Application of remote sensing and hydrological modelling in flood prediction studies

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Abstract. Remote sensing techniques have been used in various applications including agriculture, forestry, oceanography and environmental studies. This study was carried out using remote sensing techniques and hydrological modelling for flood prediction in the Klang Valley. The remote sensing satellite data that were used is the Landsat-5 Thematic Mapper (TM) data whilst the flood prediction is based on the U.S. Soil Conservation Service Technical Release 55 (SCS TR-55) model. This model involves the calculation of runoff from Curve Numbers (CN) that relate to landuse, soil type, hydrological conditions and soil moisture. In the determination of runoff, landuse information were derived from the Landsat-5 TM data and landuse maps. The runoff values were used in the calculation of concentration time, peak discharge and bankfull discharge. The peak discharge was calculated by the graphical method of SCS TR-55 model whilst the bankfull discharge was derived from the slope area method. Flood occurrence was determined by comparing the peak discharge values with bankfull discharge values. Flooding occurs if the peak discharge exceeds the bankfull discharge. In the study, watershed areas were generated and the area that would be flooded for specific amount of rainfall were determined using remote sensing techniques and the SCS TR-55 model. The results that were obtained are encouraging and indicate the potential of using remote sensing techniques with hydrological modelling for flood prediction.

1. Introduction

Flood is a major problem especially for people who live in low lying areas. Floods can cause death and at the same time bring damage to properties such as houses, buildings, plantation, livestock, etc. Studies of floods using remote sensing techniques usually involve delineating flooding areas. For example, Philipson *et al.* (1980) used Landsat Thematic Mapper (TM) data to map the flood boundary for Black River in the U.S.A. This study used visual interpretation techniques of band 7 (0.8 - 1.1 μm) Landsat MSS data. Other studies in flood delineation can be found in Sollers *et al.* (1978) and Kalensky *et al.* (1979). Remote sensing techniques are also used to monitor lake and swamp areas. Barret *et al.* (1982) used the visible and infrared bands of the Meteosat data to monitor large lake and swamp such as Lake Chat and Okowango swamp in South Africa.

Generally, flood is an important subject of study in hydrology and hydrologists are able to predict floods by using hydrological modelling. The data that are needed in flood prediction are rainfall, landuse, topography information etc. These data are generally derived from field observations which are costly and time consuming. The use of remote sensing techniques can decrease the cost of data acquisition. Remote sensing can also provide up-to-date data or information for large areas in a short time compared to traditional methods (Philipson *et al.* 1980 and U.S. Department of Agriculture 1986).

The U.S. Department of Agriculture uses remote sensing techniques in determining watershed geometry, drainage network, soil moisture data and landuse information. Various studies have also been carried out in determining runoff coefficient using remote sensing data (Bondelid *et al.* 1981, Engman and Singh, 1981 and Hill *et al.* 1987). Engman and Singh (1981) reported that remote sensing is rapidly becoming an important source of data and information for hydrological modelling. Ochi *et al.* (1989), have used remote sensing data in flood damage forecasting based on flood flow modelling. Normalised Vegetation Index (NVI) from remote sensing data and slope gradient were used to calculate runoff ratio.

The flood flow modelling was later used in simulation study for flood movements in various types of vegetation.

This study reports on the use of the Landsat-5 TM data and the U.S. Soil Conservation Service Technical Release 55 (SCS TR-55) hydrological model in the prediction of floods in the Klang Valley and its surrounding areas.

2. Study area

The Klang Valley and its surrounding areas have been selected for the study. The area falls within the coordinates 366 000 m E, 360 000 m N and 444 000 m E, 330 000 m N (Fgure 1). This area was chosen since it is in a valley surrounded by hills with some major rivers flowing through the area. Many locations in the area are also prone to flooding during heavy rainfall.

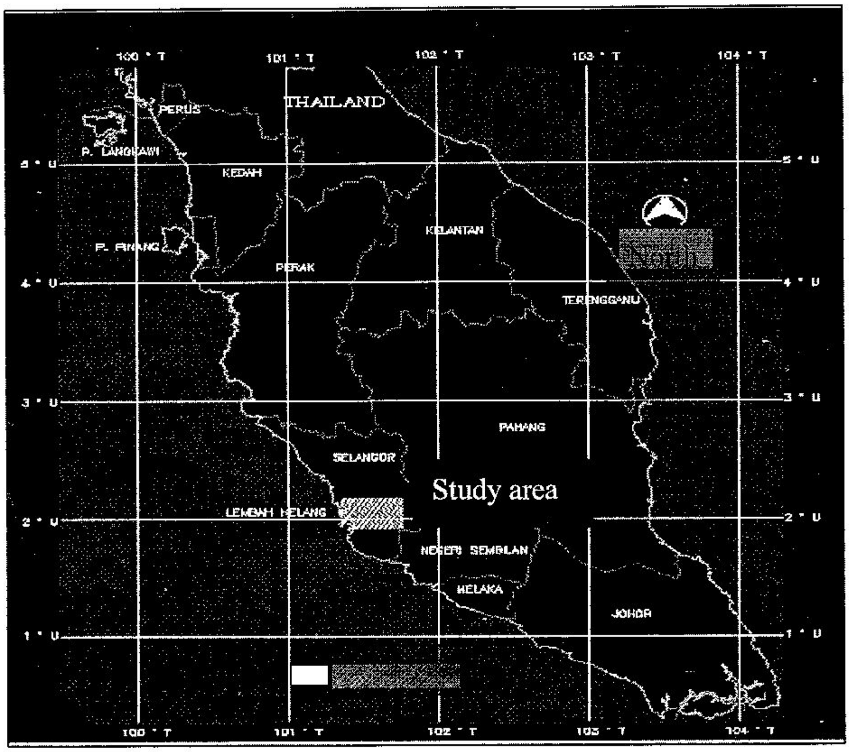

Figure 1. Study area of Klang Valley and its surrounding areas.

3. Remote sensing data and other ancillary data

The remote sensing data that were used is the Landsat-5 TM satellite data (figure 2). The satellite data is relatively cloud free and excellent for deriving various information required in this study. Other data that were collected are rainfall data, soil type data and information on hydrological conditions.

4. Satellite data processing

Remote sensing data usually contain both systematic and non-systematic geometric errors. These errors may be divided into two classes: those that can be corrected using data from platform ephemeris and knowledge of internal sensor distortion and those that cannot be corrected with acceptable accuracy without a sufficient number of ground control points (Jensen 1986).

4.1 Geometric correction

Geometric correction was undertaken to avoid geometric error from a distorted image. In this study, the Landsat-5 TM image was rectified using ground control point (GCP). The GCPs were taken from topographical map of the study area. Cubic convolution resampling technique was used in the geometric correction which results in sharpening as well as smoothing of the image. Thirteen GCPs were used in the geometric correction which produced root-mean-square error of about 10 meters in Easting and Northing.

4.2 Image classification

Image classification was carried out to classify the landuse type in the study area. This information is required so that specific Curve Number (CN) can be assigned to the specific landuse in the hydrological modelling described in section 5. The supervised classification technique using the maximum likelihood classifier was used. In a supervised classification, the identity and location of some of the land cover type, such as urban, agriculture, wetland and forest are known a priori through a combination of field work, analysis of aerial photography, maps and personal experience (Jensen 1986). In this study, the training areas for supervised classification were identified from topographical maps and existing landuse maps. Ten classes of land cover were identified in this study area, namely (1) mangrove, (2) urban or built up areas, (3) oil palm plantation, (4) coconut plantation, (5) forest, (6) open areas, (7) rubber plantation, (8) paddy, (9) water body and (10) grassland. The overall classification accuracy is about 86%.

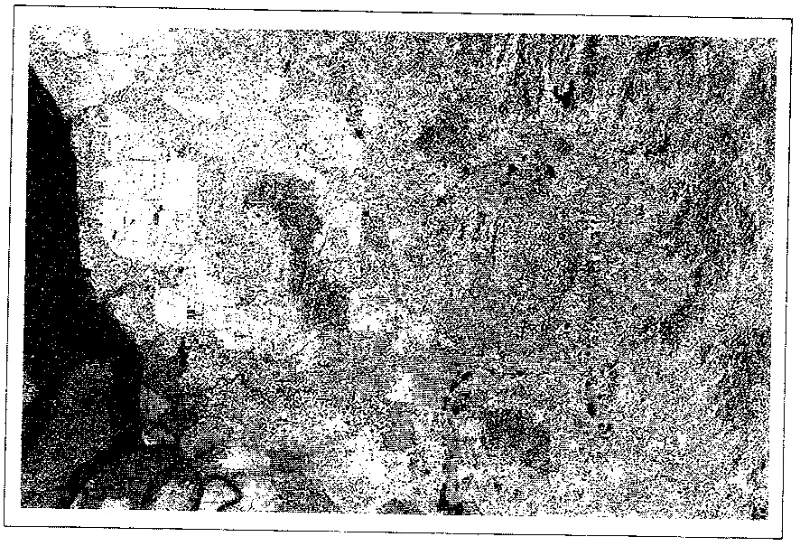

Figure 2. Landsat-5 TM image of study area.

5. Hydrological modelling

In this study the U.S Soil Conservation Service Technical Release 55 (SCS TR-55) hydrological model was used to predict floods in the Klang Valley and its surrounding areas. This model presents a simplified procedure for estimating runoff and peak discharge in small watersheds (U.S. Department of Agriculture 1986). There are several calculations involved that include the determination of runoff by SCS TR-55 Curve Number (CN) method, concentration time, peak discharge and bankfull discharge.

5.1 Determination of runoff

The U.S. SCS TR-55 method uses the Curve Number method to estimate runoff from storm rainfall. This method starts with the determination of CN which depends on the watershed's soil and cover conditions. The watershed's soil and cover conditions in SCS TR-55 model represent the hydrological soil group, cover type, treatment and hydrological condition. The SCS TR-55 runoff equation used is : -

$$Q = \frac{(P - I_a)^2}{(P - I_a) + s} \qquad (1)$$

where,
Q = runoff (in)
P = rainfall (in)
s = potential maximum retention after runoff begins (in)
I_a = initial abstraction (in).

Initial abstraction is all the losses before runoff begins. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation (U.S. Department of Agriculture 1986) : -

$$I_a = 0.2s \qquad (2)$$

By substituting equation (2) into equation (1), gives : -

$$Q = \frac{(P - 0.2s)^2}{(P + 0.8s)} \qquad (3)$$

s is related to the soil and cover conditions of watershed through CN and s is related to CN by

$$s = \frac{1000}{CN} - 10 \qquad (4)$$

Based on the SCS TR-55 model, the runoff Curve Number for the watershed's land cover, soil type and conditions in the study area is given in Table 1.

Table 1. CN for each land cover in the study area.

Land Cover / Landuse	Curve Number (CN) for Hydrological Soil Group - B
Water body	100
Open area	79
Mangrove	98
Oil palm	60
Coconut	65
Rubber	66
Forest	55
Urban or built- up area	93
Paddy	79
Grassland	65

In this calculation a rainfall amount of 3.94 inches was used based on 24-hour storm event for the study area of two- year frequency. This amount of rainfall was taken from the rainfall record published by the Malaysian Meteorological Services, Ministry of Science, Technology and the Environment from 1991 to 1995. The runoff values (Q) estimated by SCS TR-55 CN method for each watershed in the study area is given in Table 2 whilst the watersheds are showed in Figure 3.

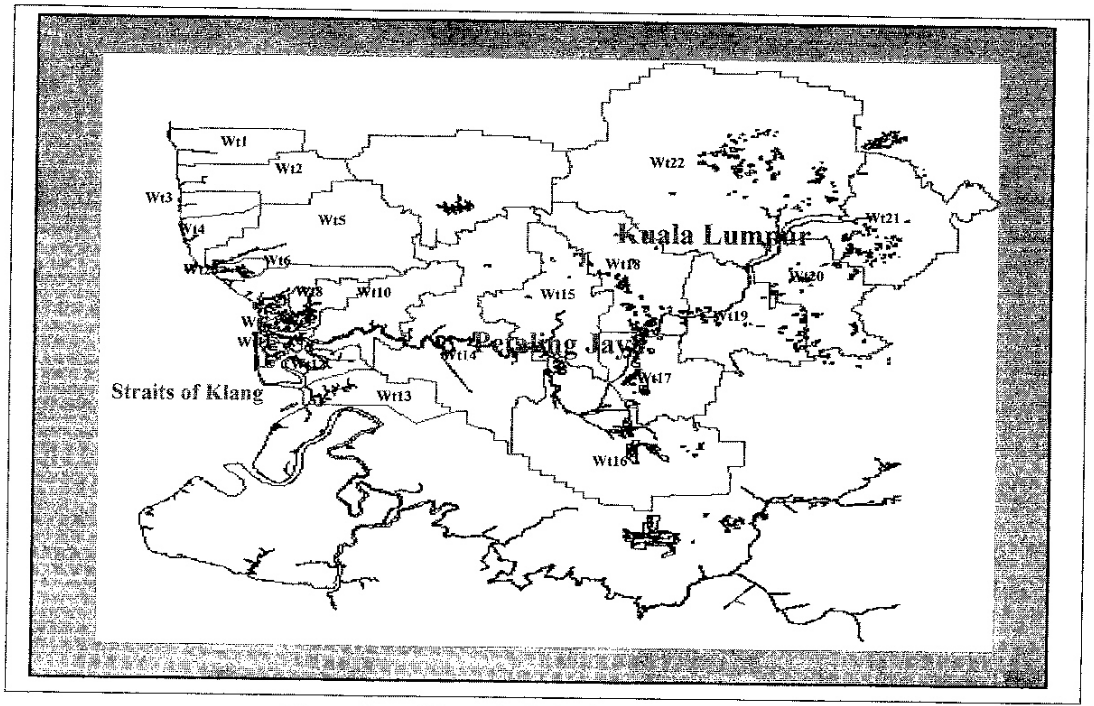

Figure 3. Watersheds in the study area.

5.2 Determination of concentration and travel time

Travel time (T_t) is the time of travel of water from one location to another in a watershed. T_t is a component of time of concentration T_c and T_c is the time for runoff to travel from the hydraulically most distant point of the watershed to a point of interest within the watershed. T_c is computed by summing all the T_t for consecutive components of the drainage conveyance system.

T_t is the ratio of flow length to flow velocity : -

$$T_t = \frac{L}{3600V} \tag{5}$$

where, T_t = travel time (hr)
L = flow length (ft)
V = average velocity (ft/s)
3600 = conversion from seconds to hour.

The average velocity (V), was computed by Manning's equation : -

$$V = \frac{1.49r^{2/3}S^{1/2}}{n} \tag{6}$$

where, V = average velocity
r = hydraulic radius (ft) and is equal to a/p_w
a = cross-sectional flow area (ft^2)
p_w = wetted perimeter (ft)
S = slope of the hydraulic grade line (channel slope, ft/ft)
n = Manning's roughness coefficient for open channel flow.

The time of concentration (T_c) is the sum of T_t of the various consecutive flow segments,

$$T_c = T_{t1} + T_{t2} + \ldots\ldots + T_{tm} \tag{7}$$

where, T_c = time of concentration (hr)
m = number of flow segment
T_t = travel time of a segment.

Table 2 shows the time of concentration for each watershed in the study area.

5.3 Determination of peak discharge

The peak discharge was determined by SCS TR-55 graphical method. In this method, the peak discharge is calculated by : -

$$q_p = q_u A_m Q F p \qquad (8)$$

where, q_p = peak discharge (cfs)
q_u = unit peak discharge
A_m = drainage area (mi^2)
Q = runoff (in)
Fp = pond and swamp adjustment factor.

The value for q_u was obtained from the Unit Peak Discharge Graph for SCS type II rainfall distribution (U.S. Department of Agriculture 1986). The results of the peak discharge for each watershed are presented in Table 2.

5.4 Determination of bankfull discharge

The bankfull discharge was determined using the slope area method. In this method, the equation that was used is : -

$$Q_b = K\sqrt{S} \qquad (9)$$

where, Q_b = bankfull discharge
K = average conveyance
S = slope energy

K is defined by Manning's formula as: -

$$K = \frac{1.49}{n} A R^{2/3} \qquad (10)$$

where, A = cross-sectional flow area (ft^2)
R = hydraulic radius
n = Manning's roughness coefficient

Slope energy S can be calculated from equation (11) as below: -

$$S = F/L \qquad (11)$$

where, S = slope energy
F = changes in surface level
L = flow length

The watersheds that are susceptible to flooding were determined by comparing the peak and bankfull discharge for each watershed. Flooding occurs if the peak discharge exceeds the bankfull discharge. From Table 2, there are a number of peak discharges that exceed the bankfull discharges in several watersheds with the rainfall amount of 3.94 in. These watersheds will be flooded. The optimum rainfall amount for every watershed before flooding occurs can be determined from equation (1) and (8) by making P as an unknown. Table 2 shows the optimum rainfall for each watershed.

6. Discussions and conclusion

The optimum amount of rainfall for each watershed has been presented in Table 2. The flood prone watershed can be determined from the optimum rainfall amount for each watershed. From Table 2, the watershed that is most prone to flooding is Wt10, which has the lowest optimum rainfall amount for a watershed. This watershed is located in low lying areas with a major river Sg. Klang flowing through it.

Table 2. Runoff, concentration time, peak discharge, bankfull discharge and optimum rainfall for each watershed.

Watershed	Runoff (Q) (in)	Concentration Time (hr)	Peak Discharge	Bankfull Discharge	Optimum rainfall (in)
Wt1	0.8775	3.4115	1117.150	1109.554	2.8
Wt2	0.8369	5.2616	1106.356	1244.394	2.5
Wt3	0.8990	2.2029	647.216	1650.850	3.6
Wt4	0.8478	2.6725	559.047	1711.801	3.8
Wt5	0.9957	4.79074	3185.522	674.229	2.2
Wt6	0.9811	4.0881	806.370	937.281	2.8
Wt7	1.7806	0.41365	809.632	1039.900	2.6
Wt8	1.4120	2.40227	1353.552	692.798	2.0
Wt9	2.2154	0.57828	924.003	982.824	2.3
Wt10	1.3406	4.49168	2294.264	642.578	1.8
Wt11	2.5235	0.54646	1523.118	1482.749	2.2
Wt12	1.9504	1.59095	2077.023	514.570	2.0
Wt13	2.2750	3.5393	3968.853	942.209	2.3
Wt14	1.4303	6.76384	5813.774	798.083	2.0
Wt15	1.8968	5.16663	5437.167	617.865	2.0
Wt16	1.6493	6.47327	2085.208	432.217	2.0
Wt17	1.2351	3.79186	2567.798	1304.564	1.9
Wt18	1.8337	6.95108	4070.095	1006.204	2.0
Wt19	1.8855	3.85335	5720.246	970.127	2.0
Wt20	2.0648	6.29147	3805.012	1278.227	2.4
Wt21	1.6273	0.62849	6572.950	618.227	1.9
Wt22	1.4428	0.32320	9154.677	862.108	2.1
Wt23	1.1375	1.09378	643.258	1139.014	3.1

The model that has been used was based on soil and landuse for the United States. The use of this model for the Malaysian environment may not be very accurate since the value for some parameters may not be representative for the soil and landuse in our environment. For example, in the determination of CN value for each landuse it was assumed to be in type B of the US Hydrological Soil Group. This assumption was based on the physical characteristics of the soil in the study area such as colour and grain size. This method is not very accurate. A more accurate way is to consider the infiltration rate of the soil type. However, such information is not available for the soil types in Malaysia.

From this study, it can be concluded that remote sensing techniques with suitable hydrological modelling can provide a useful technique for prediction of floods. Further studies with the use of digital elevation models can indicate the specific areas that are flooded within a watershed.

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