah tinggi mempunyai risiko pencemaran air tanah yang rendah. Kualiti air tanah pada masa hadapan telah juga dimodelkan dengan menjangkakan perubahan guna tanah dan pertambahan penduduk untuk tahun 2010, 2020 dan 2030.

INTRODUCTION

Groundwater forms the part of the natural water cycle and is present in various types of geological formations. It is an important source of water supply for drinking, irrigation, industrial, and municipal purposes in developed countries. On contrary, most tropical countries including Malaysia have traditionally depended on surface water for their water supply. Being a country endowed with a rainfall of approximately 2,700 mm a year, ninety percent of water supply in Malaysia is from surface water. However, in the late 1990s, some states in Malaysia had low water supply due to less rain falling on the catchment areas. The most effected areas were the state of Selangor and the Federal Territories Kuala Lumpur which are the most rapid industrial and agricultural development and population growth areas in the nation. Development activities and population growth were identified as having a direct relation with water requirements. As to solve the problem, the groundwater were used as an additional water supply. The quality of groundwater in this area, therefore, have to be studied since human activities might contribution to groundwater contamination.

Remotely sensed imagery (optical and radar) is a suitable data source for identifying groundwater problems across large areas. Its advantage of having wide spatial coverage making it as an indispensable tool for understanding the spatial relationship between various contamination sources of natural and human origin. Even though the main applications of remote sensing are in groundwater exploration, it is also valuable for studying groundwater quality. Remotely sensed data is used for two main purposes in this study. Firstly, to estimate the regional distribution of vegetation, urban areas, land surface uses and other factors important in groundwater changes, and the secondly to identify the locations and distribution of geological features that might determine groundwater flow directions. The two types of data that have been used are Landsat Thematic Mapper (Landsat TM) and Radarsat Synthetic Aperture Radar (SAR).

Groundwater by its very nature is not available for direct observation, satellite data therefore, must been used in conjunction with available borehole and other ancillary information for groundwater studies (Saraf and Choudhury, 1998; Waters, 1990). Geographic information system (GIS) techniques are used to interface satellite data with ancillary information, both spatial and non-spatial, within the same georeferencing scheme. The blending of remote sensing and GIS technologies has proven to be an efficient tool in groundwater studies (Saraf and Choudhury, 1998; Krishnamurthy and Srinivas, 1995). Therefore, the integration of remote sensing and geographic information system (GIS) techniques has been applied in this study in order to identify the sources of contamination, to evaluate the quality of groundwater in Selangor, Malaysia and to model groundwater contamination risk.

STUDY AREA

Geography

The study area is located within the quadrant of longitude 101°00'E to 102°00'E and latitude 2°45'N and 3°30'N (Fig. 1). The area is characterised by mostly lowlands with agriculture in the east, urban land uses dominating the valley bottom in the middle region and tropical forests covering steeper areas in the eastern part. The area is also characterised by uniform temperature, high humidity, light wind and copious rainfall. Situated at the equator, it is extremely rare for these areas to have a completely clear sky throughout the day. The population is estimated to be about 3.6 million based on a survey done in June-July, year 2000 (Department of Statistic, 1999). The census results showed that the approximate birth rate of the Malaysian population is about 10% of the population. The urban and suburban areas are most populated, while remote rural areas have a low population. The migration of peoples from rural areas to urban areas has increased drastically over the past ten years as they search for a better living. This activity therefore, has caused imbalance in population between the urban and rural areas. High population has also increased water supply demand and there is a risk of groundwater contamination in urban areas.

Geology

There are four major rock types over the study area, consisting of metamorphic rocks, sedimentary rocks, igneous rocks, and the alluvial plain. The granitic rocks occupy about thirty percent of the study area and forms prominent mountain ranges in the northeast section. The oldest metasediment unit in Selangor and Kuala Lumpur is the Dinding Schist. This Lower Palaeozoic metasediment is a well foliated quartz-mica schist that contains variable amounts of muscovite, biotite, and microcline (Gobbett and Tjia, 1973). The Dinding Schist is overlain by the Kuala Lumpur Limestone and rarely outcrops. Another metamorphic rock is the Howthornden Schist, located in the north and northeastern side of the study area (Fig. 2). It consists of carbonaceous schist and phyllite but no fossil has been found. The thick Upper Silurian Kuala Lumpur Limestone overlies conformably this unit and therefore, it is believed to be Lower Silurian in age (Gobbett and Tjia, 1973).

The sedimentary rocks are classified into five units, which are Bentong Group, Kuala Lumpur Limestone, Kenny Hill Formation, Tertiary Deposits and Quaternary deposits. The Bentong Group covered most of the northern region while the Kuala Lumpur Limestone and the Kenny Hill Formation are underlain the south and middle of the study area. The Quaternary deposits distributed along the coast and the Tertiary deposit was recorded in Rawang area. During the Permian to Createaceous, a large granite batholith was emplaced in the Malay Peninsula. This trends generally in the NNW-SSE direction. The most spectacular of the granite bodies is the Main Range Granite. Hutchison (1973) and Tjia (1994) classified this rock as a mesozonal granite due to the depth of its emplacement of between 5 to 11 km from the surface. The Main Range Granite occupies about thirty percent of the study area and forms prominent mountain ranges in the northeast section. The granite magma was intruded into Silurian-Devonian sedimentary rocks (Jones, 1973; Liew, 1983). Most of the granite bodies are covered by dense tropical forest.

Hydrogeology

Groundwater in Selangor and Kuala Lumpur is derived from four main groundwater sources i.e. aquifer in alluvium, aquifer in sediment, aquifer in limestone, and aquifer in granite bedrock. Recent alluvium consists of gravel, sand, silt and clay deposited along the coastal fringe of the study area and is of probable Holocene age (Abd. Rashid and Mohammad Hatta, 1998). At the Brookland Estate well field, fresh groundwater from this alluvium is being pumped at an approximately 15,000 m^3/day and supplies more than 150,000 residents in the surrounding area. The groundwater derived from this well field has reduced the water demand from the Semenyih Dam, which is the major water supply reservoir for the Selangor area. However, the groundwater from other alluvial aquifers, close to the coast, is mostly saline or brackish in nature. The salinity of the groundwater is mainly caused by a connate water origin rather than due to seawater intrusion (Ismail, 1998).

Carbonate rocks are an important aquifer for the groundwater supply in the Kuala Lumpur area. The yield from this type of aquifer occasionally rises up to 31.8 m^3/h (Ismail, 1998). Groundwater from the limestone aquifer is characterised by moderately high total dissolved solids (TDS) due to dissolution of calcium carbonate from the limestone. During the water supply crisis that affected the study area in 1998, three wells were drilled into the limestone aquifer to depths of between 167.5 and 192 meters. Groundwater from these wells is injected into the domestic tap water system at a capacity of approximately 3,000 m^3/day (Department of Minerals and Geoscience Malaysia, 1998) to support the surface water supply for the Kuala Lumpur area derived from the Batu Dam.

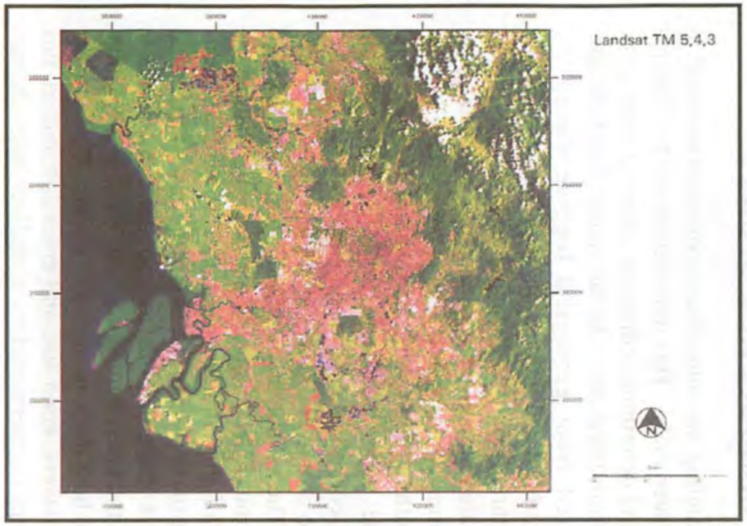

Figure 1. Study area.

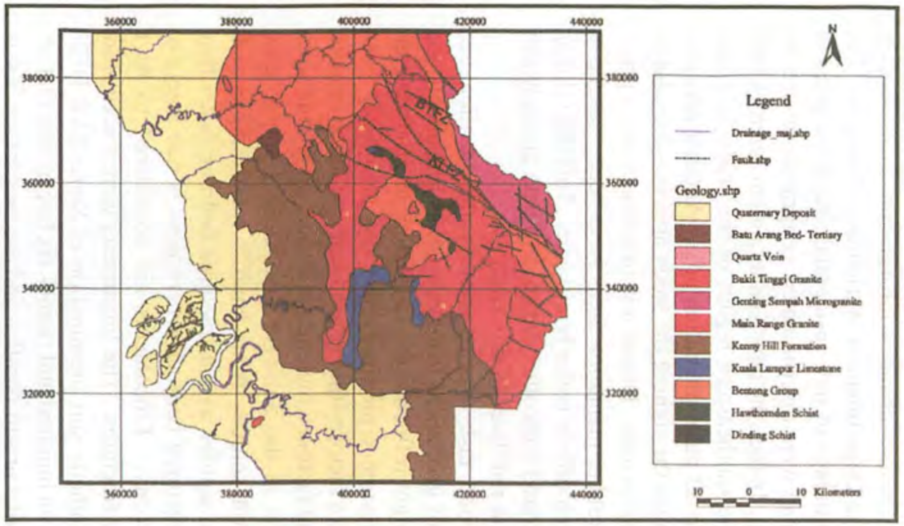

Figure 2. Geological map of the study area.

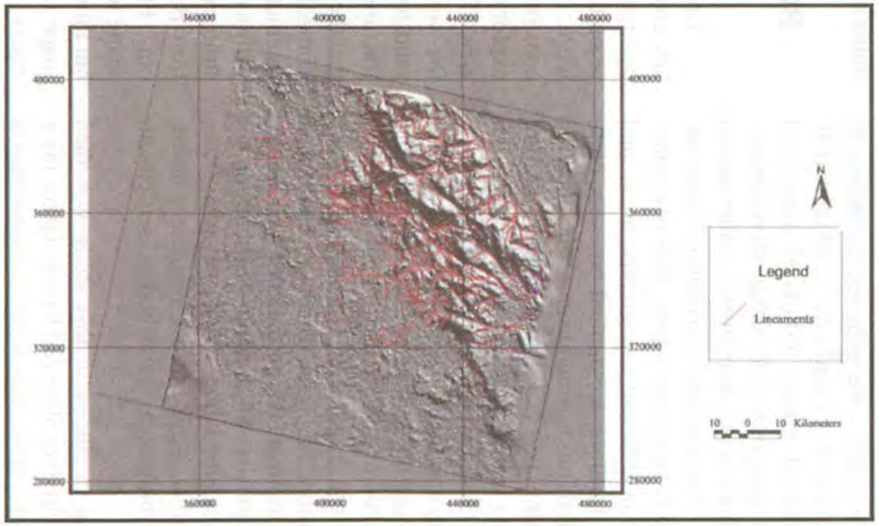

Figure 3. Lineaments traced throughout the study area.

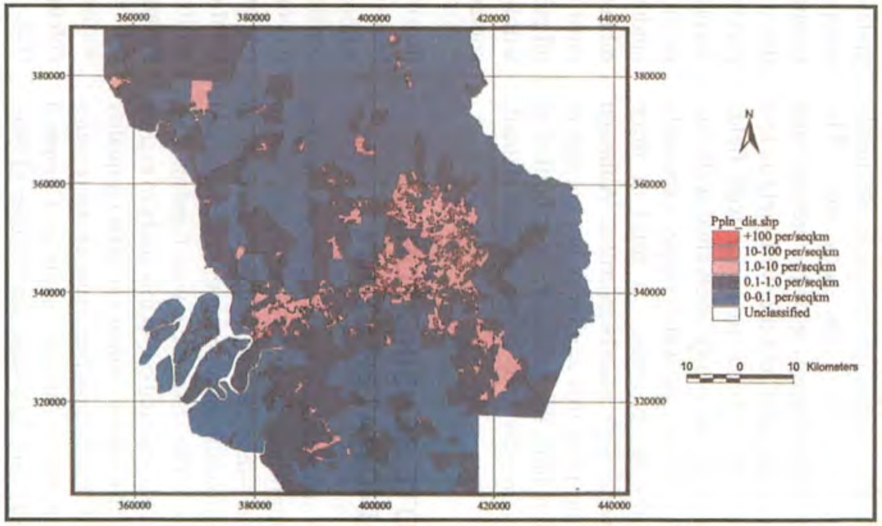

Figure 5. Population density map.

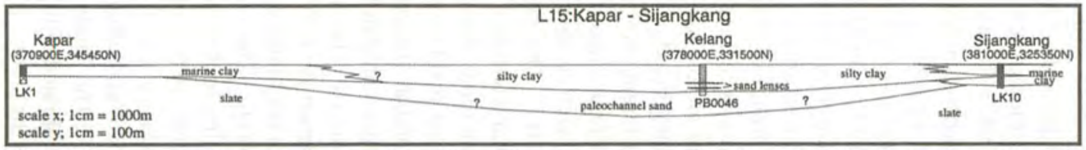

Figure 4. Cross-section from Kapar to Sijangkang showing concave paleochannel sand, which is identified as a prospect groundwater resources in the study area.

Groundwater aquifers within igneous rocks are mostly located in the eastern region of the study area. The occurrence of groundwater depends upon the presence and frequency of structural features and the well yield is less than 10 m^3/h. There have been no major well fields developed over this area. However, individual wells are commonly drilled for small-scale water supply, especially in estates and land-scheme areas. A total of three commercial groundwater wells have been drilled. Although the groundwater yield from this aquifer is not enough to satisfy any major demands, the groundwater is bottled as mineral water and currently sold in the market (Ismail, 1998).

REMOTE SENSING FOR GROUNDWATER STUDY

There were two major tasks in applying remote sensing technology for groundwater study. The first task was to derive land use and other factors which can result in groundwater contamination throughout the Selangor and Kuala Lumpur area. The data used was Landsat TM. Image interpretation was carried out in this study to extract the earth's surface information, which can affect a quality of groundwater. It is based upon the image characteristics recommended by many researchers such as Campbell (1987), Drury (1987) and Lillesand and Kiefer (1996). Preparation of the landuse map through visual interpretation is, in essence, a process of segmenting the image into a mosaic of parcels, with each parcel assigned to a landuse class. These landuse classes are assigned according to their typical contribution to groundwater contamination. For example, residential areas, industrial areas and warehouse areas are categorised as urban development area since their contributions on groundwater contamination are almost identical. Alternatively, agricultural areas are categorised according to their crop types. This is because different crops grow in different topographic areas, and different amounts of fertiliser are applied on every crop. Therefore, their contributions to groundwater contamination vary. The segmenting process also considers feature characteristics such as texture, pattern, shapes, size, site, and tone. Accurate classification is not possible due to its large pixel size, 30 m, and the low signal to noise ratio of Landsat imagery. Roughly, eighteen landuse types are represented in the Selangor and Kuala Lumpur area. The landuse classes follow a guideline produced by the Department of Agriculture, Malaysia, which was established for the Malaysian environment (Department of Agriculture, 2000). The classes consists of coconut, horticulture, oil palm, rubber, paddy, cleared land, recreational area, grass, scrub, peat swamp forest, logged forest, secondary forest, primary forest, tin mining area, water bodies, settlement, road, and urban.

The landuse map produced in this study was then calibrated with the field data observed by the author prior to the study. It was shown that this digital landuse map is updated the landuse changes information as previously mapped by the Department of Agriculture, Malaysia. For example, a numbers of new residential and urban areas in this digital map were discriminated as agricultural area in previous map. In fact, the new Kuala Lumpur International Airport in the southeastern region of the study area was previously an oil palm plantation area. Another apparent landuse changes throughout the study area is a decrease of rubber plantation area. Due to low in rubber market price, most of the rubber plantation areas have been changed to oil palm which offer a better remittance. This digital map will be integrated with other data to evaluate groundwater contamination risk later in this study

The second task was to identify the location and distribution of geological features such as lineaments and faults that might influence the movement of groundwater. Although lineament proximity has not previously been considered as a factor within groundwater pollution models, it is one of the factors which has an impact on groundwater contamination in the Selangor and Kuala Lumpur area. Contamination sources from landfill for example, will infiltrate into aquifer within fractured bedrock faster than through unfractured bedrock where flow is due solely to primary porosity. Lineaments are considered to be a surrogate for fractures. The lineaments were traced from enhanced synthetic sun illumination of StereoSAR DEM (Fig. 3). Seven hundred and twenty six lineaments that are straight, parallel or sub-parallel, and are longer then 300 m were then visually interpreted. Lineaments in the study area are believed to be due to weathering and erosion along faults and joints.

BOREHOLE DATA ANALYSIS FOR SUBSURFACE STUDY

Understanding the subsurface geology is essential in any groundwater study. This information can be obtained by logging and describing sediments collected from cores or cuttings from boreholes. In this study, borehole data were acquired from geological logging during the construction of test and production wells for groundwater exploration throughout the Selangor and Kuala Lumpur area. There are four aquifer systems identified throughout the study area consisting of semi-consolidated sand, sandstone within Kenny Hill Formation, limestone and fractured zones within the granite. Shafeen (1996), reported that the semi-consolidated sand and gravel aquifer consists of medium to coarse grain sand, gravel and some feldspar fragments. The sediments of this aquifer were deposited within numerous paleochannels. In order to understand the stratigraphy of this aquifer, a number of cross-sections from Banting in the west to Dengkil in the east were carried out. Figure 4 illustrates that this aquifer has a concave shape with a thickness between 60 and 80 m in the middle but thinner in both the west and east regions. Based on the shape of the layers, grain size and grain distribution, this aquifer system is interpreted as a shallow paleochannel sand, which formed due to river meandering.

Groundwater in the Kenny Hill Formation which consist of mudstone, shale and sandstone, however, mainly exists within the sandstone layer. As reported by Ismail (1998), voids of sandstone within the Kenny Hill Formation are often infilled and cemented by clayey matrix materials, thus the original porosity of this aquifer has been reduced. Groundwater occurrences and flows in sandstone aquifers throughout the study area are determined, mainly within the secondary porosity and permeability features such as lineaments, joints and faults. The geological logs of the five wells drilled within the limestone aquifer show that this aquifer is overlain by either *in situ* clay soils resulting from rock weathering or sandy clay filling due to development activities on the area. The thickness of the top soil is approximately 5 to 16 m. A cross-section created from Shah Alam to Sungai Besi indicated that the limestone is unconformably overlain by a mudstone layer of Kenny Hill Formation in the eastern region (Noraini Surip, 2002). The granitic aquifer has little groundwater potential. Throughout the study area, six wells were drilled within the granite bedrock. However, none of these wells were productive, with an average groundwater discharge of only 9.57 m^3/h.

The hydrogeological factors prepared from the borehole information were vadose zone aquifer, aquifer media, depth to groundwater as well as soil types and conductivity in the different aquifer types. These factors were also used for modelling a risk of groundwater contamination.

THE EFFECT OF POPULATION DENSITY ON GROUNDWATER QUALITY

The rapid growth of modernisation in Selangor and the Federal Territory of Kuala Lumpur encourages migration of people from rural areas to urban areas in search of a better quality of life. This is a major factor in the recent increase in population of these areas. As a result, the amount of municipal and industrial solid waste generated within the Selangor and Kuala Lumpur areas is increasing dramatically. Municipal and industrial solid wastes are identified as the major source of arsenic and lead contamination into groundwater throughout the study area. Therefore, it is undoubted that population has a high impact on groundwater contamination. The population density (P_d) is commonly represented as a number of people per square kilometers (person/km^2).

Based on the population census data year 1995, total population of the study area is approximately 3,281,000 people (Department of Statistics Malaysia, 1999). The study area is divided into approximately 2430 zones for the purpose of population census, established every five years. The minimum population density of the study area is 0, the maximum value is over 400 while the average value is about 1.0 person/km^2. The population density map is shown in Figure 5.

Table 1. Assigned weight for groundwater risk model.

Features	Weight
Depth to Water	5
Net Recharge	4
Aquifer Media	3
Soil Media	2
Topography (Slope)	1
Impact of the Vadose Zone Media	5
Hydraulic Conductivity of the Aquifer	3
Landuse	5
Population Density	4
Lineament Proximity Buffer Zone	3

MODELLING OF GROUNDWATER CONTAMINATION USING REMOTELY SENSED, BOREHOLE AND POPULATION CENSUS DATASETS

The groundwater contamination risk in Selangor and Kuala Lumpur was modelled based on DRASTIC approach developed by the National Water Well Association in conjunction with the Environmental Protection Agency (EPA) of the United States (Aller *et al.*, 1985) in the GIS package. The acronym DRASTIC corresponds to the initials of the seven hydrogeologic base maps: Depth to Water, Net Recharge, Aquifer Media, Soil Media, Topography (slope), Impact of the Vadose Zone Media and Hydraulic Conductivity. However, in this study the model was modified by adding three more factors; landuse (LU), population density (P) and linements (L). This is because these factors are also identified contributes into groundwater contamination throughout the study area. Each of the factors is mapped and classified either into ranges or into significant media types, which have an impact on contamination potential. All the DRASTIC factors are applied as suggested by the National Water Well Association, United States, while landuse, population density and lineament factors are classed and assigned based on the judgement of the author. The weights assigned for these ten factors are listed in Table 1. The groundwater risk of the study area was computed as the weighted sum overlay of the ten layers, which can be written as:

$$\text{Contamination Risk Index} = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw + LurLUw + PrPw + LrLw$$

where D, R, A, S, T, I, C, LU, P and L are the ten parameters, r is rating and w is the weight associated to each parameter. The risk of groundwater contamination model of the study area is illustrated in Figure 6. The areas with high risk of groundwater contamination has high score and low risk area has low score value. The urban and highly populated area with shallow limestone aquifer was identified as having the highest risk of groundwater contamination. On the contrary, groundwater located within forested mountainous

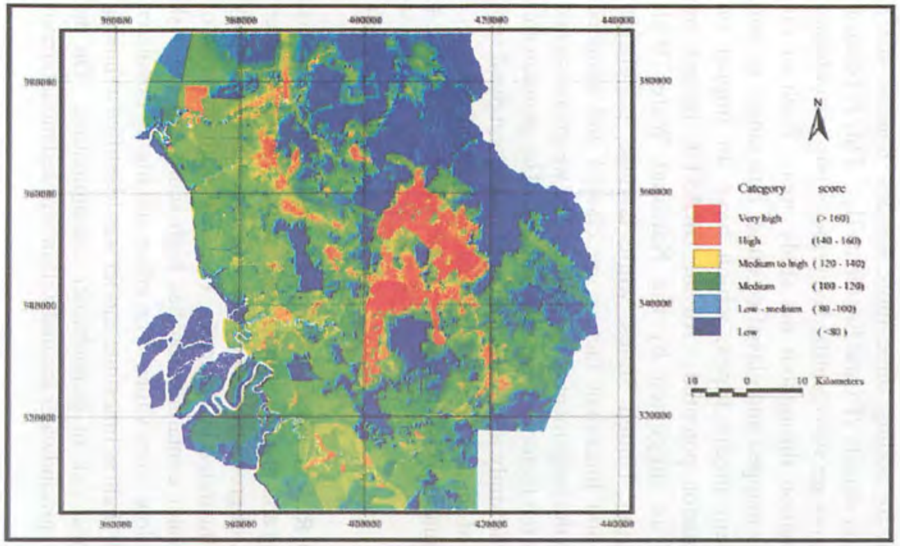

Figure 6. Groundwater contamination risk map.

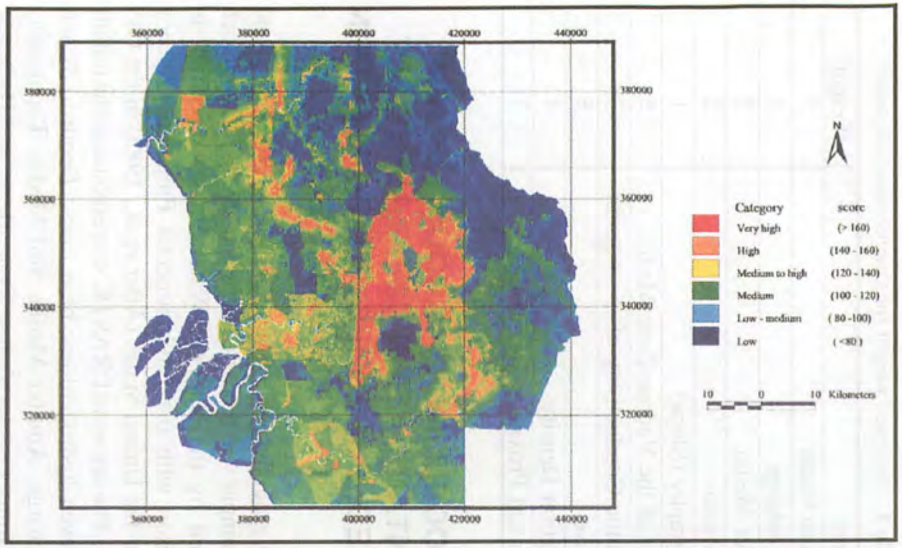

Figure 7. Prediction of groundwater contamination for the year 2010.

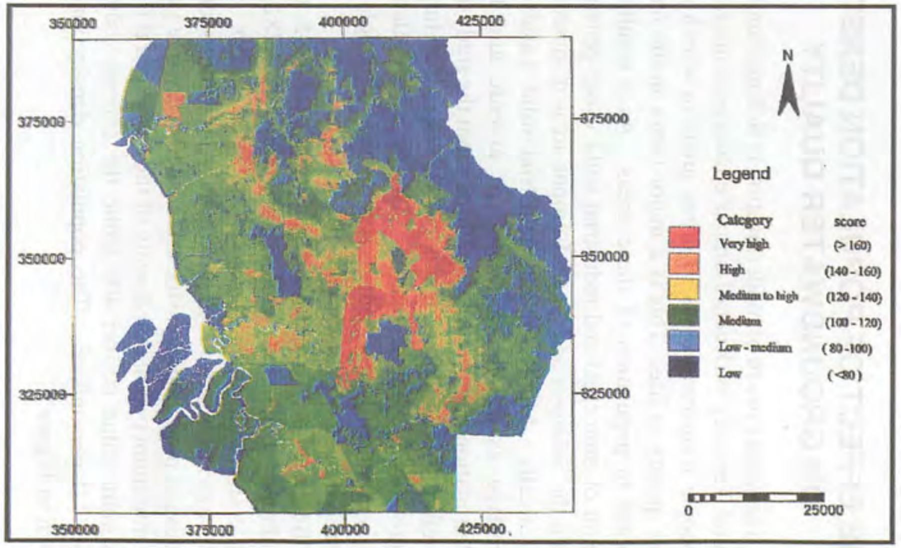

Figure 8. Prediction of groundwater contamination for the year 2020.

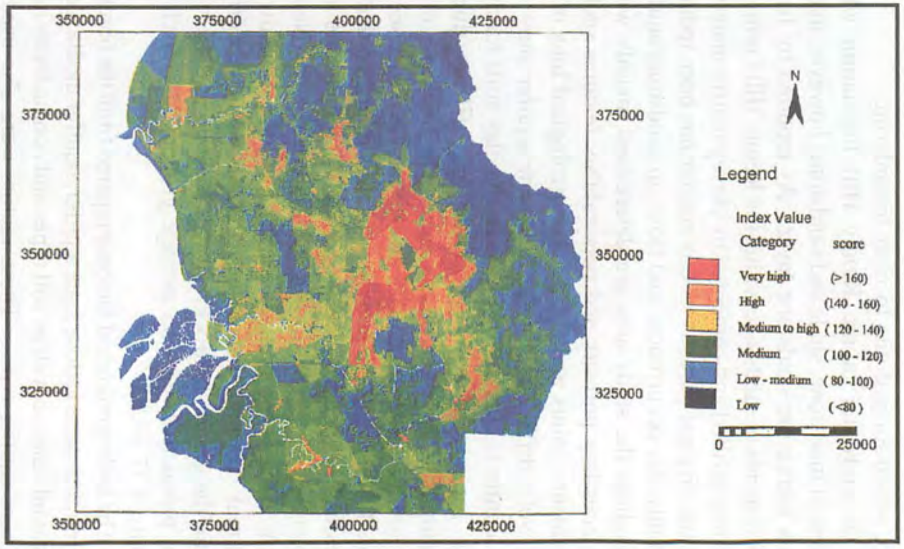

Figure 9. Prediction of groundwater contamination for the year 2030.

aquifer was identified as having the lowest risk of contamination.

PREDICTION OF FUTURE GROUNDWATER CONTAMINATION

As Malaysia's vision to be a modern country by the year 2020, it is assumed that the existing urban area will be extended and more development project will be undertaken throughout the country. The forested and vegetated lands will be occupied for a new residential and industrial area in order to accomplish future demand. The identified prospect areas for new development in the state of Selangor including Puchong, Rawang, Cheras, Kajang and Sepang. Moreover, the population density of these areas is estimated to increase by ten percent within the next ten years, as Malaysian birth rate approximately one percent per annum (Statistics Department Malaysia, 2000). Therefore, by estimating ten percent increase of population density, extending urban areas as well as predicting new development areas, the future quality of groundwater in Selangor and Kuala Lumpur is predicted. The prediction maps generated for the year 2010, 2020 and 2030 are illustrated in Figures 7, 8 and 9, respectively. These models could be used for future groundwater supply plan and also for urban planner in identifying a 'sensitive area' i.e. an area should not be developed due to it effect to groundwater quality

DISCUSSIONS AND CONCLUSION

The effectiveness of the risk map model created based on year 2000 data was then calibrated for Mg, K, As and Pb contents in groundwater samples. The borehole wells were superimposed on the map models in order to study the correlation between contamination categories with the major elements content. The result has shown that the area with low risk of groundwater contamination category in the risk map model also has a low concentration of Mg (<2.0 mg/l), K (<7.0 mg/l), As (<0.01 mg/l) and Pb (<0.01 mg/l). On the other hand, high concentrations of these four elements were determined and occurred in groundwater samples taken from wells located in the high probability of the groundwater contamination category area. This study has shown that remotely sensed, borehole and ancillary datasets are very reliable and useful in modelling groundwater contamination risk. Furthermore, the estimation of landuse changes and population density can be use for predicting groundwater contamination risk in the future. It is also found that the average value index is increasing, therefore, the quality of groundwater in Selangor and Kuala Lumpur is slowly decreased with time as shown in Figure 10.

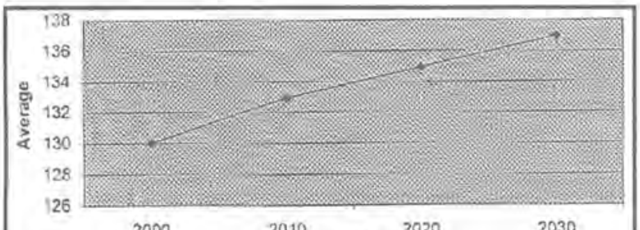

Figure 10. Average value of groundwater contamination index, year 2000-2030.

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