REMOTE SENSING, GEOGRAPHIC INFORMATION SYSTEM AND HYDROLOGICAL MODEL FOR RAINFALL-RUNOFF MODELING

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ABSTRACT: Flood is an unavoidable natural hazard. Flooding causes a lot of damage such as decay infrastructure, transportation, economic lost, human health and death. The study of rainfall-runoff relationship is important in flood forecasting and water resources planning. The aim of this study is to develop an operational framework for flood forecasting by integration of remote sensing, geographic information system (GIS) and hydrological model. Study area located at Kota Tinggi, Johor. This study is divided into three main parts. The first part is preparation of data sets for the study, such as topographic map, soil map, land use map, Landsat 5 image, DEM (Aster) and hydrological data. Flood event of 2006 rainfall and stream flow data obtained Rantau Panjang rain gauge station. The second part involved automatic catchment delineation, flow direction mapping and stream order mapping by Arc Hydro model. Landsat image was classified by maximum likelihood method and gives overall accuracy 80.84% and kappa coefficient 0.7498. Manning's roughness coefficient for each sub-catchment extract from land use map generated as input into the model. Understanding and analysis of catchment characteristic is important in better rainfall runoff modeling. The final part is concern about rainfall-runoff modeling, simulation rainfall-runoff discharge of catchment for single event and analyzed the runoff hydrograph. The observed and simulated peak stream flow recorded at 21st DEC 2006 5.00am and 0.00am are 375.266m^3/s and 370.163m^3/s respectively. In the validation part, linear regression method was used to correlate observed and simulated stream flow data and gives correlation coefficient 0.8842. The results of the study show that integration of Remote Sensing, GIS and hydrological models can solve hydrological problems.

INTRODUCTION

Flood is an unavoidable natural hazard. Flooding causes a lot of damage such as decay infrastructure, transportation, and economic lost. End of January 2011, an unexpected heavy rain during North East Monsoon resulted one of the worst flooding event in the southern region of Peninsular Malaysia. Based on International Disaster Database (2011), flood disasters in Malaysia from 1900 to 2011 had caused 311 people killed, 1,232,058 people affected and total damage around RM 3,398,325,180.93.

High intensity of rainfall can cause flooding when the city drainage system cannot ingratiate the surface runoff. The essential tool required in design and modeling the urban drainage system is the knowledge of rainfall runoff relationship. Rapid urbanization will increase the flow in the drainage system, so rainfall-runoff model can be useful to perform fault detection and supervision in design control systems for real-time storm effect management.

Abushandi and Merkel (2010) were applied the metric conceptual IHACRES model and showed good correlation between observed and simulated streamflow. Petheram et al (2012) compared five daily rainfall-runoff models and three methods of regionalizing model parameters and concluded that the more complex rainfall-runoff models performed best when locally calibrated. Afzal et al (2008) made a study on suitability of Thomas-Fiering model for generation of synthetic sequences of runoff and concluded that this model is very suitable for water resource system design of Bahuda river basin.

The aim of this study is to develop an operational framework for flood forecasting by integration of remote sensing, GIS and hydrological model. This study is divided into three main parts. The first part was preparation of data sets for the study, such as topographic map, soil map, land use map, Landsat 5 image, DEM (Aster) and hydrologic data. The second part involved automatic catchment delineation, flow direction mapping and stream order mapping by Arc Hydro model. Besides that, Landsat 5 TM image was used in land use map generation by maximum likelihood classification method. The final part of this study is concern about rainfall-runoff modeling, simulation discharge for single event and analyzed the runoff hydrograph.

STUDY AREA

This study is carried out in the district of Kota Tinggi, Johor due to the frequency of flood occurrences of flood events. Johor is the southern state in Peninsular Malaysia and receive tropical rainforest climate with monsoon rain (South China Sea) from November until February. Kota Tinggi is a part of Johor and located around 1° 44' 0" N, 103° 54' 0" E. Kota Tinggi covers an area of 3,500km^2 with population more than 200,000 people. The catchment at Kota Tinggi receives average annual precipitation around 2,470mm and temperature between 21^{o}C to 32^{o}C. The main river of Kota Tinggi is Johor River. Figure 1 shows Kota Tinggi in Johor, Malaysia.

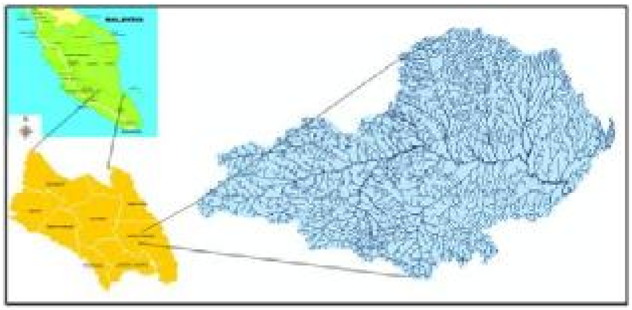

Figure 1: Location and drainage network of Kota Tinggi catchment

METHODS AND EQUATION

Three main types of data have been collected for this study. These included satellite images, ancillary data and meteorological data. Landsat 5 TM imagery (4/5/2005) was used to generate land use map for Kota Tinggi due to cloud free and data availability. ASTER DEM with 30m resolution (1/3/2012) was used in generation of flow direction and automatic delineation of catchment. Johor land use map (2006) series L7030 with scale 1:50000 was collected from Department of Mapping and Surveying Malaysia. This map was used as reference for accuracy assessment for Landsat image classification. Besides that, reconnaissance soil map (1970) no. 227-17 with scale 1: 50000 were obtained from Agriculture and Agro-Based Industry Malaysia. Infiltration input parameter for hydrological model was extracted from soil map by refer to MASMA. The hourly rainfall and stream flow data recorded at Rantau Panjang rain gauge station (no.17374751) from 17 Dec 2006 to 22 Dec 2006 was collected from Department of Irrigation and Drainage Malaysia. Furthermore, cross section data of Johor River for year 2008 also obtained from the same department. Figure 2 shows the general flow of rainfall runoff modeling.

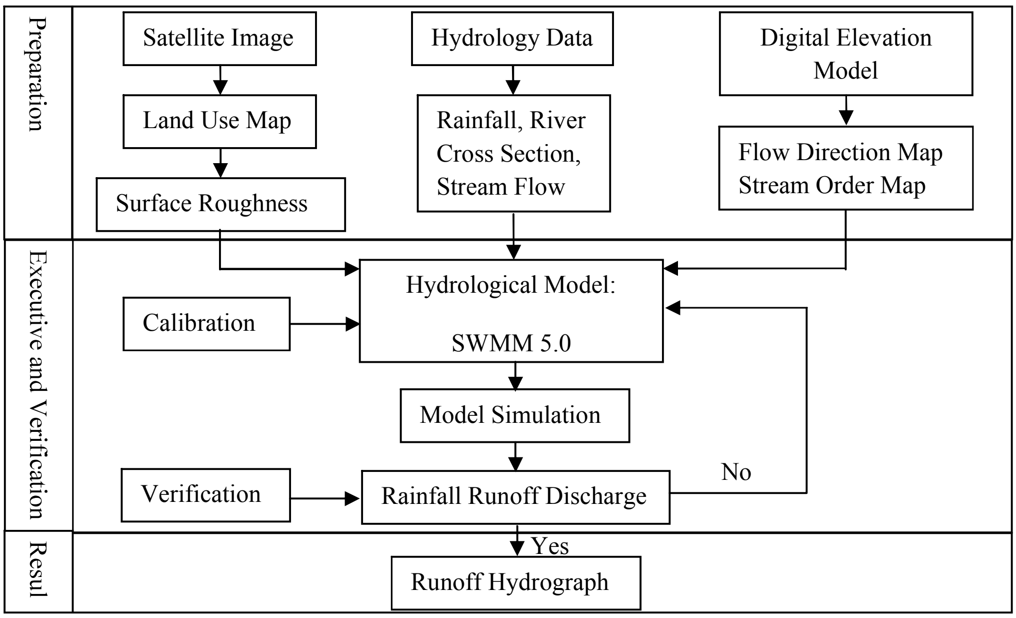

Figure 2: Rainfall-Runoff hydrograph generation flowchart

Land use mapping by Landsat 5

Land use map generated by Landsat image consist 3 general processes: pre-processing, post-processing and validation as shown in figure 3. Land use map is important in extract surface roughness information for catchment.

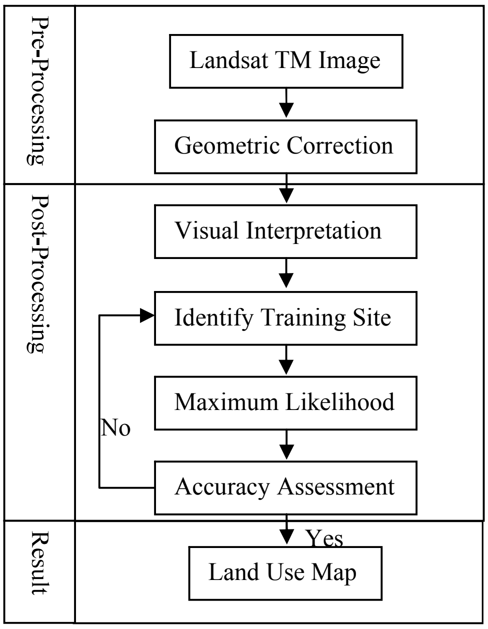

Figure 3: Land use mapping

Maximum Likehood Classification: In this study, maximum likelihood classification was chosen as the classification method to process land use map. Maximum likelihood is a supervised classification based on statistics (mean, variance and covariance). Maximum likelihood classifier performs by training the computer to recognize ranges of pixel value with the land use map and knowledge of study area. Maximum likelihood formula written as below (Hasyim et al, 2011):

$$p(x_i|w_j) = \frac{1}{\sqrt{2\pi^p}\sqrt{|C_j|}} \exp\left(-\frac{1}{2}x(x_i - \mu_i)^T x C_j^{-1} x(x_i - \mu_j)\right) \quad (1)$$

Where,

C_j = covariance matrix of class w_j with dimension p

μ_j = mean vector of class w_j

$|x|$ = denotes the determinant

$P(x_i|w_i)$ = the probability of coexistence (or intersection) of events x and w

$(x_i-\mu_i)^T$ = vector transpose $(x_i-\mu_i)$

Accuracy Assessment: Accuracy assessment is a necessary step to determine the utility of remotely sensed data and its derived classification maps. One of the most common ways to present classification data for accuracy assessment is an error matrix (Congalton, 1991). Error matrices compare the results of an automated classification to known reference data on a category-by-category basis. This method compares the number of pixels accurately classified to the total number of pixels (Congalton, 1991).

Automatic Catchment Delineation by ArcHydro

Arc hydro is a model developed for hydrologic analysis by extract topography variables for DEM (Carol and Sudhanshu, 2009). Reconditioning was required to raise the base level of the DEM values to prevent negative values in the DEM. Sinks should be filled to ensure proper delineation of basins and streams. Once sinks were filled, flow direction was calculated using the adjusted DEM values by steepest flow path algorithm and eight-direction pour path model. The next step was the calculation of flow accumulation, which was used when specifying the threshold by which streams are defined in the next step. Flow accumulation is used to generate a drainage network, based on the direction of flow of each cell. A pour point should exist within an area of high flow accumulation because they are used to calculate the total contributing water flow. In this study, location of pour points was the hydrometric gauging station located at Kota Tinggi.

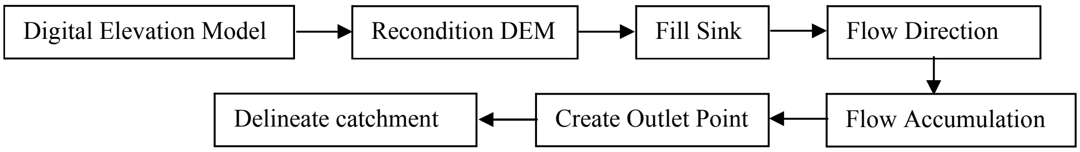

Figure 4: Delineate catchment by Arc Hydro model.

Rainfall-runoff modeling

Hydrologic model that will be used in this study is SWMM 5.0. It is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas (Rossman, 2010). The runoff component of SWMM 5.0 operates on a collection of sub-catchment areas on which rain falls and runoff is generated. SWMM 5.0 is a link-node based model used to represent characteristic of catchment and steam network. A link represents hydraulic element of flow in system while node represent junction of links and storage components such as lake. Figure 5 is represents SWMM 5.0 modeling and simulation process.

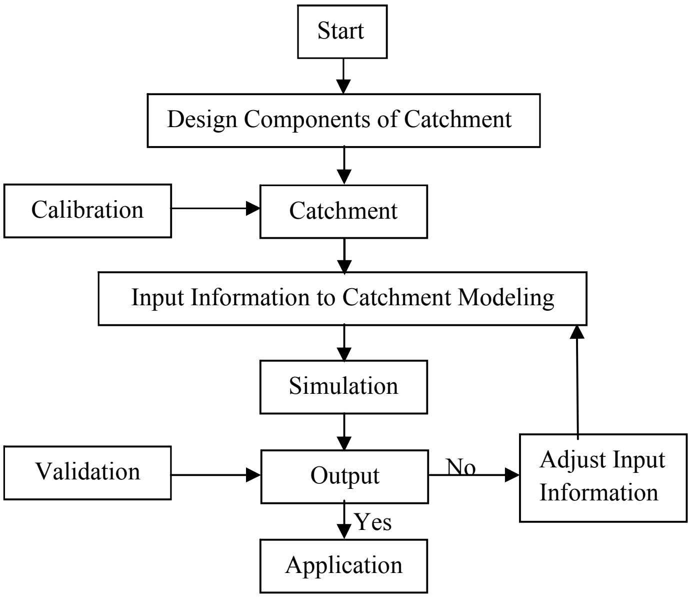

Figure 5: SWMM 5.0 modeling and simulation process (Rossman, 2009).

Infiltration model-Horton equation: Infiltration is the process of rainfall penetrating the ground surface into the unsaturated soil zone of pervious sub-catchments areas. SWMM 5.0 offers three choices for modeling infiltration such as Horton's equation, Green-Ampt method and Curve Number method (Rossman, 2009). Horton's equation is chosen to implement in this study and infiltration input parameters were refers to soil map then MASMA. Horton's equation is based on empirical observations showing that infiltration decreases exponentially from an initial maximum rate to some minimum rate over the course of a long rainfall event. Input parameters required by this method include the maximum and minimum infiltration rates, a decay coefficient that describes how fast the rate decreases over time, and a time it takes a fully saturated soil to completely dry. Horton's equation gives infiltration capacity as a function of time as:

$$F_p = F_c + (F_o - F_c)e^{-kt} \quad (2)$$

Where:

F_p = infiltration rate into soil, in./hr (mm/hr)
F_c = minimum or asymptotic value of F_p, in./hr (mm/hr)
F_o = maximum or initial value of F_p, in./hr (mm/hr)

t = time from beginning of storm, sec
k = decay coefficient, 1/sec

Routing method-dynamic wave routing: Flow routing within a conduit link in SWMM 5.0 is governed by the conservation of mass and momentum equations for gradually varied, unsteady flow (i.e., the St Venant flow equations). The SWMM user has a choice on the level of sophistication used to solve these equations such as Steady Flow Routing, Kinematic Wave Routing and Dynamic Wave Routing (Rossman, 2009). Dynamic Wave routing solves the complete one-dimensional Saint Venant flow equations and therefore produces the most theoretically accurate results. These equations consist of the continuity and momentum equations for conduits and a volume continuity equation at nodes. In this study, Dynamic wave routing was chosen as routing method because flow in natural channels is unsteady, non-uniform with junctions, variable cross-sections, and variable depth. Besides that, dynamic wave routing is the unsteady shallow surface flow equation that recommended by MASMA. Equation of dynamic wave routing is shown as below:

Continuity equation:

$$\frac{\partial y}{\partial t} + V\frac{\partial y}{\partial x} + y\frac{\partial V}{\partial x} = 0 \tag{3}$$

Momentum equation:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial Y}{\partial x} = -\frac{\tau_o}{\rho Y} + g\theta \tag{4}$$

For flow in vegetated drain or stream, the continuity equation for stream written as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = (i - f)(b + 2\delta y) + 2q_L \tag{5}$$

Where,
A = flow cross section
Q = discharge
δy = slope

Calibration: Calibration of rainfall-runoff models aim to improve model predictability by local observation data (Suresh et al., 2006). Calibration is conduct by adjustment model to make production of acceptable precision (DID, 2000). It is also adjustment to gain a match between predicted and measured output. In this study, model will calibrate with stream flow provided by DID.

Validation: Verification is the process after calibration which involves further confirmation of results (DID, 2000). It is the process testing whether a calibrated model can reproduce observation by independent set of event (DID, 2000). Validation of simulated stream flow rate was compare with observed stream flow rate done by regression method to estimate correlation between both data. Regression analysis is a technique to identify the relationship between variables (Suresh et al., 2006). Correlation coefficient, R^2 is a measure of association between two variables where value between -1 and +1. Values correlation coefficient +1 show both variables perfectly related, while -1 indicates both variables perfectly in negative linear sense. Value 0 represent there are no relationship between both variable.

RESULTS

Stream Order Map

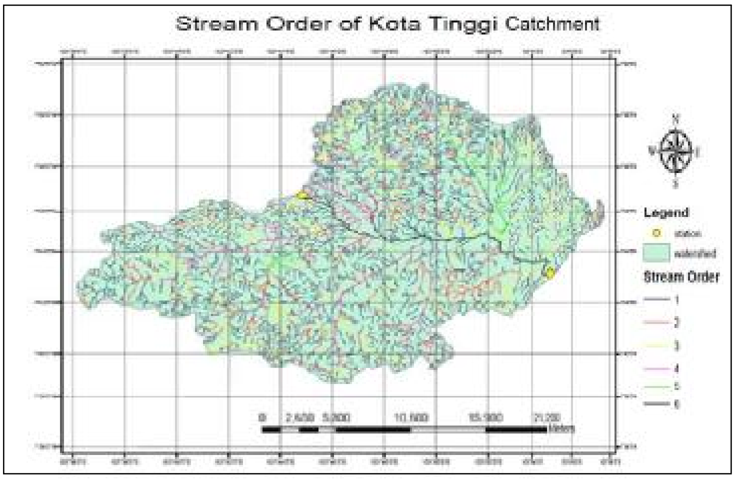

Figure 6: Stream order map

Stream order is one of classification stream size method which is important to gives an idea of size and strength of specific waterways within stream network. Stream order can be relate to expected ecological function of the stream system. The first to the third order of stream is considered as headwater streams, while fourth to sixth order is considered as medium stream. Stream which is greater than sixth order is consider as a river. Based on figure 6, stream order for Kota Tinggi catchment is sixth order stream network and it is consider as medium river. Refer to commonly observed changes associated river continuum concept that produced by Ward (1992), sixth order river has low current, receive higher sun light and its maximum temperature usually will be greater than 20^{o}C.

Land Use Map

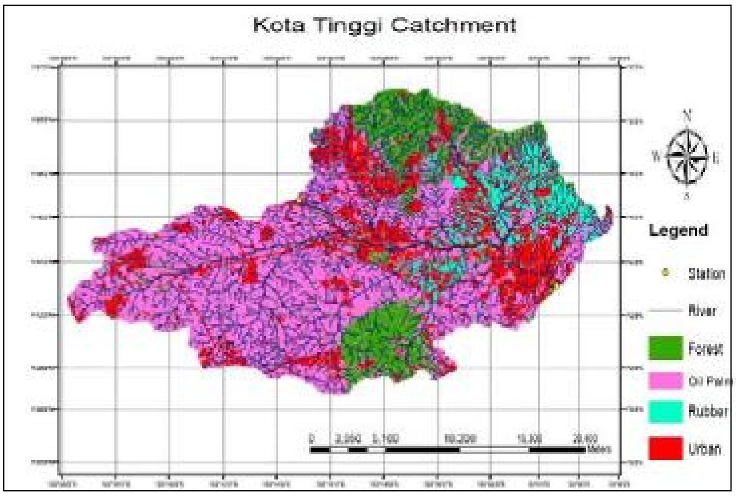

Figure 7: Land use map.

Table 1: Area of each land use class

Type	Area(km^2)	Percentage (%)
Forest	154.13936	31.02
Rubber	19.324879	3.88
Oil Palm	239.46852	48.20
Urban	83.851396	16.90
Total	496.784155	100

Catchment area's delineation and land use classification are important to extract the catchment characteristic which can be used as input parameters to the hydrological model. The perimeter of Kota Tinggi catchment is 124.933497km and the area of this catchment is around 496.796754km^2. The main river length for the catchment is given as 27.2526 km.

Figure 7 represents the Kota Tinggi catchment with land use class information that extract from Landsat 5 image. Oil palms are dominated at southern and western part and it cover around 48.2% in the total catchment area. Forest area located in the northern part and some of the southern area where its cover around 31.02%. Urban development areas are concentrated at town area. It is located at the east and middle part of the catchment area, it cover around 16.9% of total the catchment zone. Rubber plantation covered around 3.88% in the catchment area and it is located at the Northeast part. Based on manning roughness coefficient table provided by MASMA, recommended manning's coefficient for concrete and asphalt is 0.011, while dense shrubbery and forest litter are 0.40. So, surface roughness input for urban sub-catchment will be 0.011, while forest, oil palm and rubber area will be given as 0.40.

Pre-develop area in Kota Tinggi catchment only remaining 31.02%, which lead to the flood event occur frequently in Kota Tinggi. The runoff volume and rate at urban sub-catchment is higher compare to forest and agriculture area. The presence of vegetation may influence the evapotranspiration, interception, soil infiltration and depression storage. Generally, precipitation infiltrated into soil, plant use some infiltrated water and other percolates until reach the groundwater then interflow of water until enter the stream.

Different surface roughness indicates different velocity of runoff. In urban area, natural vegetation is replaced by high impervious surface such as roads, roofs, car park and so on. Impervious area will delay the hydrological processes by decrease the infiltration rate which may lead to the increasing of runoff volumes. Basically, impervious area gives the higher runoff flow velocities and the lower time of concentration. This will cause significant increase in peak discharge due to large runoff volume occurring over a short period of time. Floods occur when flow exceeds the capacity of the river channel.

Flow Direction Map

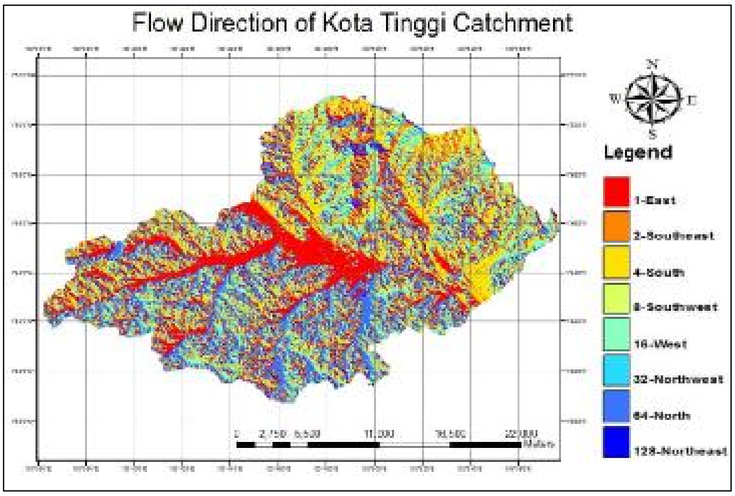

Figure 8: Flow Direction map

Table 2: Flow Direction Area

Direction	Area(km^2)	Percentage (%)
East	100.02384	20.13
Southeast	35.6139	7.17
South	91.2384	18.37
Southwest	34.5897	6.96
West	76.3173	15.36
Northwest	28.7847	5.79
North	73.672	14.83
Northeast	30.7827	6.20
unclassified	25.7596	5.19
Total	496.784155	100

Determination of flow direction is important in hydrologic modeling in order to determine the flow routing. It is necessary to determine the direction of flow for each cell in the landscape. Based on figure 8, the runoff flow direction is generally toward Johor River.

According to table 2, 20.13% of the runoff will flow toward east direction and 18.37% of the runoff will flow toward south direction. While the runoff flow toward the west and north gives the result of 15.36% and 14.83% respectively. Around 7.17% % of runoff will be flow toward southeast direction, and 6.96% of runoff flow toward southwest direction. 6.20% of the runoff is determined to be flow toward northeast direction and 5.79% of the runoff will be flow toward northwest direction.

Minimal runoff will flow into the northwest direction is due to that area located at upstream of the catchment and higher elevation area. Hence, less flood event will be occurred at Rantau Panjang area if compared to Kota Tinggi town area. East direction shows the highest amount of runoff volume flow (20.13%) into Johor River. Besides that, the second higher amount of runoff volume is from northern part of the catchment which is recorded as 18.37% to Johor River. Both incidents occur due to different of topography elevation where water flows from higher elevation to lower elevation. So the runoff will be accumulating at downstream. Rapid development of Kota Tinggi town had change the surface to impervious area which decrease the infiltration rate hence lead to the flood event always occur at Kota Tinggi town.

Rainfall Runoff Relationship

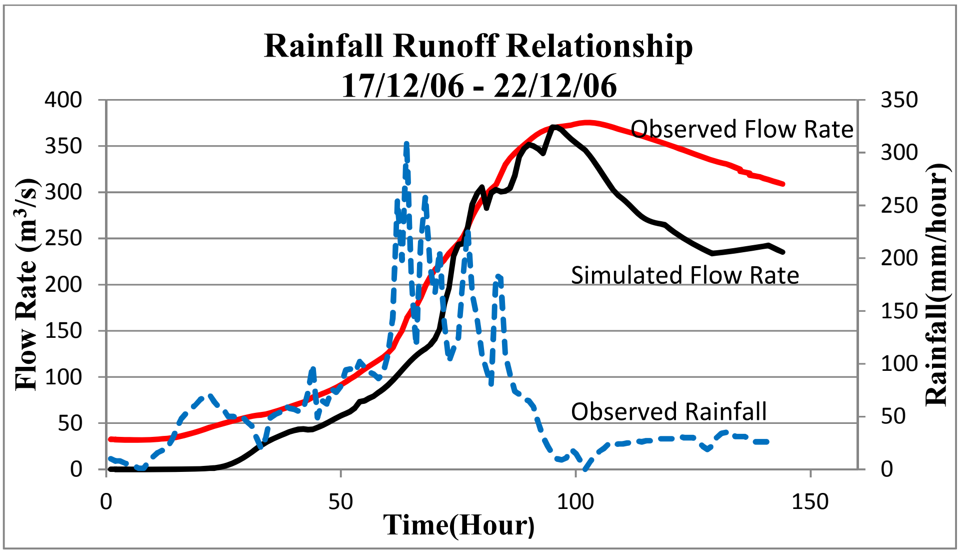

Figure 9: Hydrograph

Table 3: Peak and average flow rate

	Date	Time	Value (m^3/s)
Observed peak flow	21/6/06	5.00am	375.266
Observed average flow			209.4277343
Simulated peak flow	21/6/06	0.00am	370.1634444
Simulated average flow			235.2088148

The observed and simulated peak stream flow recorded at 21st JUN 2006 5.00am and 0.00am are 375.266m^3/s and 370.163m^3/s respectively. The time interval is 5 hours. The maximum rainfall occurred at 19 JUN 2006 (4.00pm) is 311mm/hr. From figure 4.4 the maximum observed rainfall is occurred followed by observed flow rate and simulated flow rate are 37 hours and 32 hours respectively. The time taken for runoff generation is longer because stream network for Kota Tinggi catchment classified medium river. Besides that, Kota Tinggi Catchment categories as big catchment because area greater than 150km^2. When the storm occurs, a portion of rainfall intercept by tree leaves, depression by some pond, infiltrates into ground then runoff generate. These process are taken longer period to form for bigger catchment area. Rising limb of observed and simulated hydrograph are start with 32.47m^3/s and 0.000296m^3/s respectively. This happen because observed flow rate rising limb indicate the discharge of river due to base flow or ground water flow, hence 32.47m^3/s represent flow rate of ground water into the river. In this study, we do not concern about ground water flow, so rising limb of simulated hydrograph initial with low value. Land use characteristic of catchment also influence runoff hydrograph. Peak flow of Kota Tinggi catchment is high because it only containing 31.02% of forest area. Generally, infiltrations rate and storage capacities of soil are increase by occurrences of forest area. Hence, the peak flow for Kota Tinggi is higher due to lower density of forest cover. According to Holland (1969), peak flow for agriculture cover can be 2 to 4 times greater than forest area. Kota Tinggi catchment can consider as agriculture catchment because it dominated with oil palm and rubber tree which represent 65.1% of total catchment, so peak flow of this catchment is high. Flood will occur when runoff discharge is higher than peak discharge for urban drainage system.

Accuracy Assessment

Land Use Map: The confusion matrix is the technique used to determine the accuracy assessment using ENVI 4.2 software. Error matrix has been used to report the accuracy of land use map produce by Landsat image. Overall accuracy is 80.84% and Kappa Coefficient is 0.7498. This shows Landsat images could produce high quality land use classification.

Table 4: Ground Truth (Pixels)

Class	Oil Palm	Forest	Rubber	Urban	Total
Oil Palm	2015	175	294	375	2895
Forest	806	3125	63	69	4063
Rubber	2	3	1054	58	1117
Urban	12	444	95	2635	3186
Total	2835	3748	1506	3137	11226

SWMM 5.0: A set of flow rate data (20/6/2006) from Rantau Panjang station was used in validation process. The reliability of the model was evaluated based on correlation coefficient, R^2. Correlation coefficient for rainfall-runoff model is 0.8842 as shown in figure 10.

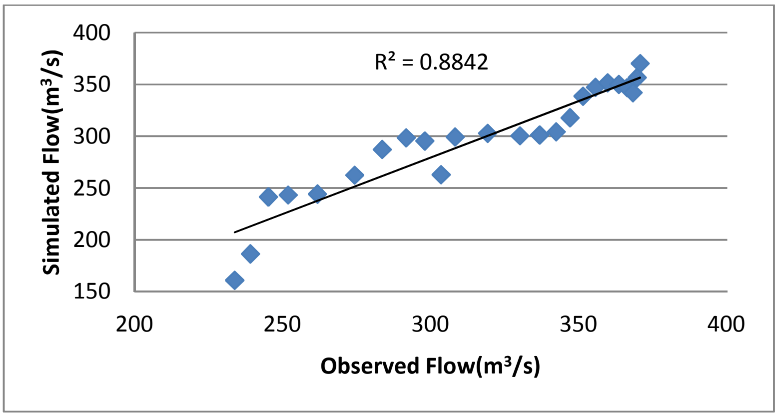

Figure 10: Validation between simulated and observed flow

DISCUSSION

The simulation and analysis of rainfall runoff relationship by SWMM 5.0 is suitable to estimate runoff in tropical region. It is preferable and suitable to be used for hydrological modeling and runoff estimation. This is because the maximum peak flow rate simulated is similar to the peak flow rate observed. Moreover, the time of peak flow rate recorded and observed has not much difference where the time interval is 5 hours. Furthermore, Correlation coefficient for rainfall-runoff model is 0.8842 which represent good correlation between estimate and observed flow rate. There are some factors may affect the hydrograph simulated by SWMM 5.0. Development at Kota Tinggi town such as construction of building, residential area, road cause expanse of impervious area that resulted the hydrological cycle becomes dynamic. Quantity and quality of water in catchment area is change constantly over a time period, hence instability of hydrological cycle occur and reduce the efficiency of the simulation model. Furthermore, the hydrological model simulated based on evaluating the existing data without taking account of any changes in the real condition, so the hydrography generated is not perfect. Groundwater is not take into account in develop of the model, hence the simulated hydrograph is not perfect.

CONCLUSIONS & RECOMMENDATIONS

Information extraction from catchment area can be done by using remote sensing and GIS technique. Maximum likelihood classification method may be used in land use classification for tropical catchment due to reasonable degree of accuracy. Arc Hydro Model is a useful tool in understanding catchment characteristic such as stream order and runoff flow direction. The runoff hydrograph may be generated using the SWMM 5.0 for estimate rainfall-runoff relationship for Malaysia region. It is important in development and management of water resources for Kota Tinggi catchment.

There are some suggestions that can improve SWMM 5.0 simulation accuracy. Study area can be separate into few divisions to input the detail of surface information. Besides that, conduct a detail study related to physical information of study area such as percentage of land impervious, ground water flow , so that more accurate input parameter obtain. Moreover, detail study of soil characteristic in catchment area should to carry out by laboratory work because soil largely influence infiltration rate of water. Accurate soil information gives high accurately of simulation model.

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