

**APPLICATION OF GEOGRAPHIC
INFORMATION SYSTEM AND
HYDROLOGICAL MODELLING OF SUNGAI
GALAS, KELANTAN, MALAYSIA**

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INFORMATION SYSTEM AND
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by

MOHD TALHA ANEES

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DEDICATION

This thesis work is dedicated to my parents, brother and sister for their kindness and devotion, and for their endless support and encouragement during the challenges of my research. I am truly thankful for having such a nice family in my life who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

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LIST OF SYMBOLS

H_r	Effective depth
H_h	Distance between the neck and the bottom of the bulb
h	Depth of hydrometer
V_h	Weight of hydrometer
L_h	Height of hydrometer
R_o'	Reading in dispersant
L_c	Height of cylinder
R_n'	Hydrometer reading
D_p	Particle diameter
ε	Viscosity of water
ρ_s	Particle density
t	Elapsed time
R_d	Difference between hydrometer reading and reading in dispersant
m_s	Mass of dry soil sample
R^2	Coefficient of Determination
P_{est}	Estimated precipitation
w_i	Weighting factor
n	Number of observation
R_{inf}	Radius of influence
d_i	Distance between a target and i th observations
d_j	Distance between the target and each of j th observations
ω_c^j	Precipitation occurrence
c	Grid cell

N	Northing
Ea	Easting
E _l	Elevation
S _l	Slope
W _s	Wind Speed
D _M	Mahalanobis distance
D _C	Cook's distance
P _{obs}	Observed precipitation
I ₃₀	Maximum rainfall intensity
E	Total rainfall kinetic energy
R	Rainfall erosivity
e _r	Unit rainfall kinetic energy
i _r	Rainfall intensity
v _r	Rainfall volume
N _u	Stream number
L _u	Stream length
L _{sm}	Mean stream length
R _L	Stream length ratio
R _b	Bifurcation ratio
R _{bm}	Mean bifurcation ratio
L _b	Basin length
D	Drainage density
F _s	Stream frequency
I _f	Infiltration number
R _t	Drainage texture

B_s	Basin shape
R_f	Form factor
R_c	Circularity ratio
R_e	Elongation ratio
L_o	Length of overland flow
A	Area of watershed
C_{cm}	Constant of Channel Maintenance
C_c	Compactness Coefficient
P_w	Perimeter of watershed
D_i	Drainage intensity
H	Total Basin Relief
R_a	Absolute relief
R_{hl}	Relief Ratio
D_I	Dissection Index
R_n	Ruggedness Number
SL	Soil loss
K	Soil erodibility factor
LS	Slope length and steepness factor
C	Cover management factor
P	Support practice factor
$m_{(xy)}$	Variable slope-length exponent
$\beta_{(xy)}$	Grid cell ratio of rill to interrill erosion
$\theta_{(xy)}$	Slope angle in degrees of a grid cell
SY	Sediment yield
MJ	Millijoule

<i>Mg</i>	Milligram
<i>ha</i>	Hectare
XS	River cross section
XSs	River cross sections

LIST OF ABBREVIATIONS

ALB	Airborne LIDAR Bathymetry
AMIRA	Australian Mineral Institute Research Association
ASOAdEK	Auto-Search Orographic and Atmospheric Effects Detrended Kriging
ASTER GDEM	Space-borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
BW	Bottom Width
CSI _{dry}	Critical Success Index-Dry
CSI _{wet}	Critical Success Index-Wet
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DWASW	Diffusive Wave Approximation of the Shallow Water
DEM	Digital Elevation model
DID	Department of Irrigation and Drainage
DS	Downstream
DTM	Digital Terrain Model
DOA	Department of Agriculture
DOE	Department of Environment
EG	Energy Gradient
EGH	Energy Gradient Height
EN	Estimated Natural
ESRI	Environmental Systems Research Institute
ET	Evapotranspiration
FA	Flow Area

GIS	Geographic Information System
GPS	Ground Positioning System
HEC RAS	Hydrologic Engineering Centre's River Analysis System
IDW	Inverse Distance Weighting
IDF	Intensity Duration Frequency
LIDAR	Light Imaging, Detection, And Ranging
LULC	Land Use and Land Cover
LUS	Land Use Survey
LWP	Locally Weighted Polynomial
MAE	Mean absolute error
MBE	Mean bias error
MLR	Multiple Linear Regression
MODIS	Moderate Resolution Imaging Spectroradiometer
MRSA	Malaysian Remote Sensing Agency
MS	Midstream
MSL	Mean Sea Level
MUSLE	Modified Universal Soil Loss Equation
NS	Nash and Sutcliffe efficiency coefficient
OLI_TIRS	Operational Land Imager and Thermal Infrared Sensor
OM	Organic Matter
ON	Observed Natural
PCP	Proportion Correctly Predicted
PE	Potential Evapotranspiration
POD	Probability of Detection

PRISM	Precipitation-elevation Regression on Independent Slope Model
RS	Remote Sensing
RUSLE	Revised Universal Soil Loss Equation
SCS	Soil Conservation Service
SDR	Sediment delivery ratio
SF	Stream Flow
SLR	Simple Linear Regression
SMAPE	Symmetric mean absolute percentage error
SRTM	Shuttle Radar Topography Mission
SW	Shallow Water
TIN	Triangulated Irregular Network
TM	Thematic Mapper
TW	Top Width
UNISDR	United Nations International Strategy for Disaster Reduction
US	Upstream
USDA	United State Department of Agriculture
USGS	United States Geological Survey
USLE	Universal Soil Loss Equation
WGS	World Geodetic System
WL	Water Level
WSE	Water Surface Elevation
WSW	Water Surface Width
XS	Cross Section

1D	One dimensional
2D	Two dimensional

**APLIKASI SISTEM MAKLUMAT GEOGRAFI DAN PERMODELAN
HIDROLOGI SUNGAI GALAS, KELANTAN, MALAYSIA**

ABSTRAK

Banjir adalah salah satu mala petaka semula jadi di dunia dan juga di Malaysia. Kelantan juga mengalami banjir dan analisis perlu dilakukan. Analisis banjir boleh dilakukan melalui pemodelan hidrologi dengan menggunakan data resolusi tinggi untuk mencari punca dan kesan sebenar banjir. Namun, jika tiada data resolusi tinggi atau data in-situ, apakah alternatif untuk menjalankan pemodelan hidrologi? Objektif kajian ini ialah (i) untuk membangunkan kaedah dan model alternatif bagi penjanaan parameter-parameter banjir yang tepat dengan menggunakan sistem penderiaan jauh dan Sistem Maklumat Geografi (GIS) dalam persekitaran data yang jarang di Kelantan, Malaysia dan (ii) menjalankan pemodelan hidrologi 1D dan 2D ke atas kawasan yang diberi keutamaan (Sungai Galas) untuk mengesahkan dan membandingkan parameter yang diperhatikan dan dianggarkan. Motivasi di sebalik objektif ini adalah untuk mencari metodologi alternatif bagi menganggarkan parameter input asas seperti hujan dan keratan rentas sungai untuk pemodelan hidrologi. Regresi linear berganda (MLR) digunakan untuk memperbaiki anggaran secara ruang bagi hujan purata harian. Keutamaan, timuran, elevasi, halaju angin dan cerun telah dipilih sebagai pemboleh ubah peramal dalam MLR. Keputusan menunjukkan dominasi keutamaan adalah dalam semua kes dan peranan penting kelajuan angin dalam peningkatan model. Hasil pengesahan menunjukkan bahawa anggaran ruang terdekat bagi purata curah hujan setiap hari bagi peristiwa 17 dan 22 Disember 2014 (151.1 dan 155.6 mm/hari) dengan purata hujan harian tercerap secara ruang (146.3 dan 164.9 mm/hari). Di samping itu, model hakisan hujan harian juga dibangunkan dengan ketepatan 8.2% anggaran

berlebihan yang lebih baik daripada model yang telah dibangunkan sebelum ini (32% auggaran berlebihan) dan kawasan-kawasan tadahan yang utamakan untuk melakukan pemodelan hidrologi. Satu metodologi untuk menganggarkan keratan rentas sungai dari Model Elevasi Digital (DEM) resolusi 30m dibangunkan dan disahkan (dengan ketepatan 1.7m auggaran berlebihan) dengan menggunakan permodelan 1D HEC RAS yang boleh membantu semasa ketiadaan data in situ atau resolusi tinggi. Akhir sekali, kaedah penambahbaikan bagi parameter input asas digunakan dalam 2D HEC RAS untuk memahami kesan perubahan Guna Tanah dan Penutupan Tanah (LULC), kadar pемendapan pada aliran atas tanah. Aliran atas tanah dianalisis berasaskan kedalaman, elevasi permukaan air, halaju, masa ketibaan dan tempoh aliran. Hasil pemodelan 2D HEC RAS menunjukkan bahawa aliran darat menurun apabila ia mengalami hutan tebal atau hutan kepada hortikultur bercampur atau tanah yang tidak ditanam dan sebaliknya manakala curahan hujan yang dianggarkan menunjukkan 2.2% auggaran berlebihan. Secara keseluruhan, kajian ini menunjukkan bahawa peranan penderiaan jauh dan GIS dalam penyediaan parameter input asas adalah didapati sangat penting. Dapat disimpulkan bahawa idea kajian ini adalah bagi mencari metodologi alternatif parameter input asas dalam persekitaran data yang jarang untuk pemodelan hidrologi adalah sangat penting, berkesan dan boleh digunakan di kawasan lain di Malaysia.

**APPLICATION OF GEOGRAPHIC INFORMATION SYSTEM AND
HYDROLOGICAL MODELLING OF SUNGAI GALAS, KELANTAN,
MALAYSIA**

ABSTRACT

Flooding is one of the natural hazard in the world as well as in Malaysia. Kelantan is also effected by flooding which need to be analysed. Flood analysis can be done through hydrological modelling by using high resolution data to find exact causes and effects of flooding. But in the absence high resolution or in situ data, what are the alternatives to conduct hydrological modelling? The objectives of this study were (i) to develop alternative methodologies and models for the generation of accurate flooding parameter's values by using remote sensing and Geographic Information System (GIS) in a data sparse environment in Kelantan, Malaysia and (ii) to conduct 1D and 2D hydrological modelling on prioritized area (Sungai Galas) to validate and to compare the observed and estimated parameters. The motivation behind these objectives was to find the alternative methodologies for estimation of basic input parameters such as precipitation and river cross section for hydrological modelling. Multiple Linear Regression (MLR) was used to improve spatial estimation of average daily precipitation. Northing, easting, elevation, wind speed and slope were selected as predictor variables in MLR. The results shown the dominance of northing in all cases and significant role of wind speed in model improvement. The validation results showed that closest spatial estimation of average daily precipitation for 17th and 22nd December 2014 events (151.1 and 155.6 mm/d respectively) with spatial observed average daily precipitation (146.3 and 164.9 mm/d respectively). Additionally, daily rainfall erosivity model was also developed with accuracy of 8.2% overestimation

which is better from previously developed model (32% overestimation) and watersheds were prioritized to conduct hydrological modelling. A methodology to estimate river cross sections from Digital Elevation Model (DEM) of 30 m resolution was developed and validated (with an accuracy of 1.7m overestimation) by using 1D HEC RAS modelling which will be considerable and helpful in the absence of in situ or high resolution data. Finally, the improved methodologies of basic input parameters were used in 2D HEC RAS to understand the effects of Land use and land cover (LULC) changes and precipitation on overland flow. Overland flow was analysed on the basis of depth, water surface elevation, velocity, arrival time and duration of flow. The output of 2D HEC RAS modelling showed that the overland flow decreases from dense forest or forest to mixed horticulture or uncultivated land and vice versa while the estimated precipitation shown 2.2% overestimation. Overall, the study reveals that the role of remote sensing and GIS in the preparation of basic input parameters were found very important. It was also concluded that the idea of this study to find alternative methodologies of basic input parameters in data sparse environment for hydrological modelling was very important, effective and can be applied in other parts of Malaysia.

CHAPTER 1

INTRODUCTION

1.0 Background

Environmental changes have always been a keen concern for researchers. Increment in precipitation, urbanization and topographic changes have led to a sharp rise in the occurrence of natural hazards. Flooding is a very common hazard found in large parts of the Earth. However, according to United Nation's report (UNISDR), flood strike in Asia and Africa more than other countries. The analysis also highlights that since 1995, floods accounted for 47 percent of all weather-related disasters, affecting 2.3 billion people, killing 157000 people and damages about US\$19.3 billion and US\$0.83 billion for Asia and Africa respectively (Nkwunonwo et al., 2016).

Flood in Malaysia is also one of the most common natural hazard, causing the loss of life, economy, environment and agriculture. Economic loss includes the damage of houses, roads, bridges, buildings and automobiles. Sometimes floods causes hazardous chemicals such as gasoline and diesel to spill out of vehicles, industrial facilities, fuel supplies, and other sources in water bodies which contaminates water. Two major types of floods occur in Malaysia, including monsoon floods and flash floods. The Department of Irrigation and Drainage in Malaysia has estimated that, in the past decade, about 29000 sq. km, or 9%, of the total land area and more than 4.82 million people (i.e. 22% of the population) are affected by flooding annually. The damage caused by flooding is estimated to be about RM 915 million (DID, 2003; DID, 2017).

Earth processes in which changes occur in land, air and ocean, are very complex. These changes are interrelated to each other causing climatic changes. Significant

urbanization during the past several years explains some important effects of land use changes on water management such as replacement of permeable to impermeable surface, reduction in infiltration and rise in overland flows (Wheater and Evans, 2009). Neupane and Kumar (2015) discussed the combined effects of climate and land use changes on water budget and predicted that the scale and intensity of flood events will increase with continuation of these processes. Furthermore, instead of high precipitation, basin shape, size, slope, stream density and spatio-temporal land use and land cover changes are important factor in controlling runoff frequency.

The processes have been estimated by researchers either by applying in situ methods or laboratory approaches. However, it is very difficult and time taken with in situ data collection spatially and temporally over large areas. To estimate accurate spatial and temporal changes over large areas, researchers use integrated approach of remote sensing, Geographic Information System (GIS) and hydrological modelling techniques.

Any flood-related study requires some initial considerations, namely, the areas to be analysed, the parameters to be measured during field data collection, the procedure and the actual collection of field data. Remote sensing and GIS play an important role in the initial stages of flood analysis. They are reportedly used over other techniques because of their broad reach in data-sparse environments. Satellite remote sensing provides useful geospatial data and is increasingly being used to expand useful sources of information for a wide array of applications (Bhaskaran et al., 2010; Mahmoud et al., 2011) while GIS can deliver a synoptic view of large areas which is very useful in analysing drainage morphometry, soil erosion and spatial-temporal mapping. Remote sensing and GIS are also useful for input data preparation either in data availability or in data-sparse environments (Hughes, 2006; Artan et al.,

2007; Asante et al., 2008). Lacking of data such as the minimum or absence of in situ stream gauge monitoring data, meteorological data, extraction of river cross-sections and hydrological data can also be prepared by using remote sensing and GIS. However, for sub-surface investigation in situ methods must be applied.

Hydrological modelling are powerful tools for visualizing the dynamic behaviour of physical systems in science and engineering fields and provide simplification of a complex reality. Hydrological modelling includes four main steps; construction of a mathematical model according to physical problems, with suitable assumptions; development of a suitable numerical model; obtaining the results by implementing the model; and interpretation of the results with the help of tables, graphs, charts and animations and finally proposing a feasible solutions. However, the modelling techniques also have some uncertainties which effect accuracy and efficiency of numerical models (Chen et al., 2012).

Ali (2018) mentioned some uncertainty definitions and its classifications while Engeland et al. (2016) mentioned some uncertainties in hydrological modelling which include uncertainties in input and model parameters. Meteorological and hydrological components such as precipitation, temperature, wind characteristics, infiltration and runoff are one of the basic inputs and model parameters for any hydrological modelling but their poor spatial distribution can affect the model accuracy. For instance, precipitation has uncertainty in its spatial distribution in complex topography because of uplifting air masses by the wind. McMillan et al. (2011) highlights the dependency of precipitation error on the data time step in hydrological modelling. Many studies related to hydrological modelling have been done in several countries which have good record of quality data but in data sparse region or lack of attention towards

hydrological modelling, in some developing countries, often prevent researchers to have an interest and accurate prediction of causes and effects of flooding.

With the advancement of computational technology, many one dimensional (1D), two dimensional (2D), coupled 1D/2D hydrological models and software have been developed for various scientific and engineering practices (Dimitriadis et al., 2016; Bladé et al., 2012; Carbonneau et al., 2006; Stoesser et al., 2003; Wu et al., 2000). Dimitriadis et al. (2016) used 1D and 2D models for uncertainty assessment in floodplain hydrological modelling. Bladé et al. (2012) studied the conservation of mass and momentum by coupling of 1D and 2D models for river channels and floodplain respectively. The use of mixed approach of 1D and 2D numerical models increases the quality of results (Horritt, 2006; Dimitriadis et al., 2016) and also save time and computer memory which can be limiting factors for the application of 2D models (Bladé et al., 2012). Results of these models also affected by the complexity and quality of topographic and input data (Cook and Merwade, 2009; Neal et al., 2012).

Several studies have been conducted in Malaysia as well using hydrological modelling. Kumar et al. (2017) reviewed dam break studies and inundation mapping by using integrated approach of various hydrological models and GIS. Other studies were conducted in Malaysia using different hydrological models were related to flood mitigation (Julien et al., 2009), flood risk assessment (Ghorbani et al., 2015; Romali et al., 2017), flood inundation mapping (Romali et al., 2018), river cross section spacing (Ali et al., 2015), distribution of rainfall intensity (Salleh and Sidek, 2016), river sand mining capacity (Teo et al., 2017) and Spatio-temporal land usage changes (Ab Ghani et al., 2010). Several 1D and 2D models have been used in river and floodplain modelling are listed in Table 1.1.

Table 1.1: The widely used 1D and 2D models with their studies references.

S.No.	Model	References of related studies
1	HEC RAS	(Julien et al., 2010; Merkuryeva et al., 2015; Ali et al., 2017; Vozinaki et al., 2017; Shelley et al., 2015)
2.	InfoWorks RS	(Chang, 2018; Ghani et al., 2010; Mah et al., 2017)
3.	MIKE 11	(Liu et al., 2007; Panda et al., 2010; Doulgeris et al., 2012; Kanda et al., 2015)
4.	HEC RAS 2D	(Wan and Konyha, 2015; Vozinaki et al., 2017)
5.	LISFLOOD-FP	(Horritt and Bates, 2002; Fernández-Pato et al., 2016; Wood et al., 2016)
6.	FLO 2D	(Hübl and Steinwendtner, 2001; Samela et al., 2015; Haltas et al., 2016)
7.	TUFLOW	(Nelson and Jones, 2014; Bertram, 2015; Kaase and Kupfer, 2016)
8.	MIKE 21	(Parvathy et al., 2014; VishnuRadhan et al., 2014)
9.	XPSWMM	(Toriman et al., 2009; van der Sterren et al., 2014; Akram et al., 2014)

1.1 Problem statement

Flood is one of the natural hazard in Malaysia (Aisha et al., 2015; Zawawi et al., 2018). The reason could be the result of increasing settlement areas along the levees (Sanyal, 2017), unexpected high rainfall which is up to 55mm hourly maximum, 134mm five hour maximum and 229mm 24 hour maximum (Syafрина et al., 2015), deforestation mainly from agricultural activities (Ismail et al., 2014); river channel changes with average alignment of sinuosity index is 1.24 to 1.48 (Kamarudin et al., 2014), sediment deposition due to high sediment yield because of topographic characteristic, vegetation type and density, climate and land use within the drainage basin (Ab Ghani et al., 2013; Teh, 2011). It is a need to find out the exact causes of flooding and it can be achieved through the high resolution data. High resolution data

such as satellite images of 5m or 2.5m resolution for land use changes and for soil erosion analysis, in situ river bathymetry for accurate hydrological modelling, precipitation intensities of less than 5 minute interval, high density of rain gauge stations for better spatial distribution of precipitation and rain drop size impact on loosening of soil. But in data sparse environment or unavailability of high resolution data what should be the other option for the estimation of basic input parameters for hydrological modelling and soil erosion analysis?

Additionally, some other questions are also arising that how the public domain coarse resolution (30m resolution) Digital Elevation Model (DEM) can be used to extract river cross sections for accurate hydrological modelling and how to conduct hydrological modelling in reduced computation time to get concrete results? Hence, the problem statements of this study are:

- (i) Lacking of alternatives for the preparation of basic input parameters such as spatial distribution of precipitation and river bathymetry for hydrological modelling in the absence of in situ and high resolution data. Additionally, lacking alternatives of rainfall erosivity estimation for tropical climate and study area need to be prioritize to reduce computation time of hydrological modelling and to get concrete results.
- (ii) Methodologies and models to estimate basic input parameters alternatively in tropical climate are also missing which need to be developed. The developed methodologies and models will be helpful to estimate basic input parameters for hydrological modelling in data sparse environment.

1.2 Research objectives

Research objectives can be defined as what is to be achieved by the study and for what purpose. To consider and to solve the problems stated above, the objectives of this study are:

- (i) To develop alternative methodologies and models for the generation of accurate flooding parameter's values in a data sparse environment.
- (ii) To validate the developed methodologies and models through 1D and 2D hydrological modelling. The purpose of the modelling is to validate and to understand the effects of these parameters on the behaviour of overland flow.

1.3 Scope of the study

Scope of the study are important guidelines in which the research was conducted which define the boundary of limitations and the specifications about the data and methodology have been used in the research. The scope of this study are:

- (i) Surface data alternatives such as precipitation, river bathymetry and rainfall erosivity were selected, their improvements and model developments.
- (ii) Publicly domain and widely used 1D and 2D hydrological modelling software (HEC RAS) on prioritized area was used to compare observed and estimated parameters.
- (iii) Only steady and unsteady flow analysis were conducted for validation of proposed river bathymetry model and understand the effects of spatio-temporal land use land cover changes on the behaviour of runoff respectively.

1.4 Novelty and Significance of the study

The study especially was focused on alternatives estimation of basic input parameters for hydrological modelling in the absence of in situ data or high resolution data. On the basis of this, the novelties and significances of this study are:

- (i) Improvement in spatial estimation of average daily precipitation which will give accurate spatial distribution of precipitation.
- (ii) Developed daily rainfall erosivity model which can be used in the absence of high resolution data for soil erosion analysis.
- (iii) Watersheds were prioritized on the basis of land use and land cover changes, morphometric parameters, soil loss and sediment yield by assigning a new criteria to conduct hydrological modelling on prioritized area.
- (iv) Developed a river cross sectional model to improve river cross section values extracted by 30m resolution elevation data which is a basic geometrical input parameter to conduct 1D hydrological modelling.

1.5 Thesis layout

The thesis layout is structured as follows:

Chapter 1 introduces the background of flooding, remote sensing, GIS and hydrological modelling. It also highlights the problem statements, research objectives as well as scope of this study. The novelty and significance of the study have been discussed briefly. The chapter concludes by summarizing the structure of whole thesis.

Chapter 2 discussed the literature review of basic input parameters for hydrological modelling, their estimation methods and alternatives of these methods in data sparse environment. A brief overview of 1D and 2D HEC RAS software were

also discussed. The chapter concludes by presenting research gaps from literature review, and finally chapter summary.

Chapter 3 describes general information of study area, data collections from different sources, laboratory experiments and methods used to estimate the basic input parameters in the absence of in situ or high resolution data. It conclude with chapter summary.

Chapter 4 presents results and discussions. The outcomes of activities described in Chapter 3 are analysed and interpreted.

Chapter 5 summarizes the significant conclusions from the research, stating the contributions from this work and providing recommendations for further enhancement and investigations.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

The entire area of a river basin whose surface runoff (due to a storm) drains into the river in the basin is called as drainage basin or watershed or catchment area of the river flowing (Raghunath, 2006). There are various factors which affect runoff from drainage basin. These factors depends upon some characteristics such as storm, meteorological, basin and storage characteristics. Among all the factors, some are very important and generally use as a basic input parameter in river and floodplain modelling. Storm parameters includes intensity, duration and distribution of precipitation while meteorological parameters includes humidity and wind speed. Basin parameters includes shape, size, slope, elevation, topography, type of soil, land use cover and type of drainage whereas storage includes streams, channels, floodplain and groundwater storages. All these parameters can be obtained from either in situ stations, laboratory experiments, satellite images or government agencies. These parameters are very important in any flood analysis. However, results accuracies depends on the resolution of the data.

This chapter will discuss about the previous studies used in the estimation of the basic input parameters such as land use land cover changes, precipitation and river bathymetry for hydrological modelling and their gaps in previous researches. Additionally, it will also discuss about the previous studies used in the estimation of rainfall erosivity, morphometric parameters, soil erosion analysis and watershed prioritization. It should be noted here that this study will focus on the alternative methodologies and models to estimate basic input parameters for hydrological

modelling which will be helpful in data sparse environment. The alternative parameters will be associated with remote sensing, Geographic Information System (GIS) and hydrological modelling.

The topics which will be covered in this chapter are: (i) spatio-temporal land use land cover changes, (ii) spatial estimation of average daily precipitation, (iii) development of daily rainfall erosivity model, (iv) morphometric analysis, (v) soil erosion analysis, (vi) prioritization of watersheds, (vii) estimation of river cross sections and (viii) 1D and 2D hydrological modelling.

2.1 Land use and land cover (LULC) changes

Among the natural hazards, flood (either monsoonal or flash flood) is common natural hazard in Malaysia which causes loss of life, properties, economy and agriculture (Pradhan and Youssef, 2011). Flash flood is caused by the combination of anthropogenic activities and topographic changes which results into high runoff and hence river's structural changes (Creutin et al., 2013; Špitalar et al., 2014). The effects of these factors on downstream flood are to be quantified to understand flood pattern and control thereof.

Land use and land cover (LULC) changes play a very important role in finding the causes of topographic changes which results land degradation (Eaton et al., 2008). It also provides invaluable information for managing land resource and their development (Al-Bakri et al., 2013). Upstream land degradation results increase in runoff and changes in river's geometry such as decrease in river depth due to sediment deposition and increase in stream power (Lecce, 2013) at downstream.

Remote sensing and Geographic Information System (GIS) is very effective tool for initial studies. High resolution data can provide accurate results but in data sparse

environment, the freely accessible data such as Landsat and MODIS are the better option to know the topographic changes. MODIS has some limitations such as its coarse resolution which limits its ability in detecting small changes (Jin and Sader, 2005), which is necessary in detecting anthropogenic activities (Zhu and Woodcock, 2014). While Landsat data has some advantages over MODIS such as long record of continuous measurement, spatial resolution, and near nadir observations (Pflugmacher et al., 2012; Wulder et al., 2008; Woodcock and Strahler, 1987). But its disadvantage is low temporal frequency and cloud cover problem. However, the mosaic of multi temporal images with less cloud cover can provides accurate results (Zhu and Woodcock, 2014). Some researchers (Kibret et al., 2016; Zhu and Woodcock, 2014) used Landsat in their studies and conclude that the Landsat data is very useful in the analysis of spatio-temporal LULC changes.

There are two methods of classification of LULC which can be done by using remote sensing and GIS. The visual classification technique has advantage in terms of accuracy over automatic or supervised classification in heterogeneous LULC classification which is based on the expert knowledge (Zhang et al., 2014).

LULC changes were analysed by several researchers in Malaysia to evaluate urban expansion (Tan et al., 2010), forest fragmentation and its correlation to human land use changes (Abdullah and Nakagoshi, 2007), effects of land use changes on sediment and nutrient balance of a reservoir (Ismail and Najib, 2011), impact assessment of runoff changes due to land cover changes (Saadatkhah et al., 2016), spatial soil loss impact by long term LULC changes (Abdulkareem et al., 2017), long term changes effects of precipitation and land use on hydrological response (Adnan and Atkinson, 2017), LULC detection by different classifications (Udin and Zahuri,

2017) and LULC changes of river catchments in Klang Valley, Malaysia (Othman et al., 2009).

In these studies, LULC changes data (in different parts of Malaysia) either collected from Soil Management Division of Department of Agriculture (DOA), Malaysia or extracted from Landsat data by supervised and unsupervised classifications with accuracy ranges from 87% to 96%. Department of Agriculture make LULC maps by doing land use survey. Alternatively, Landsat data can be used to extract LULC changes using visual interpretation technique which will be effective in terms of cost and data sparse environment. Few studies were conducted by using visual interpretation techniques (Sulong et al., 2002; Jusoff and Senthavy, 2003). None of the study is reported of visual interpretation for whole Kelantan, Malaysia. As the previous researches done to see the effects of LULC changes on sediment yield and runoff flows, there is need to analyse the effects of spatio-temporal LULC changes of upstream or high slope areas on downstream or gentle slope areas. None of the studies also reported for Kelantan in this regard.

As a preliminary study of flood analysis, a need of analysing spatio-temporal LULC changes by using publicly domain accessible data through an integrated approach of remote sensing and GIS of whole Kelantan, Peninsular Malaysia. The analysis will lead the spatio-temporal LULC changes to find out the effect of upstream LULC changes on downstream of the area. The result of this study will be helpful in identifying the effects of LULC changes on overland flow by using 2D hydrological modelling techniques.

2.2 Spatial estimation of average daily precipitation

Uncertainties, especially input parameters, in watershed hydrological modelling are great concern for researchers (Carpenter and Georgakakos, 2004). Precipitation is one of the most basic meteorological input parameter in hydrologic simulation to understand either flood risk or soil loss estimation at within a watershed (Johnson et al., 2016; Mikoš et al., 2006). In a complex topography, the spatial and temporal behaviour of precipitation are generally influenced by the variations in relief, easting, northing, slope and strong wind (Hwang et al., 2012). For accurate characterization of spatial precipitation, particularly in complex relief regions, dense rain gauges network are needed which is very difficult in terms of installation and costs (Mair and Fares, 2010). Various interpolation methods have been used by researchers to solve this problem but their accuracies vary in different climates. The choice of an interpolation method requires the understanding of the spatial variability of precipitation and the sources of uncertainty (Tao, 2009).

Several simple methods such as simple averaging, Thiessen polygons, isohyetal and Inverse Distance Weighting (IDW) have been used so far as traditional methods in spatial estimation of precipitation (Thiessen, 1911; Shepard, 1968; Tabios and Salas, 1985; McCuen, 1989). But these methods do not include any physical predictor variables. As an alternative, complex statistical methods such as Simple and Multiple linear regression (SLR and MLR) and locally weighted polynomial (LWP) are widely used models which can correlate precipitation with physical predictor variables (Rajagopalan and Lall, 1998; Goovaerts, 2000; Kurtzman et al., 2009; Hwang et al., 2012). Geostatistical methods such as kriging and co-kriging are other widely used methods for spatial distribution of precipitation. Some other methods having fewer advantages over traditional methods have been reported (Goovaerts, 2000; Drogue et

al., 2002; Buytaert et al., 2006). However, geostatistical methods are used generally for monthly and annual data (Diodato, 2005; Mair and Fares, 2010; Gong-Saholiariliva et al., 2016) because these methods are not easy to apply on daily estimation of precipitation in a complex topography (Ly et al., 2011; Castro et al., 2014). Furthermore, the accuracy of different methods varies from region to region (Hwang et al., 2012).

Interpolation methods for spatial distribution of precipitation is restricted as there is an uncertainty called discontinuity in daily precipitation which affects spatial distribution of precipitation in complex topography. Previous studies used regression models such as Precipitation-elevation Regression on Independent Slope Model (PRISM) and Auto-Search Orographic and Atmospheric Effects Detrended Kriging (ASOADEK) (Daly et al., 1994; Guan et al., 2005; Xie et al., 2007) by including orographic and meteorological predictor variables. Few studies have include wind speed as a predictor variables (Johansson and Chen, 2003; Allamano et al., 2009) but none of the studies considered spatial discontinues of precipitation.

Some of recent studies include discontinuity of precipitation (called phase estimation or occurrence/non-occurrence or wet/dry) and successfully estimated daily spatial precipitation by including different predictor variables (Seo, 1998; Hewitson and Crane, 2005; Hwang et al., 2012; Castro et al., 2014). Hewitson and Crane (2005) used conditional interpolation method for phase estimation as a function of the synoptic state in sub-tropical climate. Their method of estimation was based on the ability to reproduce the frequency of events, rather than the errors in the magnitude of the estimations as discussed by Castro et al. (2014). While Hwang et al. (2012) used daily logistic regressions to classify occurrence/non-occurrence based on monthly threshold and then applied four interpolation methods (IDW, MLR, LWP and

Climatological MLR) on wet days by including three predictor variables (northing, easting and elevation). Castro et al. (2014) also estimated phase by IDW based method and then used IDW and SLR methods on wet days by including elevation and slope as a predictor variable in the climate between Mediterranean and mildly humid. They classified slope orientation either on windward or on leeward side with respect to the prevailing wind direction which gives better results than IDW and SLR. Hwang et al. (2012) and Castro et al. (2014) both used elevation as the main predictor variable because of the importance of orographic barriers in uplifting air masses transported by wind which generate significant precipitation at high relief. However, maximum precipitation at highest point might not be necessary (Daly et al., 1994). Furthermore, the authors highlighted the necessity of multiple linear regression along with other predictor variables such as wind characteristics, relative humidity and distance from shoreline to enhance the results in precipitation estimation.

None of the studies related to discontinuity of precipitation have been reported in tropical climate. The tropical climate is important in this regard because of the dominancy of precipitation throughout the year.

2.3 Development of rainfall erosivity model

Prevention of soil loss from erosion due to the impact of rainfall and changing rainfall patterns is one of the most important global issues in soil conservation. These changes in precipitation are largely located in the tropics and hence are probably associated with convection (Tan et al., 2015). The increased precipitation causes detachments of the individual soil particles and their transportation along the slope to rivers and reservoirs. Rainfall erosivity is a predominant factor referring to the kinetic energy of raindrop's impact and the rate of associated runoff (Wischmeier and Smith,

1978). Therefore, it is essential to obtain an accurate estimate of rainfall erosivity in tropical climates for the assessment of soil erosion risk.

The Universal Soil Loss Equation (USLE) devised by Wischmeier and Smith (1978) and the Revised Universal Soil Loss Equation (RUSLE) proposed by Renard et al. (1997) for the United States are widely used models to estimate annual soil loss by both interrill and rill erosion. These include six factors such as rainfall erosivity, soil erodibility, slope steepness, slope length, cover-management, and support practice. These factors are dynamic in nature which results in heterogeneous spatial patterns of soil loss. However, RUSLE requires regional values to be developed for each factor based on local data and conditions if used outside the United States (Wischmeier, 1984).

The rainfall erosivity (R) factor is considered as the most important factor in estimation of soil loss due to its high temporal variability. The R factor was derived from more than 8000 plot years by Wischmeier (1984) and can be quantified by the product of total kinetic energy of rainfall (E) and its peak 30-minute intensity (I_{30}) which computes all individual erosive storm events. An individual rainfall event was defined as a period of rainfall with at least six preceding and six succeeding non-precipitation hours (Xie et al., 2016).

To compute RUSLE, high spatial and temporal (maximum 30 minutes) rainfall data series for the determination of the R factor is the required. Kinetic energy for the calculation of the R factor also varies for different climates. The kinetic energy can be calculated for any region by using very high temporal resolution data (1 min, 5 min) which is often difficult to obtain (Teh, 2011). Alternatively, kinetic energy and intensity relationship can be used which need 30 min rainfall data to calculate the

kinetic energy of an event. Salles et al. (2002) listed all the kinetic energy and intensity relationships developed for different locations which can be used in the absence of very high temporal resolution data for a particular location.

Apart from event based R factor calculation, other statistical models were also developed by researchers for different climates to calculate erosivity which use commonly available data such as, daily rainfall (Richardson et al., 1983; Yu and Rosewell, 1996b; Petkovšek and Mikoš, 2004; Angulo-Martínez and Beguería, 2009; Ali, 2015; Xie et al., 2016) and monthly rainfall (Renard and Freimund, 1994; Yu and Rosewell, 1996a; Ferro et al., 1999; de Santos Loureiro and de Azevedo Coutinho, 2001; Mikoš et al., 2006; Diodato and Bellocchi, 2007; Ochoa-Cueva et al., 2015). Xie et al. (2016) mentioned three aspects of the R factor that may be useful for soil erosion estimation: (i) average annual rainfall erosivity for predicting average annual soil loss, (ii) seasonal distribution curve of rainfall erosivity and (iii) event or daily rainfall erosivity. They also stressed upon the importance of event or daily rainfall erosivity in their related past studies and developed statistical models for the successful estimation of erosion index EI_{30} from the daily rainfall amounts. Due to the lack of long-term event based rainfall data, these statistical models are very useful and widely used to calculate daily erosivity. However, both event and daily rainfall amounts are not similar (Bullock et al., 1990) because daily rainfall amount includes only one event, multiple events, or only part of an event (Richardson et al., 1983; Xie et al., 2016).

Angulo-Martínez and Beguería (2009) estimated the R factor for the Mediterranean climate by using five daily models viz., the exponential model by weighted least squares (Richardson et al., 1983), the Yu and Rosewell model, the modified Yu and Rosewell model and three monthly models viz., precipitation intensity indices, the modified Fournier index and the F index (Ferro et al., 1999) in

which they found that the Yu and Rosewell model for daily and precipitation intensity indices for a monthly R factor gave the best results as compared to the other models. Xie et al. (2016) also found superiority of the Yu and Rosewell over the Richardson exponential model. All these models have some regional factors which vary for different climates and these must be determined accurately to develop an accurate rainfall erosivity model.

The tropical climate has high precipitation throughout the year. The orographic precipitation is also well-known and has been identified and studied across the world (Karnieli and Osborn, 1988; Goldreich, 1994; Michaud et al., 1995; Al-Ahmadi and Al-Ahmadi, 2013). Therefore, the regional factors values will definitely vary in high precipitation and elevation regions. An attempt was made by Yu et al. (2001) to estimate the R factor for Malaysia by using event base data for the Yu and Rosewell model but the disadvantages of this model is that the limited rainfall stations and less temporal data (two years only) were used which may not be accurate for the region (Yu and Rosewell, 1996b). Other studies also use event based data to calculate soil erosion by RUSLE in Malaysia (Shamshad et al., 2008; Leow et al., 2011; Kamaludin et al., 2013; Jahun et al., 2015; Vijit et al., 2017), while some estimate rainfall erosivity by including orographic effect such as for the Mediterranean climate (Diodato and Bellocchi, 2007) and the semi-arid climate (Nearing et al., 2015).

Previous researches focused on event based, daily and monthly precipitation data to calculate erosivity for climates other than tropical. Limited attempts were made to calculate regional factors for the tropical climate (such as Malaysia) models which are suitable for commonly available data such as daily precipitation.

2.4 Morphometric analysis

Morphometric analysis of drainage basin is a form measurement of stream and its evolution on the earth surface. Continuous but slow geomorphologic and topographic changes due to the fluvial denudation processes on the earth surface is understood by the morphometric analysis which is the most common and ideal technique in drainage basin analysis. These analyses are also important in hydrogeological investigation to analyse natural hazards such as drought and flooding which are directly linked with these changes and meteorological conditions. Stream order, stream number, stream length, basin area, basin parameter, basin length and basin relief are the initial morphometric parameters. These are useful for quantitative study in morphometric analysis.

Horton (1945), first pioneer in this field, was suggested the law of stream length. This law shows the relationship between number of stream segments in a successive stream orders and landforms (Horton, 1945). Law of basin area has been deduced by Horton (1945) and stated by Schumm (1956), according to which a plot between log of mean basin area and stream order gives a straight line. Horton's laws were later modified and developed by many geomorphologists (Schumm, 1956; Strahler, 1952; Strahler, 1964; Miller, 1953; Morisawa, 1959; Gregory and Walling, 1976; Keller and Pinter, 1996; Garde, 2006). These principles have been used by many workers for quantitative study of drainage basin as a tool for geomorphologic and topographic change analysis (Awasthi and Prakash, 1997; Stone and Clarke, 1996; Mesa, 2006; Manu and Anirudhan, 2008; Kjeldsen and Jones, 2010; Sukumar and Sukumar, 2013).

Morphometric analysis provides a quantitative description of drainage basin characteristics such as initial slope, heterogeneous rock hardness, geologic and geomorphic history of drainage system, structure control (Garde, 2006), watershed

characterization (Strahler, 1964) and hydrogeological investigation (Magesh et al., 2013). Bed rock, soil and rock structure are the main factors of drainage patterns which make inferences about structure, lithology and soil type. Rock structures generally controls higher order streams, while the behaviour of the lower order streams and their inter-relationships provide information about nature of rocks and soils (Pandey et al., 2004). In order to carry out morphometric analysis, geometry of a drainage basin and its stream channel has to be calculated by the measurement of linear aspects of the drainage network, aerial aspects of the drainage basin and relief (gradient) aspects of channel network and contributing ground slopes.

Geomorphologic and topographic changes of drainage basin through morphometric analysis have been used in various studies such as geomorphology and evolution of basin morphology (Sukumar and Sukumar, 2013; Singh and Singh, 2011), flood analysis (Angillieri, 2008; Ozdemir and Bird, 2009), terrain characterization (Nogami, 1995), sediment yield (Pandey et al., 2008) and watershed prioritization (Javed et al., 2011). Flood analysis by morphometric parameters is very helpful in identifying the flood prone areas. Identification and analysis of relationships between drainage basin characteristics, meteorological inputs, and flood hydrograph response are the basic method to relate morphology and flood (Patton and Baker, 1976).

Remote Sensing and GIS techniques are suitable for morphometric analysis because of its synoptic view of large areas and wide range of applications which yields valuable results by consuming less time and limited field checks. A very few studies were reported of morphometric analysis in Malaysia (Morgan, 1973). As the flood is common in Kelantan, it is need to divide the catchment into watersheds and morphometric analysis of each watershed need to be analysed to identify which part of the watershed has more flooding.

2.5 Soil erosion and soil probability zones

Anthropogenic activities such as deforestation, agriculture, industrialization and construction lead to soil erosion which can cause land degradation in watersheds as a result of high rainfall intensity and increased surface runoff, especially in the tropical climates. Soil erosion specifically influences soil quality and fertility (Gao et al., 2011; Khan et al., 2015), water quality and deposition of sediment on the river bed (Walsh et al., 2011), which causes reduction in river depth and hence results in channel overflow during high precipitation. Efforts in environmental protection and soil conservation have increased globally, especially, the requirement for ecologically maintainable improvement choices in watersheds with different purposes and the capacity to predict erosion and limit its natural impacts (Cunha et al., 2016).

Various erosion models have been developed that are useful for estimating, analysing and predicting soil erosion. The Revised Universal Soil Loss Equation (RUSLE), a revised version of USLE (Wischmeier and Smith, 1978b), is a widely used model to predict the long term average annual soil loss carried by runoff from particular field slopes in specified cropping and administration frameworks, and additionally from rangeland (Renard et al., 1997). It has been proven to be effective in estimating soil loss in different parts of the world (Rozos et al., 2013; Ganasri and Ramesh, 2016; Hao et al., 2017). USLE and RUSLE can predict erosion potential on a cell-by-cell basis (Shinde et al., 2010) but it does not estimate sediment yield (Renard et al., 1997).

Soil loss have been estimated in different parts of Malaysia using RUSLE such as for Penang Island (Shamshad et al., 2008), Pahang river basin (Kamaludin et al., 2013; Mir et al., 2015), Cameron Highland (Teh, 2011; Ab Ghani et al., 2013),

Kelantan river basin (Abdulkareem et al., 2017), Terengganu (Elsheikh et al., 2015) and iserodent maps of Peninsular Malaysia (Leow et al., 2011). The rainfall erosivity factor of RUSLE is the most important factor because of its rapid spatio-temporal distribution and effect of rainfall intensity on exposed soil. As it was discussed in section 2.3 that kinetic energy for the calculation of the R factor need pluviographic data, but in data sparse environment, kinetic energy and intensity relationship can be used. In these studies of Malaysia, some of them were used different kinetic energy equations. But none of them clearly mentioned the reason of using of these equations except Shamshad et al. (2008). Even the Guideline for Erosion and Sediment Control in Malaysia (DID, 2010) also did not mention the reason of using kinetic energy equation developed by Zainal (1992).

Sediment yield is the amount of eroded soil that is transported from the origin of the detached soil particles to a point in the watershed (Renard et al., 1997). Several empirical models of sediment yield have been developed but it is usually not available as a direct measurement (Ouyang and Bartholic, 1997). Sediment yield is estimated either by using runoff models (Dency and Bolten, 1976; Williams, and Berndt, 1977) or by using sediment delivery ratio (SDR) (Renfro, 1975; Vanoni, 1975; USDA SCS, 1979). Guideline for Erosion and Sediment Control in Malaysia (DID, 2010) mentioned Modified Universal Soil Loss Equation (MUSLE), developed by Williams (1975), to estimate sediment yield for which runoff volume and peak discharge data are required. Alternatively, the relationship between SDR and drainage area can be used to estimate sediment yield which is a most widely used method to calculate SDR (Zhang et al., 2015). Drainage area is inversely proportional to SDR. However, SDR computations have some uncertainties temporal discontinuity and spatial variability (Lee and Lee, 2010).

Several researches have been done in Malaysia to estimate sediment yield by using SDR. Farid (2009) mentioned various equations of SDR (USDA, 1972; Boyce, 1975; Vanoni, 1975; Renfro, 1975; Balamurugan, 1989) and also discuss its limitations and effecting factors. He used two SDR equations (Vanoni, 1975; USDA, 1972) to estimate sediment yield in Putrajaya, Malaysia. Other studies also used SDR equation developed by USDA (1972) for Cameron Highland (Ab Ghani et al., 2013) and sub-catchments of Pahang River basin (Kamaludin et al., 2013).

None of the study is reported for whole Kelantan regarding the estimation of soil loss and sediment yield. There is need of pixel based analysis of soil erosion for whole Kelantan using remote sensing and GIS which will help to understand effect of land use land cover changes on soil erosion.

2.6 Prioritization of watersheds

Hydrological modelling is becoming an effective tool due to the advancement of computational technology to understand the dynamic spatial and temporal behaviour of flooding and simplify complex system within a short processing period. However, hydrological modelling has some uncertainties such as input and model parameters which can affect the accuracy of results. Instead of considering large areas of hydrological modelling, smaller areas which have chances of flooding will be effective in considering these uncertainties which include less input data and short processing time and more accurate results. This can be achieved by prioritizing watersheds on the basis of flooding factors to conduct hydrological modelling.

A watershed is a topographically delineated area from which runoff flows from small streams, channels and drains into large rivers, lakes and oceans. The average area of a watershed is almost 500 km² as described in Watershed Atlas prepared by