GEOSPATIAL APPROACH FOR FLOOD VULNERABILITY ASSESSMENT IN KELANTAN RIVER BASIN, MALAYSIA

TAM TZE HUEY

UNIVERSITI TEKNOLOGI MALAYSIA

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DEDICATION

This thesis is dedicated to my beloved family, who have supported me throughout my academic life.

Also, this work is dedicated to my dear Ab Latif Ibrahim, who serve as my enlightenment teacher.

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ABSTRACT

Flood is the most destructive natural disaster in Malaysia, causing significant economic and human life losses. Recent flood management paid more attention to flood risk assessment to provide information on risk of flooding. It consists of three components i.e., flood hazard, flood exposure, and flood vulnerability, which can be supported directly and indirectly by remotely sensed data. The research aims to utilise a geospatial approach for flood vulnerability assessment in the Kelantan River Basin (KRB), Malaysia. For flood hazard modelling, the flood event in December 2014 over Kelantan has been simulated using the Rainfall-Runoff-Inundation (RRI) model. The model is supported by four different Satellite Rainfall Products (SRPs) (i.e., Integrated Multi-satellitE Retrievals-Late, -Early (IMERG-L, -E), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS) and Global Satellite Mapping of Precipitation (GSMaP)) and rain gauge data. The simulation results were compared to the observed discharge flow. For the flood exposure analysis, a framework to extract detailed element-at-risk information was developed by classifying detailed land use and land cover in heterogeneous urban areas of Kota Bharu using Very-High-Resolution (VHR) satellite imagery and Light Detection and Ranging (LiDAR) data. The Feature Selection (FS) algorithm was also adopted to achieve an efficient classification framework. References points extracted from existing land use was used to validate the classification results. Finally, a geospatial approach for flood vulnerability assessment of buildings has been developed, which combines outputs from flood hazard and flood exposure. The framework incorporates relevant building parameters derived from the VHR satellite image and LiDAR data, and flood hazard for a vulnerability analysis of building using Machine Learning (ML) approach. The geospatial approach-based vulnerability results were validated using in-situ flood damage data derived from questionnaire method. The results of flood inundation showed that the GSMaP has the best performance in simulating hourly runoff with the lowest relative bias (RB) and the highest Nash-Sutcliffe efficiency (NSE) of 4.9% and 0.79, respectively. The results of image classification showed that there was a significant difference between classification accuracies using two datasets (50 features and 107 features) in object-based approach. The overall accuracy increased to 93.7% from 79.2% using the Random Forest (RF) classifier. Nevertheless, the RF classifier have achieved significantly better classification results compared to other classifiers (k-NN and Support Vector Machine (SVM)). The extreme gradient boosting (xgbTree) FS method improved the classification accuracy from 93.7% to 94.1% using 26 features However, there is a statistically significant difference between the results produced by the Recursive Eliminate Feature (RFE) and Simulated Annealing (SA). The result of vulnerability showed that the geospatial approach achieved a good prediction result with an overall accuracy of 81.8%. In conclusion, the SRPs can be used to support spatially distributed flood hazard assessment in a scarcity rain gauge station area. High resolution remotely sensed data can be used to extract information of element-at-risk in highly heterogenous location in Malaysia, which allows ML method for flood vulnerability assessment.

ABSTRAK

Banjir adalah bencana alam yang paling merosakkan di Malaysia, menyebabkan kerugian ekonomi dan kehilangan nyawa manusia yang ketara. Pengurusan banjir baru-baru ini memberi lebih perhatian kepada penilaian risiko banjir untuk memberikan maklumat tentang risiko banjir. Ia terdiri daripada tiga komponen: komponen bahaya, komponen pendedahan dan komponen kerentanan. Data penderiaan jauh boleh, secara langsung dan tidak langsung, menyokong komponen bahaya dan pendedahan, dan komponen kerentanan, masing-masing. Kajian ini bertujuan untuk menggunakan pendekatan geospatial untuk penilaian kerentanan banjir di Lembangan Sungai Kelantan (KRB), Malaysia. Untuk pemodelan bahaya banjir, kejadian hujan melampau Disember 2014 di Kelantan telah disimulasikan menggunakan model RRI dengan empat Produk Hujan Satelit (SRP) berbeza (Pendapatan Berbilang Satelit Bersepadu-Lewat, -Awal (IMERG-L, -E); Anggaran Kerpasan daripada Maklumat Penderia Jauh menggunakan Rangkaian Neural Tiruan-Sistem Klasifikasi Awan (PERSIANN-CCS), Global Satelit Permetaan Kerpasan (GSMaP) dan data tolok hujan. Hasil simulasi telah dibandingkan dengan aliran luahan dicerap. Untuk analisis pendedahan banjir, rangka kerja untuk mengklasifikasikan penggunaan tanah terperinci dan pemetaan tutupan tanah di kawasan bandar heterogen di Kota Bharu menggunakan Resolusi Sangat Tinggi (VHR) imej satelit dan data pengesanan dan julat cahaya (LiDAR) untuk pengenalpastian elemen banjir yang berisiko telah dicadangkan. Sehubungan itu, algoritma Pemilihan Ciri (FS) telah diterima pakai untuk mencapai rangka kerja pengelasan yang cekap. Titik rujukan yang diekstrak daripada penggunaan tanah sedia ada telah digunakan untuk mengesahkan keputusan pengelasan. Akhirnya, pendekatan geospatial untuk penilaian kerentanan banjir bangunan telah dibangunkan, yang menggabungkan output daripada bahaya banjir dan pendedahan banjir. Rangka kerja ini menggabungkan parameter bangunan berkaitan yang diperoleh daripada imej satelit VHR dan data LiDAR, dan bahaya banjir untuk analisis kerentanan bangunan menggunakan pendekatan Pembelajaran Mesin (ML). Keputusan kerentanan berasaskan pendekatan geospatial telah disahkan menggunakan data kerosakan banjir in-situ yang diperoleh daripada kaedah soal selidik. Keputusan bahaya menunjukkan bahawa GSMaP mempunyai prestasi terbaik dalam mensimulasikan luahan setiap jam dengan bias relatif terendah (RB) dan kecekapan *Nash-Sutcliffe* (NSE) tertinggi masing-masing sebanyak 4.9% dan 0.79. Keputusan menunjukkan terdapat perbezaan yang signifikan secara statistik antara klasifikasi tentang ketepatan menggunakan dua set data (50 ciri berbanding 107 ciri) dalam pendekatan berasaskan objek. Ketepatan keseluruhan meningkat kepada 93.7% daripada 79.2% menggunakan pengelas RF. Namun begitu, pengelas RF telah mencapai keputusan pengelasan yang jauh lebih baik berbanding dengan pengelas lain (*k*-NN dan SVM). Walaupun ketepatan klasifikasi telah bertambah baik, pengelasan telah mengambil masa yang lebih lama. Peningkatan kecerunan ekstrim (XgbTree) meningkatkan ketepatan kepada 94.1% daripada 93.7% menggunakan 26 ciri, manakala masa pemprosesan dikurangkan kepada 56s daripada 634s. Walau bagaimanapun, terdapat perbezaan yang signifikan secara statistik antara keputusan yang dihasilkan oleh Ciri Penyingkiran Rekursif (RFE) dan Penyepuhlindapan Simulasi (SA). Kedua-dua kaedah telah dilatih oleh algoritma pembelajaran, dengan kata lain, lebih berhati-hati harus diambil untuk menentukan algoritma pembelajaran yang disesuaikan dengan pembalut berasaskan RFE dan SA. Keputusan menunjukkan bahawa rangka kerja berasaskan penderiaan jauh mencapai keputusan ramalan yang baik dengan ketepatan keseluruhan 0.81 dengan menggunakan pendigitalan poligon dan ciri geometri. Kesimpulannya, SRP boleh digunakan untuk menyokong penilaian bahaya banjir yang diedarkan secara ruang di kawasan stesen tolok hujan kekurangan. Data deria jarak jauh resolusi tinggi boleh digunakan untuk mengekstrak maklumat elemen berisiko di lokasi yang sangat heterogen di Malaysia, yang membolehkan kaedah ML untuk penilaian kerentanan banjir.

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LIST OF ABBREVIATIONS

1D	-	one dimensional
1D2D	-	integrated one-dimensional and two-dimensional
2D	-	two dimensional
ACC	-	Flow accumulation
AMS	-	annual maximum discharge
ASCII	-	U.S. Standard Code for Information Interchange
ASEAN	-	Association of Southeast Asian Nations
AWGWRM	-	ASEAN Working Group on Water Resource Management
bil	-	band interleaved by line
CART	-	classification and regression of trees
CC/*r*	-	correlation coefficient
CCA	-	Canonical Correlation Analysis
CCI	-	Coping Capacity Index
CFS	-	Correlation-Based Feature Selection
CLC	-	CORINE Land Cover
CREST	-	Core Research for Evolutional Science and Technology
CREST	-	Coupled Routing and Excess Storage
CS	-	Chi-Squared
DEM	-	Digital Elevation Model
DID	-	Department of Irrigation and Drainage
DIR	-	Drainage directions
DRR	-	Disaster Risk Reduction
DSM	-	Digital Surface Model
DT	-	Decision Tree
EAD	-	expected annual damage
EC	-	European Commission
EEA	-	European Environment Agency
EM-DAT	-	Emergency Events Database

ENVI	-	Environment for Visualizing Images
EO	-	Earth observation
EO-1	-	Earth Observation One
ESA	-	European Space Agency
ESP	-	Estimation of Scale Parameter
EU	-	European Union
FAO	-	Food and Agriculture Organisation
FE	-	feature extraction
FNEA	-	Fractal Net Evolution Approach
FRM	-	Flood Risk Management
FS	-	Feature Selection
FSO	-	Feature Space Optimisation
FVI	-	Flood Vulnerability Index
GA	-	Genetic Algorithm
GEO	-	geostationary
GIS	-	Geographical Information System
GLCM	-	grey-level co-occurrence matrix
GLCNMO	-	Global Land Cover by National Mapping Organisations
GPM	-	Global Precipitation Mission
GR	-	Gain Ratio
GSMaP_Gauge	-	GSMaP standard_gauge
GSMaP_Gauge_NRT)	-	GSMaP realtime_gauge
GSMaP_Gauge_RNL	-	GSMaP reanalysis_gague
GSMaP_MVK	-	GSMaP standard
GSMaP_NOW	-	GSMaP now
GSMaP_NRT	-	GSMaP realtime
GSMaP_RNC	-	GSMaP riken_nowcast
GSMaP_RNL	-	GSMaP reanalysis
GSMaP-NRT	-	Global Satellite Mapping of Precipitation-Near-Real-Time
GWP	-	Global Water Partnership
HEC	-	Hydrologic Engineering Center

HWSD	-	Harmonized World Soil Database
HydroSHEDS	-	Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales
ICAMS	-	Image Characterization and Modeling System
IFM	-	Integrated Flood Management
IG	-	Information Gain
IMERG	-	Integrated Multisatellite Retrievals for GPM
IMERG-E	-	Early Run
IMERG-F	-	Final Run
IOs	-	image objects
IR	-	infrared
ISCGM	-	International Steering Committee for Global Mapping
ISODATA	-	Iterative Self-Organizing Data Analysis Techniques
IWRM	-	Integrated Water Resources Management
JICA	-	Japan International Cooperation Agency
JST	-	Japan Science and Technology Agency
k-NN	-	*k*-Nearest Neighbor
KRB	-	Kelantan River Basin
LCCS	-	Land Cover Classification System
LDA	-	Linear Discriminant Analysis
LEO	-	low-earth orbit
LiDAR	-	Light Detection and Ranging
LULC	-	land use land cover
LV	-	local variance
MacGDI	-	National Geospatial Centre
maxdepth	-	Maximum depth
MERG-L	-	Late Run
minsplit	-	Minimum number of observations in a node
ML	-	Machine Learning
ml	-	Maximum Likelihood
MODIS	-	Moderate Resolution Imaging Spectroradiometer
MSAN	-	National Water Resources Council

MSMA	-	Storm Water Management Manual
mtry	-	Number of variables
MW	-	Mann-Whitney
NB	-	Naïve Bayes
nDSM	-	normalized Digital Surface Model
NetCDF	-	Network Common Data Form
NLCD	-	National Land Cover Database
NOAA	-	National Oceanic and Atmospheric Administration
NRT	-	Near-Real-Time
NSCE	-	Nash-Sutcliffe coefficient efficiency
NSE	-	Nash-Sutcliffe Efficiency
ntree	-	Number of trees
OA	-	overall accuracy
OBIA	-	object-based image analysis
OOB	-	out-of-bag
PBIA	-	pixel-based image analysis
PCA	-	Principle Component Analysis
PERSIANN-CCS	-	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System
PMM	-	Precipitation Measuring Mission
PMW	-	passive microwave sensors
PR	-	active microwave sensors
R^2	-	coefficient of determination
RB	-	relative bias
RF	-	Random Forest
RFE	-	Recursive Feature Elimination
ROC-LV	-	rates of change of LV
RRI	-	Rainfall-Runoff-Inundation
RVS	-	Rapid Visual Screening
SA	-	Simulated Annealing
SAR	-	Synthetic Aperture Radar
SCS-CN	-	Soil Conservation Service – Curve Number

SFS	-	Sequential Forward Selection
SFVI	-	social flood vulnerability index
SOFM	-	self-organizing features map
SoVI	-	social vulnerability index
SRPs	-	Satellite rainfall products
SRTM	-	Shuttle Radar Topography Mission
SSI	-	social susceptibility index
SVM	-	Support Vector Machine
SVM_L	-	Support Vector Machine with the linear kernel
SVM_{RBF}	-	Support Vector Machine with radial basis function kernel
SVM-RFE	-	Support Vector Machine – Recursive Feature Elimination
SWAT	-	Soil & Water Assessment
tiff	-	Tagged Image File Format
TRMM	-	Tropical Rainfall Measuring Mission
USGS	-	States Geological Survey
UTM	-	Universiti Teknologi Malaysia
VHR	-	very-high-resolution
WFIUH	-	Width Function Instantaneous Unit Hydrograph
WT	-	Watershed Transformation
xgbTree	-	eXtreme Gradient Boosting
RSO	-	Rectified Skew Orthomorphic

LIST OF SYMBOLS

h	-	height of water from the local surface
q_x	-	width discharges in *x* direction
qy	-	width discharges in *y* direction
u	-	flow velocities in *x* direction
v	-	flow velocities in y direction
r	-	rainfall intensity
f	-	infiltration rate
H	-	height of water from the datum
ρ_w	-	density of water
g	-	gravitational acceleration
τ_x	-	shear stresses in *x* direction
τ_y	-	shear stresses in y direction
n	-	Manning's roughness parameter
sgn	-	signum function
$q_x^{i,j}$	-	*x* direction discharges from a grid cell at (i,j)
$qy^{i,j}$	-	*y* direction discharges from a grid cell at (i,j)
k_a	-	lateral saturated hydraulic conductivity
da	-	soil depth times the effect porosity
k_m	-	unsaturated zone
k_v	-	vertical saturated hydraulic conductivity
ϕ	-	soil porosity
θ_i	-	initial water volume content
S_f	-	suction at the vertical wetting front
F	-	cumulative infiltration depth
f	-	infiltration loss
C	-	regularization parameter / penalty parameter
γ	-	kernel width / gamma parameter
d	-	degree of polynomial kernel
D	-	depth of river
W	-	width of river

A	-	Area basin

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Every year, floods cause massive damage throughout the world. As a result, many areas, particularly low-lying regions, are at severe risk of flooding. The effects of global warming will exacerbate the flooding in these areas as sea levels rise (Le, Nguyen, Wolanski et al., 2007; Mousavi, Irish, Frey et al., 2011). However, floods also have beneficial effects, whereby fine sediments and nutrients floating along with the floodwater can fertilise floodplains and aquatic inhabitants (Hofer and Messerli, 1997; Bonyongo, Mubyana, Totolo et al., 2002). Such benefits of flooding are important to regions that depend heavily on agriculture and fisheries, such as the Mekong delta and the Ganges–Brahmaputra delta. Nevertheless, the negative consequences of floods are still immense. Flooding was the most common form of natural disasters (47%) between 1995 and 2015, affecting 2.3 billion people, resulting in financial losses worth USD 662 billion (UNISDR, 2015). Approximately 800 million people live in flood-prone areas, of whom 70 million encounter annual flooding (UNISDR, 2011). The effects of urbanisation and climate change are the key factors that could raise the risk of flooding (Kundzewicz, Kanae, Seneviratne et al., 2013; Arnell and Gosling, 2016), making 2 billion people vulnerable to annual flooding by 2050 (UHU, 2004).

Developed areas are extremely complicated environments that contain complex components in terms of their social structure, built environment and natural environment. As a consequence, flood damage affects multidimensional components. In general, flood damage has been categorised into direct or indirect damage types, while it can be further defined as tangible or intangible damage (Chan, 2015b; Jonkman, Bockarjova, Kok et al., 2008; Messner and Meyer, 2006). Direct damage is caused by losses due to direct interaction between the floodwaters and the human body, physical structures or physical objects and their contents; indirect damage refers losses that are arise from flood occurrence without interaction with the floodwater. For instance, this could be a loss of production among businesses that are outside the affected area or a loss of trust in the relevant authorities. Tangible losses are reflected in monetary value, whereas the intangible losses are not measured in such terms, they include anxiety and nervousness.

The goal of flood management is to reduce flood damage and achieve sustainable development (Chan and Parker, 1996). Conventional flood management, which focuses pivotally on managing flood hazards (Merz, Kreibich, Schwarze et al., 2010), has concentrated on controlling or minimising the flood hazard, such as by decreasing the frequency of such events and the severity of inundation. However, past experiences have demonstrated that absolute protection or structural measures (i.e., river enhancement, and the construction of dykes, levees and dams) are unsuccessful against recurrent floods (Chan, 1997a; Kundzewicz and Takeuchi, 1999). In addition, a dam break will aggravate the flood conditions in downstream areas (Fread, 1993). On the other hand, non-structural measures (e.g., land use planning, flood forecasting, insurances and flood mapping) are an indispensable tools for providing useful information to decision makers or engineers so they can implement effective structural measures to cope with the floods (Chan, 1997a; Simonovic, 2002; Zakaria, Zin, Mohamad et al., 2017).

Flood Risk Management (FRM), a modern concept in the flood management framework, incorporates structural and non-structural measures. FRM is a synthesis of two elements, flood risk reduction and flood risk assessment (Schanze, 2006). The aims of flood risk assessment are to provide information on the risk of flooding and identify areas of unacceptably high risk. The flood risk reduction approach focuses on identifying effective measures based on a risk assessment output and reducing the risk of flooding to an acceptable level. In Malaysia, the Department of Irrigation and Drainage (DID) has implemented the Flood Risk Management concept for flood control (Chan, 2015b). Understanding flood risk is the priority process established in the Flood Directive (2007/60/EC) and the Sendai Framework for Disaster Risk Reduction 2015-2030. A comprehensive understanding of flood risk enables more efficient and effective flood management in terms of reducing flood damage to an acceptable level. Flood risk comprises three components: hazard, exposure, and vulnerability. Flood hazard is defined as the probability of an extreme event occurring in a given area during a specific timeframe. An example of a flood hazard is river discharge and water levels that have corresponding exceedance probability. Flood exposure/elements-at-risk comprises any environments, assets, and people at risk of flooding. Flood vulnerability refers to the degree to which those exposed elements are susceptible to damage. Flood risk is defined as the likelihood that floods of a particular intensity and loss (monetary damage) will occur in a specific area within a given period (Merz, Thieken and Gocht, 2007).

Earth observation (EO) satellites play a key role in Disaster Risk Reduction (DRR) by providing information on the various risk management processes, including preparedness, the emergency response, mitigation, and recovery (Tralli, Blom, Zlotnicki et al., 2005; Gillespie, Chu, Frankenberg et al., 2007; CEOS, 2003; Deichmann, Ehrlich, Small et al., 2011; Voigt, Giulio-Tonolo, Lyons et al., 2016; Denis, de Boissezon, Hosford et al., 2016). The use of satellite technology in natural disasters management is rising, especially during the response stage. Between 2006 and 2007, satellite use increased dramatically due to technological advancements such as internal mechanism enhancements and virtual online globes, which increased the awareness and adoption of geographical data (Voigt et al., 2016). The key reasons for this are the disaster community's awareness and appreciation of the use of geospatial data (Voigt et al., 2016), as well as the EO satellites' capable to deliver timely and geospatial information on areas affected by an event (Denis et al., 2016). Using EO satellites as a form of disaster support has various advantages: satellite are not vulnerable the disaster itself, satellite images are consistently collected on multiple scales, remotely sensed hazardous areas can be incorporated all disaster management phases, and the data is free (CEOS, 2015).

In the context of flood risk components, remote sensing data can contribute directly to the hazard and exposure components (CEOS, 2015; Deichmann et al., 2011; Taubenböck, Wurm, Netzband et al., 2011), and indirectly to the vulnerability component (Mueller, Segl, Heiden et al., 2006; Panagiota, Erwan, Philippe et al., 2012a). For example, satellite imagery has been used extensively in flood modelling to parameterise hydrological or hydraulic models, as well as delineate flood maps to validate flood models (Bates, Horritt, Smith et al., 1997; Bates, 2004; Bates and De Roo, 2000). Furthermore, the provision of rainfall data can be an alternative source in areas where there is no rain gauge, while the generation of a Digital Elevation Model (DEM) uses stereo satellite imagery, as does flooded area delineation. In mapping flood exposure, analysing the earth observation data is an important method for distinguishing built-up areas, buildings and their characteristics (Ehrlich, Kemper, Blaes et al., 2013; Deichmann et al., 2011), which serve as key inputs with which the flood vulnerability assessment estimates vulnerability level of a building in a flood hazard area. The current study provides an operational context for the use of remote sensing data to promote the reduction of flood risk in Malaysia.

1.2 Problem Statement

The development of an official flood vulnerability map in Malaysia continues to be relatively lacking compared to flood hazard mapping (Zakaria et al., 2017). Numerous studies on flood vulnerability assessment in Malaysia have been conducted (Ho, 2009; Tam, Ibrahim, Rahman et al., 2014; Elsheikh, Ouerghi and Elhag, 2015; Romali, 2018; Mojaddadi, Pradhan, Nampak et al., 2017; Udin and Malek, 2018b). However, none of these have focused on assessing micro-scale flood building vulnerability or used the remote sensing approach to facilitate micro-scale flood building vulnerability assessment. The term "micro-scale" refers to a study in which the unit of analysis is a single object or building (Gerl, Kreibich, Franco et al., 2016; Jongman, Kreibich, Apel et al., 2012a). Flood hazard and exposure (elements-at-risk) are the two components that must exist before conducting a micro-scale flood building vulnerability assessment as vulnerability does not apply if the building is located outside a flood hazard area.

The scarcity of rain gauge stations in basins is a major issue for the flood hazard component (Croke, Islam, Ghosh et al., 2011; Long, Zhang and Ma, 2016; Li, Yang and Hong, 2013; Dile and Srinivasan, 2014) because these stations represent the most important input variables in hydrological modelling (Croke et al., 2011). Malaysia faces this problem (Osman and Abustan, 2011; Patrick, Mah, Putuhena et al., 2017). Therefore, due to their high spatial-temporal characteristics and broad coverage, satellite rainfall products (SRPs) have become an alternative source of rainfall data with which to characterise rainfall patterns in data-sparse conditions (Stisen and Sandholt, 2010; Bui, Ishidaira and Shaowei, 2019). The reliability of SRPs must be examined before their use for hydrological applications. As such, studies have been conducted in Malaysia to assess SRPs (Semire, Mohd-Mokhtar, Ismail et al., 2012; Tan, Ibrahim, Duan et al., 2015; Mohd Zad, Zulkafli and Muharram, 2018; Tan and Santo, 2018b; Varikoden, Samah and Babu, 2010; Tan, Gassman and Cracknell, 2017). These studies did not focus on flood hazard modelling nor investigate the performance of near-real-time products (temporal resolution up to 30 minutes to one hour), such as Global Satellite Mapping of Precipitation-Near-Real-Time (GSMaP-NRT) and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS). These have not yet been evaluated in Malaysia, particularly in characterising an extreme rainfall event. Hence, this study attempted to examine how these products performed in characterising extreme rainfall-induced flooding events.

The results of the detailed land use/land cover classification used Very-High-Resolution (VHR) satellite imagery and LiDAR data, and the findings were overlaid on flood inundation maps to identify flooded buildings as elements-at-risk. The highly varied building rooftops colours increased the variation of the intra- and inter-class spectral responses caused by renovation or degradation, consequently posing a considerable challenge for image classification. In Malaysia, several studies have focused on using Very-High-Resolution (VHR) satellite imagery and LiDAR data to classify detailed land use/land cover (Rizeei, Pradhan and Saharkhiz, 2018; Ziaei, Pradhan and Mansor, 2014; Su, Li, Chen et al., 2008) as well as conducted intra-urban mapping (Gibril, Shafri and Hamedianfar, 2017; Hamedianfar and Shafri, 2015). Most of these studies utilised the standard image features (i.e., the grey level co-occurrence matrix, indices, spectral bands, and topography). Hypothetically, these features are inadequate for differentiating the building types. To address this issue, more spatial features were considered in the classification process used in this study.

Using large image features can lead to model overfitting due to redundant and insignificant information, which creates a complex model that eventually requires a longer computation time to complete a classification task (Georganos, Grippa, Vanhuysse et al., 2017a). Feature Selection (FS) is one method that has been used to address these issues, and it value has been proven in previous studies (Yu, Gong, Clinton et al., 2006; Laliberte, Browning and Rango, 2012; Zhou, Zhang, Wang et al., 2018; Cánovas-García and Alonso-Sarría, 2015). However, these researchers did not thoroughly evaluate the wrapper method to select a subset of features by training various machine learning algorithms on them. Hence, the present study attempted to compare the performance of two wrapper methods (Recursive Elimination Feature and Simulated Annealing) used to wrap different machine learning algorithms and select a group of features. Hence, this study attempted to investigate a feature selection approach to improve the operational framework of detailed land use/land cover classification.

Flood vulnerability assessment has widely been conducted in Malaysia (Mojaddadi et al., 2017; Ibrahim and Asmawi, 2018; Roslee, Tongkul, Mariappan et al., 2018; Wahab and Muhamad Ludin, 2018; Lawal, Matori, Yusof et al., 2014a; Matori, Lawal, Yusof et al., 2014b). However, none of these studies focused on micro-scale flood vulnerability assessment, which had been reported by de Ruiter, Ward, Daniell et al. (2017) when conducting a comprehensive review to compare flood and earthquake vulnerability assessments. Furthermore, the traditional method of determining the vulnerability level of a building is time-consuming and labour-intensive, particularly for large areas (Anbazhagan, Giridhar, Ganesha Raj et al., 2010; Panagiota et al., 2012a). Hence, several studies have demonstrated that Very-High-Resolution (VHR) remote sensing data can provide the building parameters be used to determine flood vulnerability assessment (Taubenböck, Post, Roth et al., 2008; Mueller et al., 2006; Mück, Taubenböck, Post et al., 2013). Nevertheless, this research is still at an early stages (Geiß and Taubenböck, 2013). To date, no such study has been conducted in Malaysia, especially on a micro-scale. Hence, this study attempted to provide a geospatial approach to flood vulnerability assessment by considering flood hazards. Table 1.1 summarises of the research problem and gaps, as well as the contribution of this study.

Table 1.1 Summarises of issues, gaps, and contributions of this research.

No.	Issues	Gaps	Contributions
1.	• The number of rain gauge stations in the basin to characterise rainfall events, which is an important input to hydrological modelling for flood simulation, is inadequate for hazard modelling.	➢ Different types of satellite rainfall products (SRPs) have been used to address this issue but there is no local study using near-real-time SRPs to characterise extreme rainfall events	❖ Contribute to the improvement of satellite retrieval algorithms that used to characterise extreme rainfall event-induced flooding
2.	• Land use is widely used to provide information on elements-at-risk. The advent of VHR satellite imagery enables detailed land use and land cover classification, but the condition of rooftops has changed over time due to deterioration and restoration. As a result, using ordinary image features to characterise building types is relatively difficult task. • Using large image features lead to overfitting of classification, classification model become more complex, and requiring longer computational times.	➢ Numerous classifications of detailed land use and land cover studies have been conducted in Malaysia but none of these studies attempt to address the issue of heterogenous urban areas, particularly heterogenous rooftop of a building. ➢ Various feature selection methods (i.e., filter, wrapper, and embedded) have been applied to object-based classification but few studies focused on examine the advantages of wrapper approaches trained by different machine learning algorithms.	❖ Contribute to the improvement of an operational framework for detailed land use and land cover classification for a highly heterogenous rooftop of building types in an urban area
3.	• Conventional method based on field measurement to obtain building vulnerability is time consuming, tedious and labour-intensive, especially for large-scale area	➢ Flood vulnerability assessment have been conducted in Malaysia but most of these studies less focus on micro-scale and none of the studies using remote sensing technology to derive building parameters to characterise building vulnerability	❖ Contribute to the enhancement of the framework for assessing building flood vulnerability using a geospatial approach. Unlike previous studies, this framework took hazard intensity into account

1.3 Research Aim and Objectives

The aim of the current study is to utilise a geospatial approach for flood vulnerability assessment in the Kelantan River Basin (KRB), Malaysia. The specific objectives are outlined below followed by the research questions and hypotheses:

(a) To improve flood hazard modelling in a basin that lacks rain gauges by employing Near-Real-Time (NRT) Satellite Rainfall Products (SRPs) in the Rainfall-Runoff-Inundation (RRI) model to undertake flood inundation mapping of the 2014 event in Kota Bharu.

(b) To improve an operational framework of detailed land use/land cover classification for the highly heterogeneous rooftops of the buildings in Kota Bharu using Very-High-Resolution (VHR) satellite imagery and LiDAR data, before overlaying this with the flood inundation map to identify flooded buildings as elements-at-risk.

(c) To improve a micro-scale flood vulnerability assessment in Kota Bharu based on flooded buildings and using a geospatial approach.

1.3.1 Research Questions

Two questions address the first objective:

i. How reliable is the RRI model in predicting streamflow and flood inundation map for the 2014 Kelantan flood event?

ii. How reliable are the Near-Real-Time (NRT) satellite rainfall products for capturing extreme rainfall events for hydrological modelling and flood simulation?

Four questions address the second objective:

i. Which classification methods (pixel-based or object-based) produce better classification accuracy?

ii. Would the advanced classifiers (random forest, the support vector machine and decision trees) yield better classification accuracy than the traditional classifier (*k*-nearest neighbour)?

iii. Is it adequate to employ detailed land use/land cover classification for highly heterogeneous rooftops of buildings using common image features?

iv. Which feature selection algorithms produce efficient workflow in terms of classification accuracy and computation time?

Two questions address the third objective:

i. How reliable is the geospatial approach for assessing building flood vulnerability?

ii. Which remote sensing data-derived building parameters are the most important for determining the building flood vulnerability assessment?

1.3.2 Research Hypotheses

One hypothesis was tested to address the first objective:

i. NRT satellite rainfall products with high spatial and temporal resolution are more likely to capture extreme rainfall events for hydrological modelling and flood simulation than rain gauges are.

Four hypotheses were tested to address the second objective:

i. Hypothesis: An object-based classification is more likely to improve the overall accuracy than a pixel-based classification.

ii. Hypothesis: The advanced classifiers are more likely to outperform the traditional classifier.

iii. Hypothesis: The addition of spatial features to the classification process is more likely to increase the classification accuracy.

iv. Hypothesis: The use of feature selection in the classification process is more likely to maintain the classification accuracy and reduce the classification computational time.

One hypothesis was tested to address the third objective:

i. The geospatial approach is likely to be useful in determining the building flood vulnerability assessment.

1.4 Significance of the Study

This study provides three outputs. The first is a framework for a large-scale assessment of flood hazards. The first breakthrough was the evaluation of the applicability of hourly satellite rainfall products using the Rainfall-Runoff-Inundation (RRI) model to facilitate a large-scale flood hazard assessment in Malaysia. The outcomes of this research could provide useful guidelines for the related agencies (e.g., the Department of Irrigation Drainage, the Department of Mineral and Geoscience, the Malaysian National Hydraulic Research Institute, National Disaster Management Agency) to use in selecting suitable SRPs, especially for flood modelling or runoff estimation in cases where rain gauge stations are extremely scarce or unavailable during the flood season.

The second output is the technical framework for extracting elements-at-risk from the high-resolution remotely sensed and LiDAR data. The novelty of the second output focuses on improving the existing method for elements-at-risk extraction over a highly heterogeneous area by combining feature selection methods and machine learning classifiers. This framework acts as an exposure aspect to address what the exposed elements are. This technical framework can be a useful guideline for those agencies (e.g., the Department of Irrigation Drainage, the Department of Mineral and Geoscience, the Construction Industry Development Board, National Disaster Management Agency) could use to extract related elements-at-risk for specific hazard types, such as flooding.

The third output is the remote sensing-based approach for micro-scale flood building vulnerability assessment. The innovative third output focuses on improving the remote sensing-based approach for assessing flood building vulnerability by considering the hazard component using the machine learning method. In a developing country such as Malaysia, which is still in the early stages of establishing a flood risk management policy, this study can be a starting point for encouraging the implementation of flood vulnerability assessment. This approach of micro-scale decision making in flood vulnerability assessment can form a guideline for different agencies, such as the Department of Irrigation Drainage, the Department of Mineral and Geoscience, the Construction Industry Development Board, and the National Disaster Management Agency.

1.5 Study Area

Kelantan is situated in the north of Peninsular Malaysia. It is surrounded by Terengganu (east), Pahang (south), Perak (west), and Thailand (north). Kelantan has 10 districts, the main one being Kota Bharu, the capital city of Kelantan state.

Kelantan has a population of approximately 1.9 million (DOS, 2019), with a population density of 124.8 persons per square kilometre, as shown in Table 1.2. However, Kota Bharu has a larger population density of 1,481.1 persons/km^2. Its district size, economic opportunities and topography are the primary determinants of the population distribution in Kelantan (DID, 2011). As the state capacity city, Kota Bharu has the largest commercial centre and state government office. However, its geographical characteristics and unplanned urbanisation make Kota Bharu vulnerable to floods every year, which are mainly caused by the northeast monsoon.

Correspondingly, the study area included two parts: the Kelantan River Basin for the flood hazard modelling, and Kota Bharu town for the detailed land use/land cover classification as well as the extraction of elements-at-risk.

Table 1.2 The population of Kelantan by districts.

District	**Land (km^2)**	**Population (*000)**	**Population Density (Persons/km^2)**
Bachok	280	162.5	580.4
Kota Bharu	403	596.9	1,481.1
Machang	530	113.6	214.3
Pasir Mas	572	231.8	405.2
Pasir Puteh	425	143.1	336.7
Tanah Merah	884	149.2	168.8
Tumpat	179	187.3	1,046.4
Gua Musang	8,213	113.9	13.9
Kuala Krai	2,287	135.2	59.1
Jeli	1,325	50.8	38.3
Total	15,099	1,884.3	124.8

1.5.1 The Kelantan River Basin

The state of Kelantan has a total area of 15,099 km^2, of which the Kelantan, Kemasin, Semarak, and Golok Rivers are the four major river basins. The Kelantan River Basin covers approximately 85% of the state area, while the other three basins cover only 15%. All the rivers' basins flow in a northerly direction, eventually into the South China Sea.

The Kelantan River Basin covers a total area of approximately 12,981 km^2 and consists of four main tributaries, namely the Nenggiri, Galas, Lebir, and Pergau Rivers (Figure 1.1). The Galas River is formed by a junction between the Nenggiri River and the Pergau River. The former originates in the south-west of the central mountain range (Main Range). The latter comes from the Tahan Mountains. About 95% of the catchment area is steep, mountainous and rises to a height of 2,183 m, while the remaining area is flat. The land use/land cover in the Kelantan River Basin are dominated by tropical forests (71.5%), followed by rubber (11.1%), oil palm (6.3%), urban (1.2%), paddy (1.8%), and other agriculture (6.8%). The Kelantan River Basin is characterised by a tropical monsoon climate, with an average annual rainfall of ≥ 2500 mm, most of which falls from November to January. The average annual temperature of the basin is about 27.5 °C (Tan et al., 2017). The Kelantan River Basin is regularly affected by monsoon flooding events during the northeast monsoon season.

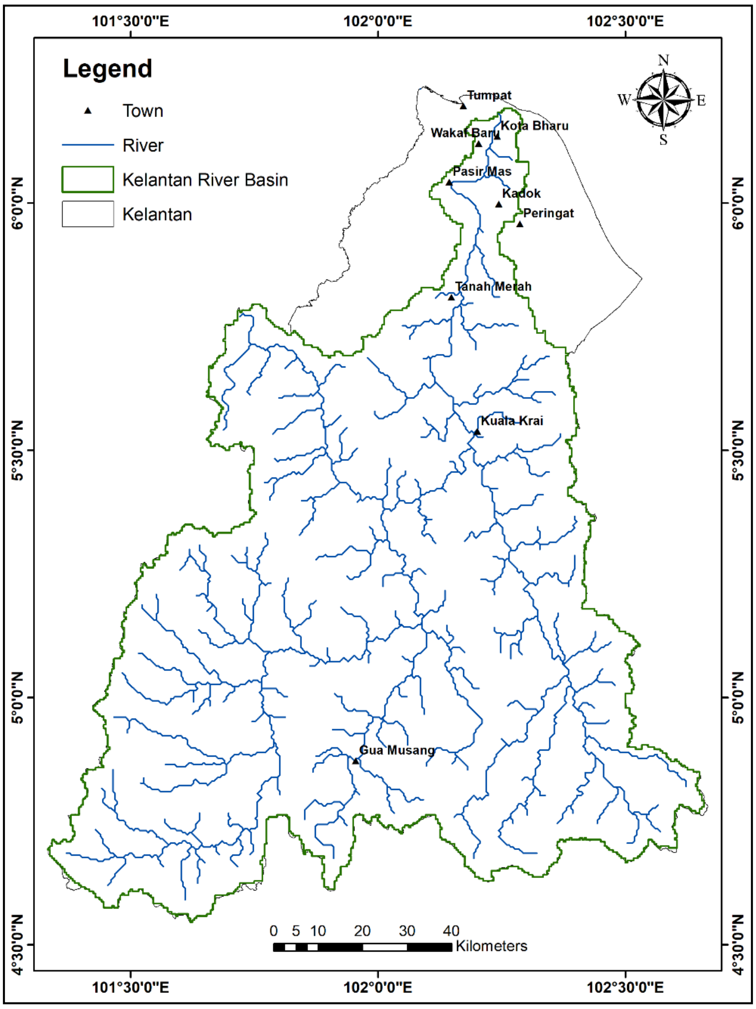

Figure 1.1 The Kelantan River Basin.

1.5.2 Kota Bharu Town

The growth of Kota Bharu began around the new palace, the Istana Balai Besar, which was built in 1845 by Sultan Muhammad II. Since then, Kota Bharu has been the centre of administrative and economic activity for the state of Kelantan and has acted as the capital city. Kota Bharu was dominated by the British in the 19th century; the overall landscape of Kota Bharu is therefore based on two eras of growth, with the development of urban patterns remaining unplanned until the 19th century. Thereafter, however, the urban fabric was designed according to the form of the box (Aiman Abdullah, Mohd Noor and Abdullah, 2018). Both patterns remain to this day, as seen in Figure 1.2. The only variations are in the building designs and façade.

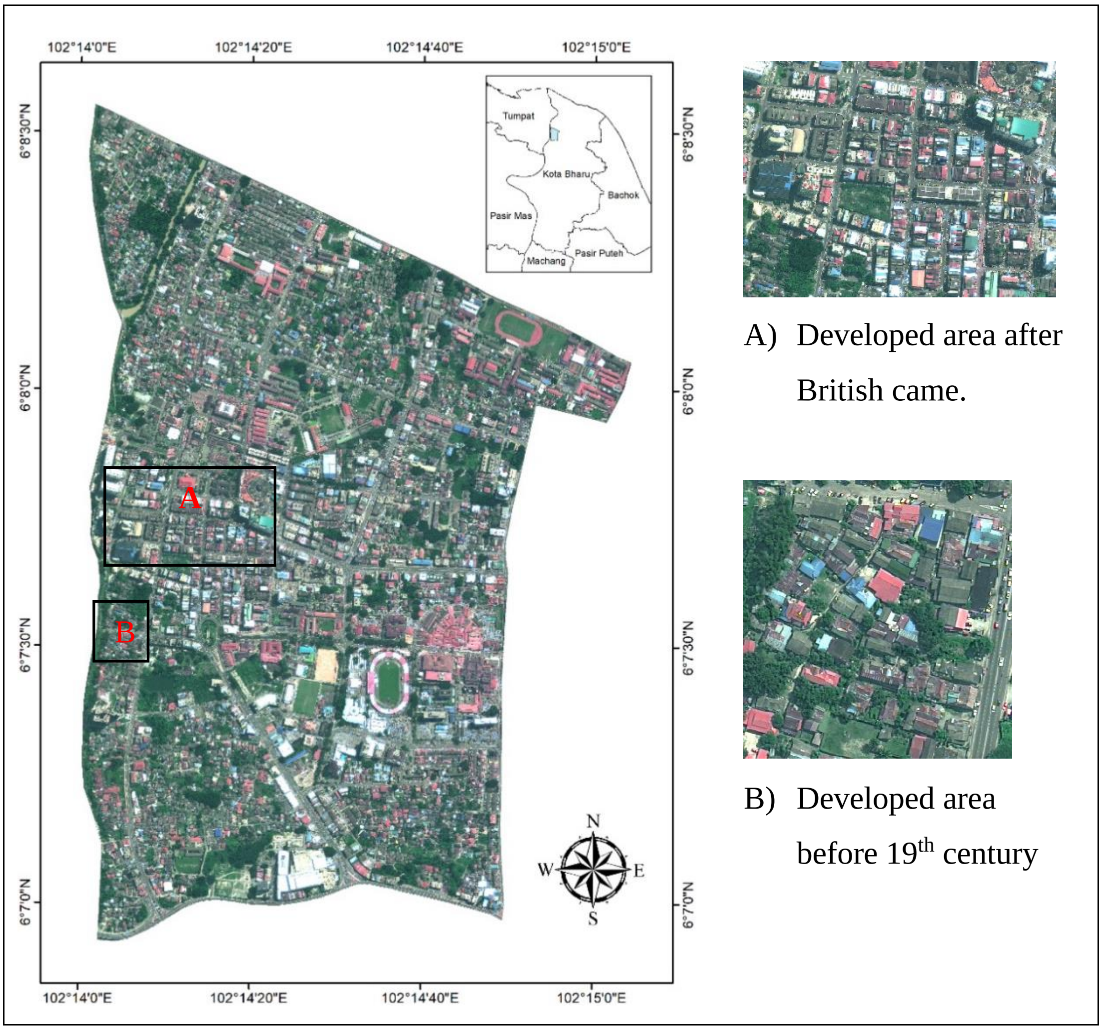

Figure 1.2 Study Area (WorldView-4 image with 0.5 m) (a) developed area after British came, (b) developed area before 19th century.

The Malay village in Peninsular Malaysia is known as the *kampung*, which traditionally comprises many wooden houses. In Kelantan, Malay villages can easily be found in Kota Bharu and other districts (Mohd Nasir, 2011). The urban design of Kota Bharu is therefore relatively unique compared to other cities in the Peninsular. The *kampung* is composed of several Malay houses and their compounds (delimited by vegetation but without physical boundaries, such as fences). Furthermore, a *kampung* does not develop according to a plan (Chen, 1998). As a result, a number of traditional houses may be in one lot of land, while different types of buildings may share a land parcel. For example, schools, dwellings, and commercial lots might coexist in a parcel of land. This landscape is therefore characterised as highly heterogeneous.

As previously mentioned, Kota Bharu is denser than the state's districts. As a result, most lands in the Kota Bharu district, particularly the Kota Bharu sub-district, has been developed. Residential areas are the dominant form of land use (1.27 km^2), followed by the area allocated to infrastructure and community facilities (0.67 km^2), as well as commercial activities (0.55 km^2). The remaining land use classes occupy minimal portions of land. Of the types of buildings, Malay village occupy the largest area, followed by retail store, schools and government offices, with the remaining building types occupying only a small area.

1.6 Scope of the Study

i. Flood exposure and vulnerability mapping only covers the Kota Bharu area, which has a high density of elements-at-risk. To obtain the flood exposure, a December 2014 flood event simulation was simulated, while this study attempted to assess the reliability of SRPs during an emergency response, so no bias adjustment was made.

ii. The satellite imagery was captured in 2017, while the LiDAR data was obtained in 2008 so the datasets have a nine-year time gap. However, minor changes were detected after cross-checking with Google Earth software and using the historical imagery tool. Consequently, these changes would have impacted on the accuracy of the classification.

iii. Due to the scarcity of building vulnerability field data, only a small number of buildings were evaluated in the building vulnerability assessment.

1.7 Structure of this Thesis

This thesis consists of five chapters, with each section focusing on various aspects. Chapter 1 provides an overview of the study, which includes a brief introduction, the problem statement, the research objectives and questions, the location of the study area, as well as study's scope and significance.

The core of this thesis is set outlined in Chapter 2, which analyses the relevant studies that informed this research. This chapter initially offers an overview of the flood situations across Malaysia before defining flood risk and other terminologies. The most significant aspect of this chapter is the discussion regarding the contributions of remote sensing data to the hazard and exposure dimensions. Finally, the chapter outlines the current applications of remote sensing techniques in terms of the mapping of exposure and hazard components.

Chapter 3 provides the detailed methodology and explains how this study conducted, including the data acquisition, pre-processing, post-processing, and the results assessment method.

Chapter 4 focuses on the presentation and interpretation of the findings. In addition, an insight is provided into the findings. Lastly,

Chapter 5 provides thorough conclusion compassing all the study objectives and outlines several recommendations.

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