

Integration of Geographic Information System and 2D Imaging to Investigate the Effects of Subsurface Conditions on Flood Occurrence

K. A. N. Adiat (Corresponding author)

School of Physics, Universiti Sains Malaysia

Penang 11800, Malaysia

Tel: 60-1-7428-1916 E-mail: adiatnafiu@yahoo.co.uk

M. N. M. Nawawi

School of Physics, Universiti Sains Malaysia

Penang 11800, Malaysia

Tel: 60-1-9445-3720 E-mail: mnawawi@usm.my

K. Abdullah

School of Physics, Universiti Sains Malaysia

Penang 11800, Malaysia

Tel: 60-1-4653-2477 E-mail: khirudd@usm.my

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Abstract

Availability of accurate flood maps and adequate understanding of the subsurface conditions can enhance the effective management of flood disasters. In this study, the GIS and the 2D resistivity imaging had been employed to carry out the preparedness phase of flood management. The objectives of the study include developing flood risk map and establishing link between the subsurface conditions and flood occurrence. The results showed that about 93% of the area is vulnerable to flood occurrence. The subsurface investigations revealed that the area is characterized by the presence of thick column of impermeable clayey overburden material. Correlation of 78.57% was established between the thickness of clayey overburden and the flood vulnerability. This suggests that the flood occurrence in the area is largely dependent on geologic factor. The study is useful in reducing flood damages and planning mitigation measures.

Keywords: Multi-criteria, Decision Analysis, Subsurface geology, 2D resistivity imaging, Flood vulnerability

1. Introduction

Floods are among the most devastating natural hazards in the world. Floods are among the most frequent and costly natural disasters in terms of human and economic loss. The devastating effects of floods on lives and property can be more severe than any other natural phenomena. As a result, floods are one of the greatest challenges to weather prediction.

Flood can be described as a situation in which water temporarily covers land where it normally does not. This water comes from the sea, lakes, rivers, canals or sewers, it can also be rainwater. Although flood is triggered by nature, it affects areas where people settle and can bring severe hardship and misery to those that live in the area. Flood can therefore be seen as an event that leave social, cultural and economic impacts on the people it affects.

Floods account for about 90% of the natural disasters related damages in Malaysia. The average annual flood damage is as high as US 100 million (Pradhan, 2009). Floods have become a common feature in the lives of a significant number of Malaysians. Kedah State is one of the Malaysian States that is always affected by flood. Chan et al. (2001) estimated that over half a million Malaysian Ringgit (RM0.5 m) was lost to flood in Kedah and

over 10,000 persons were evacuated. Similarly, the State was adversely affected by flood in the last quarter of the year 2010. The effects of the flood left untold hardship on the people of the affected areas.

Floods have been linked to different types of factors. Environmental degradation such as deforestation, intensified land use and the increasing population have greatly contributed to the occurrence of floods and other natural disasters in the recent decades (Vincent, 1997). Rains, although are needed for agriculture, have been identified as being largely responsible for bringing seasonal floods in Malaysia (Chan, 1995). Increase in urbanization and economic activities into flood plains are also capable of triggering flood disasters. Some other factors have also been linked to occurrence of floods. These factors are human activities such as unplanned rapid settlement development and uncontrolled construction of buildings, topography, geomorphology, drainage, engineering structures and climate (Pradhan, 2009). However, within the scope of literature review did for this study, it was observed that flood occurrence had not been linked with subsurface conditions of the area being affected by flood disaster.

The impacts of floods on any society are primarily dependent on management of flood reduction. Mitigation is a series of activities and measures that are put in place before the occurrence of any natural hazard event in order to reduce or eliminate the impacts of such hazard on the society and the environment at large. Accurate flood maps can be the most valuable tools for avoiding severe social and economic losses from floods. Flood preparedness is the first phase of flood management. In this phase, the vulnerable or risk zones in a given area are identified. The identification of the vulnerable or risk zones will assist in the effective implementation of the other aspects of the preparedness phase which includes early warning, alert system and awareness raising campaign and flood response by emergency assistance and disaster relief (Chapman & Canaan, 2001).

Remote sensing and Geographic information systems have been incorporated in the evaluation of the geo-environmental hazards in the recent years. The uses of remote sensing include: investigating the susceptibility of the land and the vulnerability of the society, constructing hazard zoning and potential damage maps, monitoring potential hazards and dealing with emergency situations after a disaster (Verstappen, 1995). Many studies have been conducted on flood susceptibility mapping using remote sensing data and GIS tools. Radar remote sensing data have been used extensively for flood monitoring around the world (Hess, et al., 1995; Le Toan, et al., 1997). Different methods have been adopted in these studies. Probabilistic methods were used by many researchers (Landau, et al., 2000; Farajzadeh, 2001; Pradhan & Lee, 2009). Logistic regression methods have also been used to model some natural hazards such as landslide hazard and susceptibility mapping (Dai, et al., 2001; Dai & Lee, 2002; Lee & Pradhan, 2007). In some areas, hydrological and stochastic rainfall methods were used for flood susceptibility mapping (Cunderlik & Burn, 2002; Haeng, et al., 2001; Yakoo, et al., 2001). On the final note, GIS and neural network methods have also been used to map flood susceptibility in various case studies (Islam & Sadu, 2001; Sanyal & Lu, 2005; Merwade, et al., 2008).

In this study, the principles of multi-criteria decision analysis (MCDA) in the context of the analytical hierarchy processes (AHP) have been integrated with the 2D imaging to carry out the preparedness phase of flood management. The objectives of the study are to create flood vulnerability/risk map for the area using some hydrogeological indexes and to investigate the effect of the subsurface conditions with a view to establishing link or relationship between the subsurface conditions and flood vulnerability in the area. The process of data preparation and integration would be carried out in GIS environment.

2. Description of the Study Area

2.1 Location

The study area is in Kedah State, Peninsula Malaysia. It is bounded by longitudes $100^{\circ} 5'$ - $100^{\circ} 35'E$ and latitudes $5^{\circ} 50'$ - $6^{\circ} 25'N$ (Figure 1).

2.2 Geology

South Kedah consists of the Ordovician that belongs to early Devonian Mahang and the Permo- Triassic Semanggol formations. There is however no exposure of Carboniferous rocks. Deposition of Paleozoic rocks is continuous in the area as well as in the north Kedah area with a relatively deep depth of occurrence within the marine environment and without any trace of unconformity related to major tectonic event (Jasin, et al., 2005). Courtier (1974) proposed the Tawar formation as a probable new Carboniferous lithostratigraphic unit; Burton (1988) on the other hand, opined that the Tawa chert was part of the Semanggol formation. The surface and subsurface geology are made up of the Setul, the Kubang Pasu and the Chuping formations. The Setul limestone is continental shelf deposits consisting of hard brittle dark grey crystalline limestone with minor detrital rocks in the upper parts. Having undergone major folding and faulting, this formation forms steep-sided topography. The

Kubang Pasu sediments unconformably overlie the Setul limestone and dips eastward. The Kubang Pasu formation is overlying by the eroded residues of the Chuping limestone. The rocks are largely composed of thick-bedded quartz and felspathic sandstone (grey, red or purple) and interbedded with subordinate varicolored mudstone. The sequence is folded with a general north-south strike. The base of the Kubang Pasu formation is nowhere exposed, but it is assumed to rest unconformably on the Setul formation. The upper part of the formation passes up into the base of the Chuping formation. The geology map of the area is shown in Figure 2.

3. Methodology

3.1 Selecting Hydrological Indices Considered in the Study

The effects of the following hydrological indices on flood occurrence in the area were examined.

3.1.1 Drainage Density (Dd)

Drainage is studied according to its pattern and its density. Drainage pattern is associated with the nature and structure of rock type obtainable in an area while the density is a function of rock/soil permeability. When the drainage density is high, it implies that the rock/soil is largely impermeable. Consequently, there will be lesser rate of infiltration (i.e. high flood vulnerability) of rain water/or high runoff (Prasad, et al., 2008). Drainage pattern merely displays the spatial distributions of streams as linear features. Dd is the ratio of the sum of lengths of streams to the size of area of the grid under consideration (Greenbaum, 1989). This is expressed in equation 1 below:

$$Dd = \sum_{i=1}^{i=n} \frac{D_i}{A} \quad (\text{km}^{-1}) \quad (1)$$

Where $\sum D_i$ = total length of all streams (km) and A = area of the grid (km^2) = 9 km^2 .

Using the center coordinates of the grid, the values of Dd obtained for each grid was used to produce the drainage density map (Figure 3).

3.1.2 Lineament Density (Ld)

Lineaments provide important information on surface and subsurface features that may control the movement and or storage of groundwater. They are responsible for infiltration of surface run off into subsurface (Subba Rao, et al., 2001). Lineaments of the area were extracted from the landsat TM image. The Ld is the total length of all recorded lineaments divided by the area under consideration (Edet and Okereke, 1997). This is expressed in equation 2 below:

i.e.
$$Ld = \sum_{i=1}^{i=n} \frac{L_i}{A} \quad (\text{km}^{-1}) \quad (2)$$

where $\sum L_i$ = total length of all lineaments (km) and A = area of the grid (km^2).

The Ld map for the area (Figure 4) was produced by adopting the same procedure used for the Dd map. High Ld in an area is indicative of high transmissivity of the rock/soil of the area. It therefore follows that the higher the Ld for an area, the lower the vulnerability of the area to flood occurrence.

3.1.3 Lithology (Lt)

Lithology is the spatial distribution of the rock types obtainable in the area under study. The lithology is presented as the geologic map in Figure 2. Two rock types present in the area are: the sedimentary rocks of carboniferous period and the recent alluvium deposits of quaternary period. The carboniferous belongs to the Kubang Pasu formation. The alluvium deposit is made up of largely clay sediments (Mineral and Geosciences Department, Malaysia, 2004). The contribution of lithology to flood occurrence is determined by the hydrologic significance of the rock units that constitute the lithology. The hydrologic elements of the rock determine its hydrologic significance. Clay content of rock is the hydrologic element considered in this study. Clay controls the degree of infiltration. If the clay content of the rock is high, the rock will have low degree of infiltration or high degree of runoff and consequently will be highly susceptible to flood occurrence. Consequently therefore, the alluvium deposit, because it is largely made up of clay sediments, is considered to have lower degree of infiltration while carboniferous will have higher degree of infiltration. Thus, this suggests that the alluvium will be more susceptible to flood occurrence than the carboniferous. Accordingly, the alluvium is rated as having very high flood vulnerability while the carboniferous has very low flood vulnerability (Table 3).

3.1.4 Rainfall (Rf)

Rainfall determines the volume of water available for infiltration and or runoff. Even if all the hydrological indices favourable to flood occurrence are present, an area might not be susceptible to flood if the rainfall is minimal.

Rainfall is therefore the most important hydrologic index of flood occurrence considered in this study. The available monthly records of rainfall from all the meteorological stations in the study area for period of ten years (i.e. 2000-2010) were obtained from the Malaysian Meteorological Department. The data were used to produce the rainfall map for the area (Figure 5).

3.1.5 Slope (Sl)

The Slope determines the velocity with which water flows. Hence, slope controls the rate of infiltration of groundwater into subsurface. When the slope of an area is gentle, the surface runoff is slow allowing more time for rainwater to percolate and consequently, the area will be highly susceptible to flooding. On the other hand, an area of high slope facilitates high runoff allowing less time for rainwater to percolate thereby making the area to be less vulnerable to flooding. The slope map of the area (Figure 6) was produced using the ASTER DEM image of the area. The classification adopted on the map was based on the Soils and Terrain model (European Commission, 1995).

3.1.6 Temperature (T)

Temperature determines the rate of evaporation of rainwater. The higher the temperature in an area, the lower is the flood vulnerability of the area. The mean temperature data of five years obtained from the Malaysian Meteorological Department was used to prepare the rainfall map for the area (Figure 7).

3.2 Assignment Weights and Ratings of the Indices

Weights were assigned to the hydrological indices using the technique of multi-criteria decision analysis (MCDA). MCDA is a technique that allows each index to be weighted according to its relative influence/importance (Eastman, 1996; Navalgund, 1997). Field experience and experts opinions were used to evaluate the weight of each index.

The method of the Analytic Hierarchy Process (AHP) was used to determine the weights of the indices. In this method, the pairwise comparisons technique (Saaty, 1980) was adopted to create pairwise comparison matrix (Table 1). The best set of weight for each index was produced by computing the Eigen vectors (Table 2). These averages give an estimate of the relative weights of the criteria being compared (Jace Malczewski, 1999). Consistency ratio (CR) is the measure of the level of consistency of the pairwise comparison that was used to obtain the estimated weights (Table 2). For the comparisons to be consistent, the consistency ratio (CR) must be less than 0.1. By adopting steps described by Saaty, 1980, the CR for table 1 was established to be 0.08. Since this value is less than 0.1, it implies that the estimated weights shown in Table 2 can be adopted.

Rate gives the ranges of flood vulnerability/potentiality within each index. Rates (R) were assigned to each class according to the order of the influence of the class on flood occurrence. Rating range (R) of 1 to 5 was adopted where rates 1, 2, 3, 4 and 5 respectively represent Very Low, Low, Medium, High and Very High flood occurrence potential. The classes of the thematic layers for all the indices and their corresponding ratings (R) are shown in Table 3.

3.3 Conversion of Thematic Layers to Point Layers/Computation of Flood Vulnerability Index (FVI)

The hydrologic indices used in the study are prepared as thematic layers shown in Figures 2 – 7. In order to be able to compute the flood vulnerability index, the thematic layers are converted to point layers. This was achieved by dividing the study area into grids of equal size. The center of each grid represents the point location. The products of the normalized weights (w) and the ratings (R) were used to compute the flood vulnerability index for each grid (i.e. the pixel values in each of the grid coverage are based on the rating and the normalized weights of each parameter/factor). The flood vulnerability index is the sum of the products of the normalized weights (w) and the ratings (R) over all the factors. This is expressed in Eq. 3 below:

$$FVI = Rf_w Rf_R + T_w T_R + Lt_w Lt_R + Dd_w Dd_R + Sl_w Sl_R + Ld_w Ld_R \quad (3)$$

Where the subscripts w and R indicate weights and ratings for each factor respectively.

3.4 Subsurface Investigation Using 2D Resistivity Imaging

The 2D resistivity imaging geophysical technique was used to investigate the subsurface condition. The investigation was carried out at twenty nine locations within the study area (Figures 2 and 9). The objective of the investigation was to delineate the presence/absence of geologic features that can trigger/prevent the flood occurrence in the area. The investigation was carried out using multi-electrode system. The equipment used for the investigation was the multi-electrode resistivity imaging system, ABEM Terrameter Signal Averaging System (SAS) 4000. The length of the profile in all the sites was 400 m. The minimum inter-electrode spacing adopted for the survey was 5 m. The field data collected was modeled using the inversion algorithm (RES2DINV) developed

by Loke and Barker (1996). Since the geology of the area is largely homogeneous, a common colour code and resistivity ranges were adopted for presentation of the results. This will assist in the uniform interpretation of different true resistivity sections along the profiles. The final outputs were displayed as the inverse model resistivity sections.

4. Results and Discussions

4.1 Flood Vulnerability Map

The FVI value computed for all the grids was used to generate the flood vulnerability map shown in Figure 8. Kriging interpolation technique was used. The prediction map was evaluated using the geostatistical technique of cross validation. The prediction errors obtained from the cross validation report are:

- Mean Prediction error = 0.004
- Root-Mean-Square error = 0.67
- Root-Mean-Square-Standardized error = 0.85

The results of the calculated statistics shown above reveal that the predictions are: unbiased (the prediction error is close to zero), close to the measured values (Root-Mean-Square error is small) and the standard errors are accurate (Root-Mean-Square-Standardized error is close to 1).

The study area was classified into four classes of flood vulnerability zones which are the high, the moderate, the low and the very low zones. About 989.42 km² representing about 70.77% of the total area was classified as moderately vulnerable zone while about 318 km² representing 22.75% of the total area was classified as highest vulnerable zone. On the other hand, about 86 km² (or 6.15%) and 4.8 km² (or 0.34%) of the area were classified as low and very low vulnerable zones respectively.

4.2 Results of the Subsurface Investigations and Its Effects on the Flood Occurrence

The in-situ information obtained from about fifteen bore hole records at various locations within the study area were used as constraints for the interpretation of the 2D imaging data. Maximum of three subsurface layers were delineated. These were the clayey top soil, the weathered layer comprising of silt and gravel and the bedrock of sandstone. The resistivity ranges of these layers are 5-50 ohm-m, 100-400 ohm-m and 500-3000 ohm-m respectively. It was observed that the area is characterized by thick column of clayey overburden materials. The thickness of this layer at each of the 2D location was interpolated to produce the clayey overburden thickness map shown in (Figure 9). The thickness of the clayey overburden materials in the area was zoned into four classes which are the very low, the low, the moderate, and the high zones. The thickness ranges of these zones are (0-13 m); (13-28 m); (28-52 m) and (52-117 m) respectively. In order to establish whether or not there exists any relationship between the flood vulnerability and the clayey overburden thickness, comparison between them at various locations within the study area was done. The result of the comparison is presented in Table 4. From the table, the correlation between the flood vulnerability and the clayey overburden thickness was estimated as follows:

Total number of locations = 14

Number of locations where correlation exists between the two variables = 11

Number of locations where there is no correlation between the two variables = 3

$$\text{Percentage Correlation (PC)} = PC = \frac{11}{14} * 100 \quad (4)$$

$$PC = 78.57\%$$

The value of PC obtained from the equation 4 above suggests that the flood vulnerability of the area is largely dependent on the subsurface geology. The area is characterized by thick column of clay overburden, clay is impermeable; thus, this suggests that the rate of infiltration of rainwater in the area will be very low and thereby making the area to be susceptible to flooding. Since the geology of the area cannot be changed, it implies therefore that the area might have to live with flood occurrences. This further explains the reason why the flood vulnerability of over 90% of the area lies between moderate and high.

5. Conclusion

In this study, the integration of the geographic information system and the geophysical subsurface investigation using the 2D resistivity imaging were used to examine the effects of subsurface conditions on flood vulnerability/occurrence of the study area. The results of the study revealed that more than 90% of the area is

vulnerable to flooding. The subsurface investigations revealed that the area is characterized by the presence of thick column of impermeable clayey overburden material. The percentage correlation of 78.57% obtained between the clayey overburden materials and the flood vulnerability/occurrence establishes that there is a link between subsurface condition and the flood vulnerability of the area. This further explains why the area is vulnerable to flooding.

The findings established from this study have enhanced the hydrogeologic knowledge of the area. Furthermore, it has also been revealed from the study that there is need to put appropriate strategies in place to cope with flooding occurrence in the area.

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Table 1. Pairwise Comparison Matrix of the indices

	Rf	T	S	Lt	Dd	Ld
Rf	1	3	3	5	5	7
T	1/3	1	3	5	5	7
S	1/3	1/3	1	3	5	7
Lt	1/5	1/5	1/3	1	3	5
Dd	1/5	1/5	1/5	1/3	1	3
Ld	1/7	1/7	1/7	1/5	1/5	1
Column Total	2.2089	4.8759	7.6759	14.533	19.2	30

Table 2. Determining the relative criterion weights

	Rf	T	S	Lt	Dd	Ld	Weights (w)
	Wij (j = 1)	Wij (j = 2)	Wij (j = 3)	Wij (j = 4)	Wij (j = 5)	Wij (j = 6)	w = 1/n∑Wij
Rf (i = 1)	0.4527	0.6153	0.3908	0.344	0.2604	0.2333	0.3828
T (i = 2)	0.1509	0.2051	0.3908	0.344	0.2604	0.2333	0.2641
S (i = 3)	0.1509	0.0683	0.1303	0.2064	0.2604	0.2333	0.1749
Lt (i = 4)	0.0905	0.041	0.0434	0.0688	0.1563	0.1667	0.0945
Dd (i = 5)	0.0905	0.041	0.0261	0.0229	0.0521	0.1	0.0554
Ld (i = 6)	0.0647	0.0293	0.0186	0.0138	0.0104	0.0333	0.0284
Column Total	1	1	1	1	1	1	1.0001

Table 3. Ratings (R) for classes of the parameters

Influencing Indices	Category (Classes)	Susceptibility to flood occurrence	Rating (R)	Normalized Weight (W)
Drainage Density (Dd)	0 – 0.19	Very Low	1	0.095
	0.019 – 0.06	Low	2	
	0.06 – 0.13	Medium	3	
	0.13 – 0.28	High	4	
	0.28 – 0.58	Very High	5	
Lineament density (Ld)	0 – 0.003	High	4	0.028
	0.003 – 0.013	Medium	3	
	0.013 – 0.05	Low	2	
	0.05 – 0.09	Very Low	1	
Lithology (Lt)	Quaternary (Recent Alluvium)	Very High	5	0.175
	Carboniferous (Sedimentary rocks)	Very Low	1	
Rainfall (Rf) mm/yr	1,749 – 2,092	Very Low	1	0.383
	2,092 – 2,218	Low	2	
	2,218 – 2,276	Medium	3	
	2,276 – 2,324	High	4	
	2,324 – 2,532	Very High	5	
Slope (Sl)	0 - 2	Flat (Very High)	5	0.055
	2 – 8.47	Undulating (High)	4	
	8.47 - 15.88	Rolling (Medium)	3	
Temperature (T)	25.8 - 26.7	Very High	5	0.264
	26.7 - 27.1	High	4	
	27.1 - 27.7	Medium	3	
	27.7 - 29.1	Low	2	
	29.1 - 32.5	Very Low	1	

Table 4. Correlation between Clayey overburden thickness and Flood vulnerability

Locations	Classification of Clayey Overburden Thickness	Classification of Flood Vulnerability	Remarks
Pendang	Moderate	Moderate	correlate
Jitra	Moderate	Moderate	correlate
Kodiang	High	Moderate	not correlate
Kota Setar	Moderate	Moderate	correlate
Pokok Sena	Very Low	Moderate	not correlate
Kubang Pasu	Moderate	Low	not correlate
Kg. Alor			
Janggos	High	High	correlate
Tujang	Moderate	Moderate	correlate
Kepala Batas	Moderate	Moderate	correlate
Langgar	Moderate	Moderate	correlate
Guar Napai	Moderate	Moderate	correlate
Tanah Merah	Moderate	Moderate	correlate
Alor Setar	High	High	correlate
Kota S.			
Semut	Moderate	Moderate	correlate

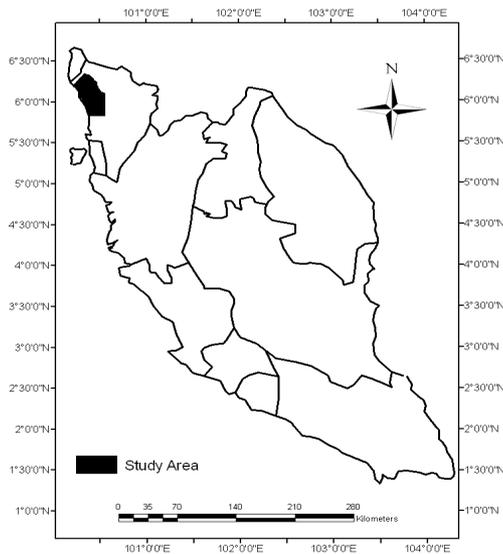


Figure 1. Map of the Peninsula Malaysia showing the study area

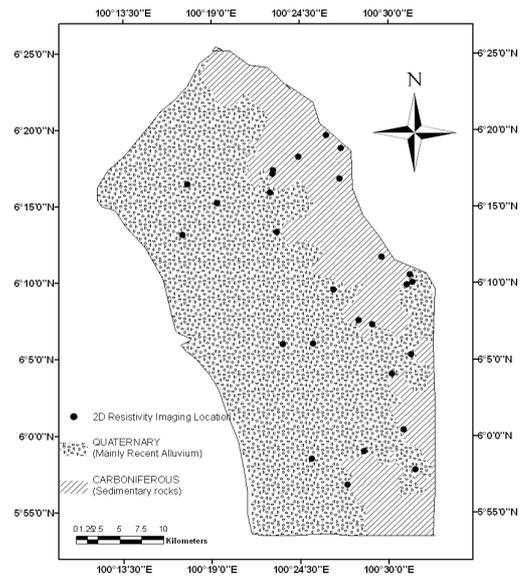


Figure 2. Geology map of the area

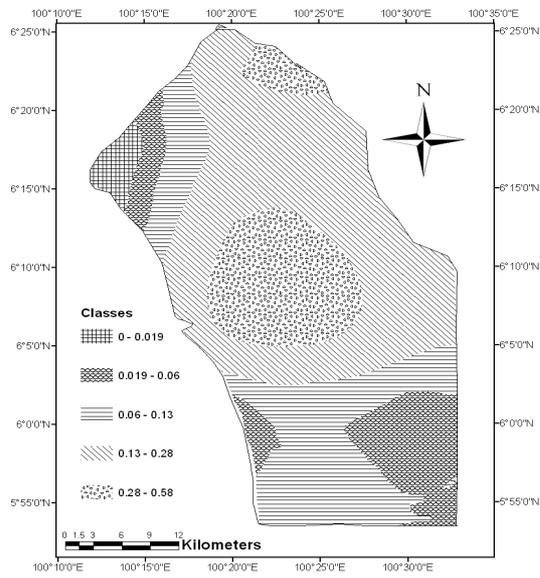


Figure 3. Drainage density map

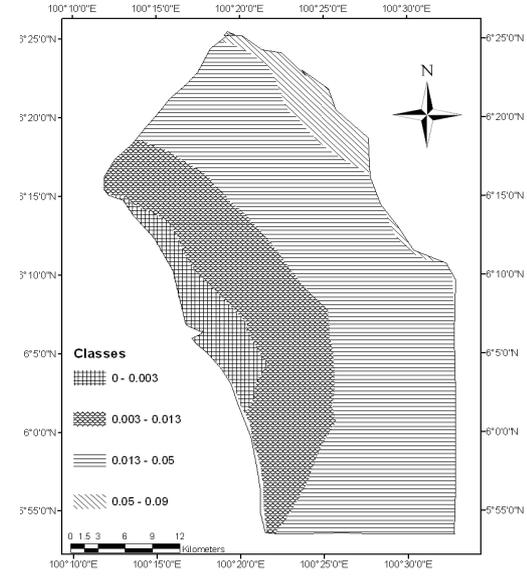


Figure 4. Lineament density map

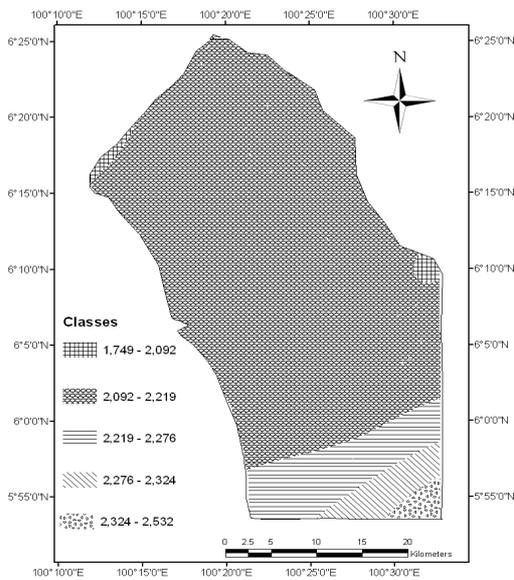


Figure 5. Average annual rainfall map

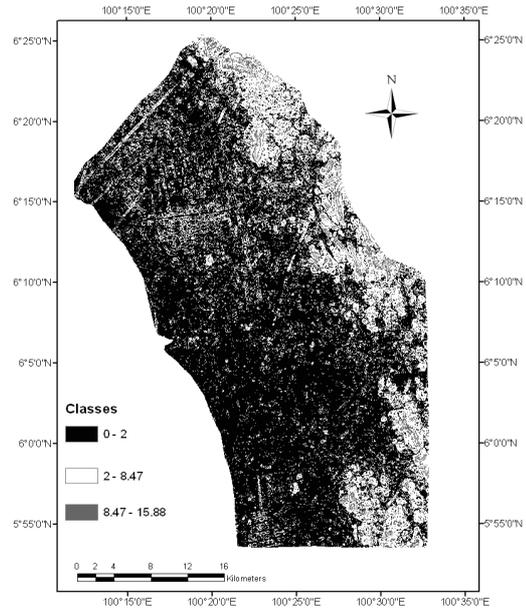


Figure 6. Slope map for the area

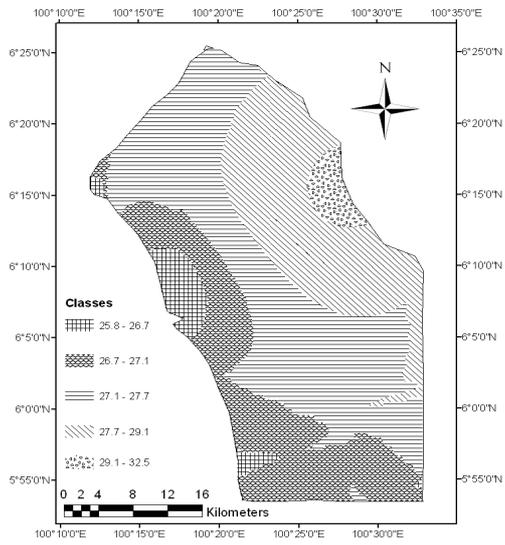


Figure 7. Average annual temperature map

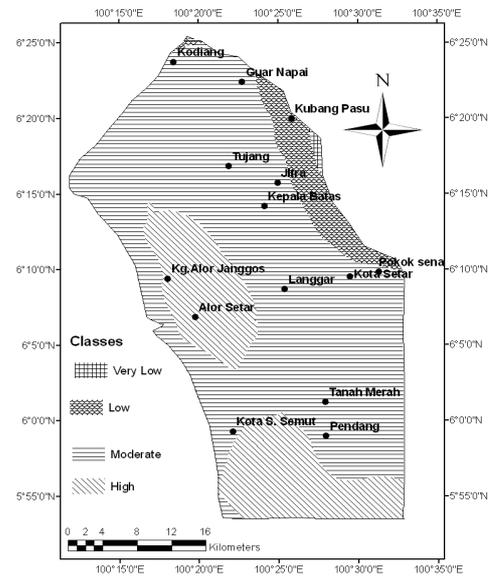


Figure 8. Flood vulnerability map

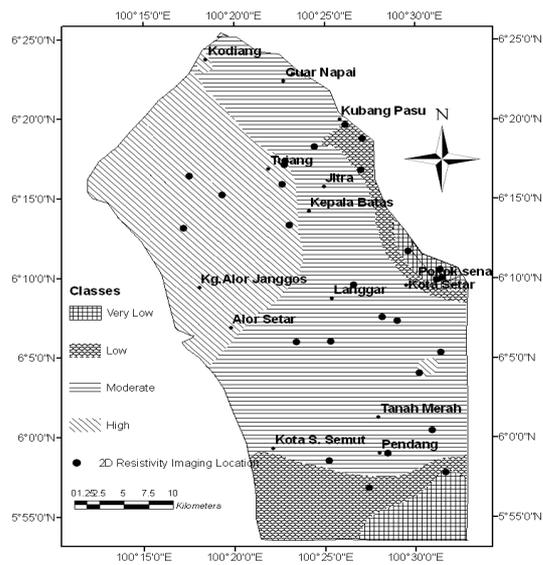


Figure 9. Clayey overburden thickness map