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DEVELOPMENT OF AN INTEGRATED SPATIAL DISTRIBUTED TRAVEL TIME METHOD USING GIS TO MODEL RAINFALL RUNOFF IN BENTONG CATCHMENT, MALAYSIA

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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Chairman : Professor Wan Nor Azmin Sulaiman, PhD
Faculty : Environmental Studies

Rainfall runoff (RR) modelling over a catchment wide basis is a challenging task. The emerging of GIS technology has make the usage of distributed GIS more convenient nowadays. There many types of distributed model but in this study, it is performed using combination of kinematic wave approximation (KWA) and manning's equation along with National Resources Conservation Services Curve Number (NRCS CN) to provide the estimation of effective rainfall. This study proposed an improved method by introducing the usage of new way to route the overland flow with enhancing the applicability of Digital Elevation Model (DEM) characteristics. One of parameter used in KWA calculation is distance a flow path or ridges, x (m). Previously, most models used assumption or estimated input namely overland flow, L and length of slope, ls to be applied for the whole grids. This approach deems not fully suit with the term distributed model, which every single grid supposedly has their own unique value. Therefore, an improvement proposed by multiplying the rainfall intensity with the longest perpendicular distance in a grid. Then, to predict discharge at the outlet, time area (TA) approach is applied. This model named as Spatial Distributed Travel Time (SDTT) in this study. Besides SDTT, spatial lumped model (SLM) is also applied to compare the result of both model. From DEM resolution and sensitivity analysis (SA), it is determined that using 30 m DEM size with input of x equal to 42.2 m gave the best predicted hydrograph. Using coarser DEM resolution increase the peak discharge and shorten the time to peak. SDTT model performed better than SLM when compared to the observed discharge. For calibration, SDTT gave result of NSE = 0.86; PBIAS = -1.95; r = 0.87 ($p<0.0001$) and SLM produce NSE = 0.78; PBIAS = -21.58; r = 0.85 ($p>0.0001$). In validation, SDTT result NSE = 0.81; PBIAS = 0.17; r = 0.88 ($p<0.0001$) and SLM produce NSE = 0.62; PBIAS = 15.87; r = 0.85 ($p<0.0001$). Furthermore, SDTT also perform better in predicting peak discharge (PD and time to peak (TP) compare to SLM. Land use land cover change (LULC) effect on flood hydrology of Bentong catchment

also indicate there is significant of LULC changes from period of 2000 to 2016 found out through Chi- square goodness of fit test with result ($\chi^2 = 7.403$, p –value = 0.0006 ($P < 0.05$)). There is also significant increase of peak discharge and decrease in time to peak and travel time.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN MODEL INTEGRASI RERUANG WAKTU PERJALANAN TERAGIH MENGGUNAKAN GIS UNTUK MEMODELKAN LARIAN AIR HUJAN DI LEMABANGAN BENTONG, SEMENANJUNG MALAYSIA

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Kajian ini memberi penekanan kepada model bergrid dengan menggunakan gabungan persamaan KWA dan persamaan *manning* bersama NRCS CN untuk memberikan anggaran hujan berkesan. Kajian ini telah mencadangkan kaedah yang lebih baik dengan memperkenalkan penggunaan cara baru untuk mengalir aliran darat dengan meningkatkan kebolehgunaan ciri-ciri DEM. Sebelum ini, kebanyakan model menggunakan andaian atau anggaran input iaitu aliran darat, *L* dan panjang cerun, *ls* untuk digunakan bagi keseluruhan grid. Pendekatan ini tidak menepati dengan model bergrid, yang setiap grid akan mempunyai nilai yang unik. Oleh itu, peningkatan adalah dicadangkan dengan mengubah persamaan sebelumnya untuk mengira aliran darat. Model ini dinamakan sebagai *Spatial Travel Time Distributed* (SDTT) dalam kajian ini. Selain SDTT, *spatial lumped model* (SLM) juga digunakan untuk membandingkan hasil kedua-dua model. Keputusan dari resolusi dan analisis kepekaan DEM (SA), menunjukkan bahawa menggunakan saiz DEM 30 m dengan input *x* sama dengan 42.2 m memberikan hidrograf ramalan yang terbaik. Penggunaan resolusi DEM kasar meningkatkan puncak pelepasan dan mempercepatkan masa ke puncak. Model SDTT didapati lebih baik daripada SLM. Untuk penentukuran, SDTT memberikan keputusan NSE = 0.86; PBIAS = -1.95; r = 0.87 (p <0.0001) dan SLM menghasilkan NSE = 0.78; PBIAS = -21.58; r = 0.85 (p> 0.0001). Dalam pengesahan, SDTT memberikan keputusan NSE = 0.81; PBIAS = 0.17; r = 0.88 (p <0.0001) dan SLM menghasilkan NSE = 0.62; PBIAS = 15.87; r = 0.85 (p <0.0001). Tambahan pula, SDTT juga menunjukkan prestasi yang lebih baik dalam meramal pelepasan puncak (PD) dan masa ke puncak (TP) jika dibandingkan dengan SLM dengan R^2 0.975 dan 0.8274. Kesan perubahan perlindungan tanah (LULC) tanah di hidrologi banjir di kawasan Bentong juga menunjukkan bahawa terdapat banyak perubahan LULC dari tempoh 2000 hingga 2016 melalui ujian kebaikan Chi-square dengan hasil (χ^2 = 7.403, p -value = 0.0006 (p <0.05)). Berdasarkan ujian korelasi, korelasi negatif

antara TP dan PD, r = -0.993 (p = 0.078) dan PD dan Tt dengan r = -0.995 (p = 0.067). Namun terdapat korelasi yang positif antara TP dan Tt, r = 0.974 = 0.144). Terdapat juga korelasi yang positif antara TP dan Tt, r = 0.988 (p = 0.099). Masa perjalanan dari tahun 2000 hingga 2016 juga berkurangan selama 2.5 hingga 3.5 jam.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

GIS	Geographic Information Systems
NRCS CN	National Resources Conservation Services Curve Number
SDTT	Spatial Distributed Travel Time
SLM	Spatial Lumped Model
DEM	Digital Elevation Model
DOA	Department of Agriculture
DID	Department of Irrigation
LESTARI	Institute of Environment and Development
NSE	Nash Sutcliffe Efficiency
R^2	Coefficient of Determination
PBIAS	Percent of Bias
HEC-HMS	Hydrologic Engineering Centre- Hydrologic Modeling System
.shp	Shapefile
WHAT	Web Based Hydrograph Analysis Tool
LiDAR	Light Detection and Ranging
HSG	Hydrologic Soil Group
AMC	Antecedent Moisture Content
SRTM	Shuttle Radar Topography Mapping
InSAR	Interferometry Synthetic Aperture Radar
JUPEM	Department of Survey Malaysia
ESRI	Environmental System Research Institute

CRWR	Center for Research in Water Resources
TauDEM	Terrain Analysis Using Digital Elevation Models in Hydrology
HI	Hypsometric Index
SDUH	Spatially Distributed Unit Hydrograph
TA	Time Area
TAD	Time Area Diagram
USACE	United States Army Corps of Engineers
CUH	Clark Unit Hydrograph
SA	Sensitivity Analysis
MSMA	Urban Stormwater Management Manual for Malaysia
SCS	Soil Conservation Services
N_u	Stream Order
L_u	Stream Length
L_{sm}	Mean Stream Length
R_l	Stream length ratio
L_b	Basin Length
D_d	Drainage density
F_s	Stream frequency

D_t	Drainage texture
F_f	Form factor
R_c	Circularity ratio
R_e	Elongation ratio
HI	Hypsometric Index
IDW	Inverse Distance Weight
NEH	National Engineering Handbook
USDA	United States Department of Agriculture
WGS84	World Geodetic System 1984
TP	Time to peak
PD	Peak discharge
Tt	Travel time
KWA	Kinematic wave assumption

CHAPTER 1

INTRODUCTION

1.1 Introduction

Floods is known as the most catastrophic natural hazards and occurred frequently in many parts of the regions in this world. The flooding issue is being highlighted as the most destructive natural hazards (UN, 2004; Sun et al, 2017) as it can destroy the environment, socio-economic condition, human livelihood and their properties. The impact of flood hazards is enormous at the global scale (Berz et al, 2001; Hajat et al, 2003; Ahern et al., 2005; Jonkman, 2005; Jonkman and Vrijling, 2008; Romshoo et al., 2012). Flooding is responsible for more than one – third of the total estimated costs incurred and two – third of the affected people due to natural disasters (Coates, 1999; UN 2004; Jonkman and Kelman, 2005; Jonkman, 2005; Re, 2007). The flood hazards is mainly caused by the anthropogenic human activities such as deforestation (Barasa and Perera., 2018), rapid urbanization and uncontrolled land development land use change (Gigović et al., 2017). These factors of flood hazards is arise due to the population growth and migration of population to coastal areas and river valleys (Arsiso et al., 2017) which subsequently increased in the global temperature due to the effects of climate change (Parry et al., 2007). Therefore, in such situation, the spatial and temporal dimensions of flood threat had trigger the related agencies bodies on how to minimize the impact of flood consequences such as human and economic losses at international scale (Arsiso et al., 2017).

Flash floods is one of the type of flood that occurred frequently in or close to upstream runoff generating areas and are characterized by rapid release of water from a catchment (Bout and Jetten, 2018). Flash floods often take place within a few hours of rainfall event and often lasting less than a day. Therefore, the basin or watershed modelling has become widely used and offered with various type of models with the purpose to simulating the rainfall runoff model within the catchment area. Previously, lumped based model had been widely used to model rainfall runoff in watershed sized basis. However, lumped model represents the catchment as a single unit. They are characterized by minimal data requirement which is averaged over the catchment. In these types of models, the parameter values are determined through calibration, not from the physical behaviours of the catchment (Wakigari, 2017). In addition, the spatial inhomogeneities of the input variables and parameters are not represented which limit their capability to simulate all the hydrological processes of catchment. Thus, only the dominant ones are properly described.

Nowadays, the application of spatial technology, geographic information system (GIS) and remote sensing (RS) have been widely used as the computer technology evolved. Distributed based hydrological model has rapidly emerged due to the extensive application of spatial technology. Distributed models characterize the catchment in details, unfortunately the required of intensive data are not available in most developing countries (Sandholt et al., 2002). Distributed hydrological models represent the heterogeneity of the catchment by considering the spatial variability of hydrometeorological variables, topography, geology, soil type and land use. Nevertheless, due to their complexity, long computation time and enormous data requirement lead them to have a limited practicality in most contexts (Carcano et al., 2008).

1.2 Problem Statement

Flash flood is frequently occurred in urban area due to the rapid urbanization and development which lead to the high number of impervious surface and subsequently reduce the infiltration process and generate the high volume of surface runoff. However, the rural area such as Bentong catchment also has been described as the prone area of flash flood due to the land use land cover change and climate change. In year of 2002 and 2004, a disastrous flood had occurred within the Bentong catchment which leads to a high damage of properties. Recently, in year 2010, flash flood once again struck heavily the catchment. Based on DID report, it was determined that the short period and heavy intense rainfall is the main cause of the flood occurrence. Thus, the critical study on flood hazards issue and hydrological process aspect is crucial and highly required in order to determine the rainfall-runoff characteristics within the Bentong catchment by highlighting on land use land cover change.

The watershed model can be categorized into two main classes known as lumped and distributed based model. Lumped based model is spatially averaged, or regarded as a single point in space without dimensions; they ignore the internal spatial variation of watershed flow while distributed model consider the hydrologic processes taking place at various points in space and define the model variables as functions of the space dimensions. However, the application of lumped based model in hydrologic model is mainly used to simulate rainfall-runoff on catchment wide basis (Halwatura and Najim, 2013; Széles et al., 2016; Jian et al., 2017). This scenario also occurred in Malaysia as most of the previous study carried out by Shamsudin and Hashim (2002) and El – Shafie et al (2011) are still using the application of lumped based model at Layang catchment in Johor state and Klang river basin, respectively.

There are also few attempts from various researchers such as Kang and Merwade (2011); Sinha et al (2016) and Fenicia et al (2016) performing rainfall-runoff by using distributed model approach. However, in certain cases, it might not be considered as a fully distributed model if there are few parameters used a constant value or average value in the model analysis. The application of distributed model approach in rainfall-runoff model has been used widely in terms of continuous rainfall event such as daily rainfall data at global scale (Suliman et al., 2014; Sinha et al., 2016). Therefore, in such situation, this study will introduce an event based rainfall-runoff model to ameliorate flash flood issue that has become frequent and major threats to the human lives including their socio-economic condition and properties in the rural area specifically in Bentong catchment, Pahang, Malaysia. Currently, the hydrological modeling by using the event based rainfall input in distributed model is very lacking in Malaysia.

Although there are many distributed based model available, many studies applied distributed model on continuous model. This study was focusing on event based model that is important to develop a flood hazard map as it represent the real condition (Diakikis, 2011). One of the main challenges for GIS based event model is the flood routing method Kalogeropoulos et al., (2013). This study had introduced a combination of kinematic wave approximation (KWA) and manning's equation along with NRCS CN to model rainfall runoff of Bentong catchment in a fully distributed based approach. Previous study by several researchers used the kinematic wave equation by integrating the overland flow, *L* (Maidment, 1996) and length of slope, *ls* (Gioti et al., 2013; Chalkias et al., 2016). However, the problem when using this approach, the input will be at the same and implemented to all grid without taking consideration the resolution size. This condition will not fully represent distributed based model and effect the results of the modeling. This study introduce solution for this problem which is by introducing KWA in order to calculate flow velocity in every cell without neglecting the DEM resolution characteristic. In this process, the depth of flow at equilibrium equation was modified from (Overton and Meadows, 1976) with manning equation (Eq.1.1).

$$\boldsymbol{V_0} = \frac{(\boldsymbol{i_e} * \boldsymbol{x})^{\mathbf{0.4}} * \boldsymbol{S_0}^{\mathbf{0.3}}}{\boldsymbol{n}^{\mathbf{0.6}}} \qquad \text{Eq.1.1}$$

Where y is the depth of runoff flow at equilibrium (m), i.e. the rainfall excess intensity (m/s), n the manning roughness coefficient, $\boldsymbol{x}$ is the distance along the flow path (m) and $\boldsymbol{S_0}$ the slope (m/m). Equation 1.1 will be used in the calculation of overland flow. Details equation generation available in section 3.8.1.1. In order to determine *x* value, DEM resolution analysis and sensitivity analysis will be performed. This step will be able to determine the most fitted *x* value for Bentong catchment because using inappropriate *x* value will affect result especially on time to peak.

One of challenges when using distributed model is to create the hydrograph at the output. Previous studies by (Diakikis, 2011) create hydrographs by using time are (TA) approach. Conversion of TA histograms to hydrographs by converting area to discharge was done by applying a 1 mm uniform rainfall and dividing by the associated time segment (Usul and Yilmaz, 2002; Noorbakhsh et al., 2005; Diakikis, 2011). In this study modification is made by using real rainfall intensity was used instead of using 1 mm uniform rainfall.

This study will be acknowledged as a pioneer study in Malaysia that applies a fully distributed GIS to model rainfall-runoff simulation. The recent flash flood hazard map will be produced by using time area (TA) approach in order to classify the runoff according to specific time. Moreover, a newly proposed method to improve the route, the overland and channel flow will be introduced in this study by combining the kinematic wave approximation and manning's equation distributed model which considered the hydrologic processes taking place at various points in space and define the model variables as functions of the space dimensions. In addition, the flow routing methods of watershed models are also subjected by these two main classifications which are known as a lumped flow routing (hydrologic routing; unsteady uniform flow) and distributed flow routing (hydraulic routing; unsteady non-uniform flow) (Chow et al., 1988; Vieux, 2004).

1.3 Research Aim and Objective

The aim of this study is to model rainfall runoff in Bentong catchment using an integrated distributed GIS model combining NRCS CN, kinematic wave approximation and manning's equation. In order to achieve the main objective, the specific objectives as shown below have to be completed:

1. To determine optimum resolution size of DEM towards the distributed model output
2. To develop the distributed GIS rainfall runoff model (SDTT) and spatial lumped model (SLM)
3. To determine the effects of land use changes in 16 years towards rainfall runoff
4. To compare the model output from SDTT model with spatial lumped based model (SLM)

1.4 Research Questions

A few questions required to be answered in this study?

1. Based on GIS technology, is it possible to develop a prototype watershed GIS based model?
2. Can the model developed able to simulate different kind of watershed land use satisfactorily?
3. How sensitive the spatial distributed model towards parameter input manipulation?
4. Does spatial GIS based using a fully distributed approach performed better in rainfall runoff modelling compared to traditional lumped based approach?

1.5 Scope of study

In this study, Digital Elevation Model (DEM) was downloaded freely from website of Shuttle Radar Topography Mission (SRTM) in order to obtain the topographic features for Bentong catchment and also watershed delineation. Recently, study by Khalid et al., (2016) stated that DEM generated from SRTM produce better result of correlation and RMSE compared to DEM generated using ASTER and GMTED2010 with RMSE = 4.714 and $R^2 = 0.912$. This finding used as the basis of using SRTM DEM for modeling purposes. There are several parameters required to model the rainfall runoff such as land use, soil map and hydrologic soil map. In this study, land use map of Bentong catchment in year 2000, 2010 and 2016 were used. Land use map for the year 2000 and 2010, soil map and hydrologic soil map were obtained from Department of Agriculture (DOA) Malaysia. Meanwhile, the land use map for the year 2016 have been obtained by using the Landsat 8 satellite image. The land use map produced by Landsat 8 was validated at the site and supported by topographic map from Department of Survey.

According to Yu et al (2017), when faced with flood issues, a finer time scale is required in dealing with flood forecasting issue as it is realistically capture the changes of flood processes characteristic. The event based analysis was preferred in this study in order to model the flash flood occurrence within Bentong catchment. Therefore, evaporation and ground water effect can be neglected (Sulaiman et al., 2010). The 15 minutes interval of rainfall and discharge data according to specific year that reflect the land use were collected from Department of Irrigation and Drainage (DID) and will be used during the calibration and validation process. To maintain data reliability, only complete rainfall records on selected event will be used. Furthermore, since DID adopts 0.2 mm tipping bucket at their rain gauges station to be considered as one tip, value less that 0.2 mm in 15 minutes (0.2 mm/15 min) (e.g. 0.1 mm in 15 min) will not be considered (DID, 2009). Rainfall or storm events was selected based on specific storm event using the standard procedure of Antecedant Moisture Condition (AMC) suggested by NRCS CN. This will act as the quality control for the rainfall data used in the rainfall runoff analysis. Only rainfall data and events comply with the stated criteria will use as the input for the modeling purposes. No stochastic procedure will be perform to the rainfall data as the main purpose of this study is to apply distributed based method to perform rainfall runoff modeling as previous study also by (Domnita et al., 2010; Giotti et al., 2013) also apply the same procedure.

This study will evaluate two types of rainfall runoff models which are known as distributed GIS based model and spatial lumped model. There are several types of distributed model which are available in rainfall runoff modelling but most of them are designed for continuous based rainfall such as SWAT, TREX and others. These models are also used a lot of parameters and it requires intensive calibration and validation process. In this study, distributed model will be performing using combination of kinematic wave approximation (KWA) and manning's to route the channel and overland flow to the outlet. Both are mathematical models in routing the water flow both in channel and land. The function of Grid Calculator in ArcGIS software will be used to write and run the grid analysis and to run the model. NRCS CN model will be incorporated in the model also using grid calculator function with the purpose to estimate the effective runoff. Since it is a distributed based model, the area and parameters used in the model will be aggregated into grid cell that contain unique value. To develop the hydrograph at the outlet, time area (TA) method was used with isochrones of 15 minutes interval. All of the distributed model will be built using GIS. The distributed based model in this study will be referred as spatial distributed travel time or SDTT.

For the lumped based model (SLM), there are three major components that need to be considered in developing the lumped based model which are known as the estimation of loss volume, transformation of excess rainfall to runoff and channel routing. GIS was used to prepare the parameter input and hydrologic software called HEC-HMS 4.0 and will be used in the calibration and validation process of the model.

The lumped based model and distributed based model also have been used in this study with the purpose to evaluate the comparison of model performance for both models. In order to assess the evaluation of model performance, the statistical parameters such as NSE, PBIAS, POE and correlation coefficient will be used.

1.6 Significance of study

The application of event based rainfall analysis is rarely used in Malaysia as most of the researchers are more prefer to use the continuous based rainfall analysis in their studies. Therefore, in the present study, the actual rainfall intensity value was obtained from interpolation of rainfall station value using IDW and subsequently used as a distributed model input to simulate rainfall runoff which are more precisely represent the real flash flood event. It was reported that the distributed based model was performed well and in some cases, the model performance of distributed based model was performed much better than lumped based model. Unfortunately, based on the literature review, the distributed based model approach in hydrological modeling carried out in Malaysia is still scarce and limited. The previous studies have used various types of distributed model such as SWAT (Abbaspour et al., 2015), GSSHA (Sharif et al, 2017), TOPMODEL (Nourani et al., 2011), CASC2D (Downer et al., 2002) and TREX (Abdullah et al., 2018) which are commonly used more complex parameters and continuous rainfall based as input. The parameterization is very critical and highly required in this study as it used a lot of parameters and input in the distributed based model approach.

This study used a simple method which combining kinematic wave approximation (KWA) with manning's equation to produce a travel time map. Previously, both equations have been used in hydraulic-based study and lumped based model (Pawar et al., 2013). In the previous study, the lumped based model has been using KWA; the capability of KWA equation was not optimized as the parameterization of parameter in the equation often used in single average value for each sub – catchment wide basis. In this study, the improvement is made as the equation of KWA used and applied in grid size. Due to the GIS capability to process a grid based resolution data; they can be used together with spatial analysis to produce hydrographs at the outlet. This study also used the DEM resolution analysis in producing an accurate input for KWA. From the DEM resolution analysis, the longest line within grid size used as the input for distance to ridges or x which required in the KWA equation.

Each model will be applied for different purposes depending on the desired objectives of water resources management and flood management teams to take into account in mitigating this critical environmental issue. Based on the previous studies that have been reviewed and discussed, there are several studies on distributed model approach have been carried out in globally such as US, China, Iran, Germany, Chile and Austria. However, there is no study in distributed model approach found in developing country such as Malaysia. This study will be the pioneer study in Malaysia specifically Bentong catchment by using KWA equation in distributed form. Moreover, due to the high number of ungauged area and limited gauging station in Malaysia, the GIS based hydrologic model using the Time – Area (TA) method have been adopted and applied in Bentong catchment (tropical catchment) as it can be a plan and strategies for the researchers, planners and engineers in managing the development in sustainable way for the future.

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