ESTIMATION OF MONSOON RAINFALL BY SINGLE POLARIZATION WEATHER RADAR

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DEDICATION

"Knowledge is better than wealth, Knowledge guards you while you have to guard wealth. Wealth decrease by spending while knowledge increase by spending, and the results of wealth die as wealthy decay. With it a man acquires obedience during his lifetime and a good name after his death. Knowledge is a ruler while wealth is ruled upon."- Saidina Ali Bin Abi Talib

This thesis is dedicated to my parents and in laws, who encourage me to gain knowledge, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my husband, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Weather radar can offer synoptic measurement at a higher temporal and spatial resolution to extract the rain information. Rainfall can be inverted from the radar reflectivity using the power-law relation to ground rain gauge measurement. The relationship known as Z-R model has been established in many variants but the uncertainty from the sampling bias and the Z-R variability of single-polarization radar observation on monsoon rain becomes subject to research. This study reports a novel research framework to systematically estimate the monsoon rainfall using new *Z-R* model on the single-polarization weather radar in Kelantan. The sampling bias was quantified by the pixel matching procedure while the non-linear Levenberg Marquardt (LM) regression and the Artificial Neural Network (ANN) regression at different rain intensity and radar range were introduced to minimise the Spatio-temporal variability of the new *Z-R* model. This study uses 10-minute reflectivity data recorded in Kota Bahru radar station and hourly rain record at the nearby 58 gauge stations in 2013 to 2015. The three-dimensional nearest neighbour interpolation proves that the sampling bias can be quantified. The LM shows an improvement of about 12% if the spatial adjustment was applied in the regression. Unlike LM, the ANN is more robust and independent to the spatial adjustment thus it could provide more accurate and reliable monsoon rain information in heterogenous rainy condition. The ANN model provides accuracy of ± 0.4 mm/hr, ± 1.0 mm/hr and ± 8.2 mm/hr for low, medium and high rain intensity respectively with correlation coefficient > 0.7 ($p < 0.05$). Comparing to other *Z-R* models, the ANN gives model efficiency ratio of > 0.5 and accuracy improvement about 8 %, 10% and 5% for abovementioned rain intensity respectively. Radar derived rainfall maps present the rain distribution was more concentrated in all downstream but only covered 1/3 of the upstream in Kelantan rivers. Further research is needed before the technique could be applied to any single-polarization system in Southeast Asia to achieve better accuracy of rain information extraction.

ABSTRAK

Radar cuaca mampu memberikan ukuran secara sinoptik pada resolusi masa dan ruang yang tinggi dalam penghasilan maklumat hujan. Maklumat hujan dapat diperolehi daripada penukaran radar pantulan melalui hubungan hukum kuasa dengan pengukuran tolok hujan di permukaan tanah. Hubungan ini dikenali sebagai model Z-R yang telah banyak diwujudkan dalam pelbagai varian tetapi terdapat keraguan daripada persampelan berselisih dan kepelbagaian Z-R dari pengukuran radar jenis pengutuban tunggal pada hujan monsun yang menjadi subjek penyelidikan ini. Kajian ini melaporkan rangka kerja penyelidikan yang terkini untuk menganggarkan hujan monsun secara sistematik dengan menggunakan model Z-R yang baru pada radar jenis pengutuban tunggal di Kelantan. Selisih persampelan dihitung dengan prosedur pemadanan piksel manakala regresi bukan linear Levenberg Marquardt (LM) dan regresi rangkaian neuron buatan (ANN) pada keamatan hujan yang berbeza dan jarak dari radar telah diperkenalkan untuk mengurangkan kebolehuabahan ruang dan masa untuk model Z-R yang baru. Kajian ini menggunakan data pantulan yang direkodkan pada setiap 10 minit dari stesen radar Kota Bahru dan rekod hujan setiap jam di 58 stesen tolok yang berhampiran dari tahun 2013 hingga tahun 2015. Interpolasi kejiranan terdekat tiga dimensi telah membuktikan bahawa selisih persampelan boleh diukur. Model LM telah menunjukkan penambahbaikan pengukuran hujan sebanyak 12 % jika pelarasan ruang dilakukan dalam regresi. Berbeza dengan LM, ANN adalah lebih mantap dan tidak bergantung kepada pelarasan ruang, seterusnya ia dapat memberikan maklumat hujan monsun yang lebih tepat dan digunapakai dalam keamatan hujan yang tidak seragam. Model ANN menghasilkan nilai ketepatan $\pm$ 0.4 mm/jam, $\pm$ 1.0 mm/jam and $\pm$ 8.2 mm/jam bagi setiap intensiti hujan yang rendah, sederhana dan tinggi, dengan pekali kolerasi > 0.7 ($p < 0.05$). Berbanding dengan model Z-R yang lain, ANN memberikan nisbah kecekapan model > 0.5 dan menambah baik nilai ketepatan sebanyak 8 %, 10 % dan 5 % untuk setiap intensiti hujan yang telah disebutkan. Peta hujan hasilan radar menunjukkan taburan hujan lebih tertumpu di seluruh kawasan hilir tetapi hanya meliputi 1/3 kawasan hulu Sungai Kelantan. Penyelidikan yang lebih lanjut diperlukan sebelum teknik ini boleh digunakan untuk sistem radar jenis pengutuban tunggal di Asia Tenggara bagi mencapai ketepatan cerapan hujan yang lebih baik.

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LIST OF ABBREVIATIONS

2DVD	-	Two-Dimensional Video Disdrometer
3-D	-	Three Dimensional
ANN	-	Artificial Neural Network
ANOVA	-	Analysis of Variance
AP	-	Anomalous Propagation
APHRODITE's	-	Asian Rainfall - Highly-Resolved Observational Data Integration towards Evaluation
ARM	-	Atmospheric Radiation Measurement
ASEAN	-	Association of Southeast Asian Nation
BMKG	-	Indonesian Agency for Meteorology, Climatology, and Geophysics
BOM	-	Bureau of Meteorology
BPANN	-	Backpropagation Feed-Forward Neural Network
CAPPI	-	Constant Plan Position Indicator
DEM	-	Digital Elevation Model
DID	-	Department of Drainage and Irrigation
DMLP	-	Deep Multiplayer Perceptron
DSD	-	Drop Size Distribution
EASM	-	East Asian summer monsoon
ECV	-	Essential Climate Variable
EEC	-	Enterprise Electronics Corporation
ENSO		El Niño-Southern Oscillation
FY	-	Feng Yun
GCOS	-	Global Climate Observing System
GFDRR	-	Global Facility for Disaster Reduction and Recovery
GOES	-	Geostationary Operational Environmental Satellite
GPI	-	GOES precipitation Index
GPM	-	Global Precipitation Measurement
HMFB	-	Hourly Mean Field Bias
HTI	-	Height Time Indicator
IDW	-	Inverse Distance Weight

IPCC	-	International Panel on Climate Change
IRIS	-	Interactive Radar Information System
ITU	-	International Telecommunication Union
JMA	-	Japan Meteorological Agency
JWD	-	Joss–Waldvogel disdrometer
KB	-	Kota Bharu
LM	-	Levenberg Marquart
LMI	-	Levenberg Marquardt Intensity
LMR	-	Levenberg Marquardt Range
MAE	-	Mean Absolute Error
METOP	-	Meteorological operational satellite
MFANN	-	Multilayer Feed-Forward Neural Network
MFB	-	Mean-Field Bias
MMD	-	Malaysia Meteorological Department
MODIS	-	Moderate Resolution Imaging Spectroradiometer
MP	-	Marshall Palmer
MSE	-	Mean Squared Error
MSS	-	Meteorological Service Singapore
NADMA	-	National Disaster Management Agency
NAHRIM	-	National Hydraulic Research Institute of Malaysia
NCHMF	-	National Centre for Hydro-Meteorological Forecasting
NEM	-	Northeast Monsoon
NEXRAD	-	Next-Generation Weather Radar
NN	-	Neural Network
NOAA	-	National Oceanic and Atmospheric Administration
OPERA	-	Operational Programme for the Exchange of Weather Radar Information
PACRAIN	-	Comprehensive Pacific Rainfall Database
PARSIVEL	-	PARticle SIze and VELocity
PAGASA	-	Philippine Atmospheric, Geophysical, and Astronomical Services Administration
PCA	-	Principal Component Analysis
PDF	-	Probability Density Function

PERSIANN	-	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PPI	-	Plan Position Indicator
Py-ART	-	Python Atmospheric Radiation Measurement Radar Toolkit
QC	-	Quality Control
QPE	-	Quantitative Precipitation Estimation
RBFANN	-	Radial Basis Function Neural Network
RHI	-	Range Height Indicator
RMSE	-	Root Mean Square Error
ROS	-	Rosenfeld
RPMM	-	Region Probability Matching Method
SACA&D	-	Southeast Asian Climate Assessment and Dataset
SD	-	Standard Deviation
SDG	-	Sustainable Development Goal
SEA	-	Southeast Asia
SWM	-	Southwest Monsoon
SNR	-	Signal-To-Noise Ratio
SRTM	-	Shuttle Radar Topography Mission
TAMSAT		Tropical Applications of Meteorological Satellite
THORPEX	-	The Observing System Research and Predictability Experiment
TMPA	-	TRMM Multi-satellite Precipitation Analysis
TMD	-	Thai Meteorological Department
TRMM	-	Tropical Rainfall Measuring Mission
US	-	United States
VPR	-	Vertical Profile Reflectivity
WCMM	-	Window Correlation Matching Method
WMO	-	World Meteorological Organization
WPMM	-	Window Probability Matching Method
WSR	-	Weather Surveillance Radar
WWRP	-	World Weather Research Programme

LIST OF SYMBOLS

r	-	Range of radar observation
H	-	Horizontal polarization
V	-	Vertical polarization
Z	-	Radar Reflectivity [dBZ]
ϕ	-	Azimuth Angle [degree]
θ	-	Elevation Angel [degree]
Θ_e	-	Resolution Volume
R	-	Rainfall Rate [mm/h]
x	-	Latitude [m]
y	-	Longitude [m]
z	-	Height [m]
P_r	-	Power Received [w]
C	-	Calibration Constant
$\lvert K\rvert^2$	-	Dielectric Constant (0.93)
α	-	Alpha (*Z*-*R* coefficient)
β	-	Beta (*Z*-*R* coefficient)
B	-	Bias
G_i	-	Accumulated Rainfall [mm]
t	-	Time [hour]
$\hat{R}\left(g_o\right)$	-	Predicted Rainfall at Gauge Location
$R(g_i)$	-	Observed Rainfall Point at A Location
R_j	-	Rainfall [mm/h] at *j*th rain gauge stations
W_{ij}	-	Spatial weight matrix
$\bar{R}$	-	Spatial mean of the rainfall [mm/h]
S^2	-	Sample variance
I_i	-	Moran's I index
$E(I)$	-	Estimated value of *I* for a random spatial pattern
ω	-	Weight

d_i	-	Distance [m]
L_{rad}	-	Latitude at Radar [degree]
l_{rad}	-	Longitude at Radar [degree]
z_{rad}	-	Altitude at Radar [m]
L_p	-	Latitude of The Pulse [m]
l_p	-	Longitude of The Pulse [m]
a_e	-	Earth Radius [km]
k_e	-	Earth Approximation (4/3)
$\cos\theta$	-	Cosine of The Elevation Angle
A	-	Constant of Area [m^2]
n	-	Number of Samples
h_{cg}	-	Altitude Correction [m]
h_g	-	Rain Gauge Altitude [m]
h_a	-	Altitude of The Radar [m]
Z_{int}	-	Reflectivity Integration [dBZ]
N	-	Number of Match Pairs
j	-	Index of Minute
i	-	Index of Hour
D	-	Distance from Radar [m]
$f_v(D)$	-	Probability distribution of drop sizes in a unit volume of air [mm^{-1}]
$N(D)$	-	Number of drops [$m^{-3}mm^{-1}$]
$D + dD$	-	Number of the raindrops with diameter [m]
Nt	-	Total number of drops falling per meter [m^{-3}]
D^6	-	Diameter drop size a power of sixth [mm]
$N_vD\ dD$		Mean number of raindrops [$mm^{-1}m^{-3}$]
z	-	Reflectivity factor [mm^6/m^3]
$V(D)$	-	Functional relationship between the raindrop terminal fall Speed [ms^{-1}]
(a, b)	-	Gauge Position at particular coordinates
(x, y)	-	Radar Position at particular coordinates
J	-	Rainfall Estimates from The Radar [mm/h]
$f_t^{(i+1)}$	-	Transfer Function

W^{i+1}	-	Neuron Weight
b^{i+1}	-	Bias of The Neuron
b_2	-	Output Bias in Layer 2
b_1	-	Input Bias in Layer 1
L_W	-	Output Weight
I_W	-	Input Weight
R_z	-	Radar Rainfall Estimate [mm]
$\overline{R}_z$	-	Sample Mean of Radar Inversion Rainfall [mm]
R_g	-	Rain Rate Measurement from the Rain Gauge [mm]
$\sum {R_g}^2$	-	Sum of Squared Rain Gauges Reading [mm]
$\sum R_z$	-	Total of The Radar Rainfall Measurement [mm]
$\sum {R_z}^2$	-	Sum of Squared Radar Rainfall Measurement [mm]
R_c	-	Correlation Coefficient
${R_c}^2$	-	Coefficient of Determination

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Precipitation is literally defined as either liquid or solid form with a large surface area that falls from the atmosphere and reaches the ground (Stull, 1995). This includes hail, snow and rainfall. Water droplets from the rain that reaches the ground surface have diameter which is greater than 0.5 mm (Schneider et al., 2011). Rain can be categorized by its intensity, from light rainfall to heavy rainfall with ≥ 1 mm/hour of accumulation rate (Barry et al., 2009). The rain intensity is associated with the cloud type, namely convective, stratiform, orographic and frontal. Convective rainfall is formed through evaporation in a vertical motion and by convection, and it is commonly experienced in the tropics where these areas are prone to thunderstorms and floods, whereas stratiform rainfall is the result of a forced lifting of air and is typically associated with light to moderate rainfall. Rainfall is one of the components in the hydrological cycle and is therefore an input parameter in a hydrological modelling (Mehran et al., 2014; Tang et al., 2009; Gurung, 2017; Gabriele et al., 2017; Beneti et al., 2019), urban drainage estimation (Barszcz, 2018; Ochoa Rodriguez, 2016; Thorndahl et al., 2017; Cifelli et al., 2011; Wang et al., 2017) and flood modelling (Smith et al., 2007; Yokoi et al., 2012; Seo et al., 2015; Lyu et al., 2018).

The study of precipitation provides knowledge of spatio-temporal impact of climate to human and this would support all initiatives for world sustainable future. Torrential rain that leads to flooding greatly impacts the economy of a region and causes casualties and health problems. ADRC (2013) reports that flood and storm are major natural disasters in Asia which have caused fatalities by 41.7 % and affected 44.5 % of the region’s economy. Under the United Nations’ Sustainable Development Agenda, Sustainable Development Goal (SGD) number 11 which aims at reducing the number of people affected by natural disasters like floods and the consequential economic losses necessitates the implementation of policies and plans such as Pilon (1998) Framework for Disaster Risk Reduction to improve the awareness and early warning system of areas affected by flood. Moreover, rainfall is a sub-parameter in an Essential Climate Variable (ECV), from among the 54 ECVs observed by the Global Climate Observing System (GCOS) programme that is co-sponsored by the World Meteorological Organization (WMO). The significance of the ECV's output leads up to SDG 13 which focuses on dealing with the impacts of climate changes. The study of rainfall is therefore important in many applications because changes in the precipitation pattern alter the hydrological cycle and affect water resources, resulting in extreme intense precipitation that may cause flooding in certain regions (Pachauri et al., 2014). Since rainfall is a pertinent input in a hydrological model for delineating floodplain and risk assessment, accurate rainfall measurement is needed.

A rain gauge is a conventional instrument for measuring rain intensity at certain time interval and point location. The instrument provides an instantaneous and direct measurement about rain information on the ground surface. However, the measurement can be affected by wind induced errors (Strangeways, 2006; Devine et al., 2008), evaporation loss (Saidi et al., 2014), splashing of rain out of the gauge (Rodda, 2012; Devine et al., 2008), other limitations of mechanical instruments for measuring intense rainfall (Habib et al., 2001; Molini et al., 2005), spatial sampling errors (Ochoa-Rodriguez et al., 2019) and sparse distribution or absence of gauges at isolated areas. Malaysia currently has 1075 rain gauge stations operated by the Department of Irrigation and Drainage (DID) and 164 rain gauges operated by the Malaysian Meteorological Department (MMD), but the distribution is mainly along the rivers and is sparser over higher terrains. This network of gauges is commonly used for weather forecasting, flood inundation mapping and risk assessment, urban storm water management (MSMA) and flood forecasting and warning system.

Remote sensing offers continuous observation on a wider spatial coverage and higher temporal resolution for rainfall estimation from satellite precipitation products (Bellerby et al., 2000; Li et al., 2010; Toté et al., 2015; Rossi et al., 2017; Tan et al., 2017b; Trinh-Tuan et al., 2019) and ground weather radar data (Kumar et al., 2011; Craciun et al., 2016; Tan et al., 2018a; Roy et al., 2019; Berg et al., 2016; Zhang et al.,

2018) at grid-scale through refraction, attenuation and scattering properties of aloft rain. It can therefore complement the ground gauge in measuring rainfall on ground. The onboard optical sensors of satellite precipitation measure the rain based on cloud properties but have intermittent records in every instrument replacement schedule. These optical precipitation satellites are operated during daytime (passive sensor) and thus limit to all night-time weather forecasting to support the ground measurements (M. M. Hasan, 2014; Villarini et al., 2010; Islam et al., 2014; Thorndahl et al., 2017). Microwave satellite provided a vertical structure of the rainfall system and spatial distribution of water vapour in the atmosphere. However, the revisit time is less frequent and it has lower spatial resolution (Menzel et al., 2008; Ackerman et al., 2010).

Ground weather radar is a vital instrument for rain measurement. It can detect severe rain type and help to issue early weather warning to the public effectively. Radar with Doppler peripherals is effective in detecting the development of microburst and wind shear occurrences on near ground surfaces (Nechaj, 2019; Eilts, 1987; Tse et al., 2019). In addition, it is important in the aviation industry by providing near real-time weather conditions and forecasting of the storm position to traffic managers, which helps to secure airlines safety. The potential of weather radar in hydrological and meteorological application has been acknowledged by many researchers. Hydrologists and meteorologists commonly utilize radar data to better understand the atmosphere constituent, propose advance weather forecasting, and improve hydrological modelling input. Ever since the radar was introduced in weather-related applications, assessments on the current radar system have been conducted to fulfil the needs of the public by improving weather forecasting (rain and thunderstorm) and early warning system. Recently the increase use of weather radar can be found in hydrology for flood forecasting and urban drainage (Ehret et al., 2008; Liguori et al., 2014; Abon et al., 2015; Thorndahl et al., 2017; Ochoa-Rodriguez et al., 2019; Wright et al., 2014; Gabriele et al., 2017) by virtue of the higher temporal resolution provided by the radar. The weather radar application was also extended in meteorology particularly for weather forecasting purposes.

A weather radar measures the precipitation in planimetry basis of x and y, elevation (h) and scanning elevation (θ), and it consists of a complex data structure represented as volumetric rain rate information. Basically, the radar transmits and receives echoes of electromagnetic signals (in the form of microwave spectra) using the transmitter and the receiver at the distance of a target defined as the range, r, by specifying the signal delay time at the speed of light. The echoes are generally weaker than the transmitting pulse as they go through attenuation, scattering and absorption from atmospheric gases, clouds and precipitation during the measurements (Meischner, 2004; Montopoli et al., 2011; Skolnik, 1980). The utilization of weather radars for rainfall estimation has been going on for more than 50 years. This was after the scientists discovered that radar could be used for other purpose than war, in this case, it was to study weather activities. This technology offers unprecedented observational capabilities through vast spatial coverages and high temporal observations of atmospheric constituents in quasi-real time. By all these advantages have made it applicable to study the variability of rainfall accurately. To date, many organizations, primarily national weather service associations and national climatological organizations, have been established to study rainfall using radar, among them are the Bureau of Meteorology (BOM) Australia, Netherland Met. Institute, United Kingdom Weather Service (The Meteorological Office) and Malaysia Meteorological Department (MMD).

To quantify rain information from the radar measurement, three basic inversion methods that manipulate the relationship between the rain rate, R, and reflectivity, Z, of Z-R model have been designed through drop size distribution (DSD), statistical and pixel matching methods. The first and the last techniques are usually performed using a disdrometer (Chakravarty et al., 2015; Souverijns et al., 2017; Rosenfeld et al., 1994; Piman et al., 2007; Hashiguchi et al., 2018; Kumar et al., 2011; Ayat et al., 2018; Silver et al., 2019) while the second one relies on rain gauges commonly fitted in the power-law empirical model either formed by non-linear least square regression or machine learning techniques (Wu et al., 2018; Suzana R., 2011; Yang et al., 2016b; Yoon et al., 2017; Alqudah et al., 2013; Ahmad, 2017; Sahlaoui et al., 2019). The first technique has the advantage of measuring the rain rate aloft in real time, but the availability of disdrometer is limited in many countries particularly Malaysia. The parametric technique can be either implemented empirically to solve for the regression coefficients (α and β in *Z-R* model) or estimated using non-parametric in the machine learning form which is more efficient in inverting results but demands massive input data. The third technique is the simplest one but it is associated with errors of selecting the exact volume and height in the atmosphere for the rain gauge measurements. In this study, the second technique is considered to estimate rainfall from the radar reflectivity.

1.2 Problem Statements

Flood is a common natural disaster in Malaysia and frequently exist during the northeast monsoon. Kelantan is one of the states that receive major floods accounting for severe damages of infrastructure. The worst flood was occurred in late December 2014 to January 2015 with the cost of damage was up to RM 1 billion (Davies, 2015). The flood was started at the upstream of the Kelantan river which received higher rain intensity and subsequently affected the downstream areas causing the first and second waves of flood hit. Besides urbanization and deforestation, Nashwan et al. (2018) stated that these severe floods are due to the increase in rainfall frequency, which leads to the change of flood volume and duration. Thus, precise rainfall measurement is needed to get reliable assessment of flood impact and mitigation planning. Ground gauge can provide rain information and this measurement becomes a routine and one of the practical way to get the real time rainfall data. However, the gauge does not present the spatial field of rainfall in the point-based observation and also experienced system malfunction during the flood. The satellite precipitation and ground weather radars are identified to complement the disadvantages of gauge. Yet, rain information derived from the remote sensing measurements requires thorough data processing to minimise the substantial systematic and random uncertainties and this remains a challenge to the scientific users.

Radar derived rainfall is subject to geometric and radiometric bias in the match of reflectivity pixel and gauge vector data. This is due to the complexity of the radar geometry which provides volumetric rain rate information in time and space, whereas the rain gauge measures the accumulation of surface rainfall at certain time in areal point. Matching these two measurements leads to geometric discrepancy which is due to different spatial reference of rainfall area, thus resulting in misidentification of the rainfall type. The *Z-R* model is best to apply using disdrometer measurement to determine the rain DSD which highly correlates to the radar reflectivity perpetuated in the radar equation. However, the practice of using disdrometers in Malaysia is limited. The more common practice is the window probability matching method which matches the same cumulative distribution function of grid reflectivity and gauge vector. However, this approach does not represent the individual rain rate and is sensitive to higher reflectivity. Study by Ayat et al. (2018) has found that poor statistical correlation of *Z-R* model was obtained (i.e., $R_c = 0.13$, with a maximum error of 30 % and an average mean absolute error of 6.59 mm/h), when the correction on geometric bias was not applied

Radiometric bias occurs when surface rainfall measurements from the gauge are being matched with the volumetric rainfall data from the radar. The local gauge network is sparsely distributed on flat surfaces and is mainly available along the river. The radar rainfall measurements thus experience spatial and temporal discrepancies, resulting in a low correlation with the gauge. The low correlation of the radiometric data is due to the void radar reflectivity pixel where low reflectivity (0 dBZ) and extreme reflectivity (more than 70 dBZ) exist. A comprehensive review on radiometric correction by bias adjustment has been done for Europe (Gjertsen et al., 2003) but is scarcely documented in the Southeast Asia, particularly Malaysia. Pixel matching in radar calibration is very crucial to minimize the spatial and temporal bias in radar rainfall estimation. Without a proper calibration, the error can reach up to 76 % (Borga et al., 2002) and lower statistical correlation (Ayat et al., 2018). They proposed the region probability matching method (RPMM) to overcome the limitations of the conventional matching. However, the method was only tested for light rainfall intensity and had uncertainties in determining the exact range for the coefficients of α and β in the *Z-R* model, where the cumulative rain estimation had a maximum error larger than 30 %.

The inconsistence of the *Z-R* model exemplifies the main disadvantages of radar rainfall estimation. Previously proposed universal *Z-R* models, such as the

Marshall-Palmer (MP) and Rosenfeld, are inadequate to be applied in Malaysia due heterogenous rain patterns and intensity during monsoon seasons (southwest, inter-monsoon and northeast). Studies on the accuracy of *Z-R* model are lacking for many reasons. The radar has a complex data structure, requires a large data storage and is very expensive when used for long-term observations. The parametric approach, namely non-linear least square regression, requires empirical coefficients α and β to estimate the rainfall. Determining both coefficients is not straightforward because these coefficients are completely dependent to the DSD, rainfall types, geographic location and climate. The default Marshall-Palmer model had overestimated the accumulated rainfall by 80% with the maximum rain estimation about 160 mm/h (Suzana R., 2011; Adam et al., 2012; N.H.M. Sobli, 2013). This approach requires a priori knowledge on the *Z-R* modelling coefficients (α and β) to initiate the inversion in the least square optimization but the typical coefficients ($\alpha = 200$ and $\beta = 1.6$) are always used regardless of the rain variation. Goudenhoofdt et al. (2017) and Seo et al. (2015) also found that the MP had underestimated the individual rainfall by more than 30 % and 50 %, respectively. Nevertheless, the parametric technique is fairly robust for heterogenous rainfalls during the northeast monsoon. With the appropriate processing steps, the classification of the rain type can improve the accuracy (Chumchean et al., 2008; Prat et al., 2009; Lei et al., 2019; Dehart et al., 2020), although the process then becomes lengthy (Meena et al., 2019; Ostrovsky et al., 2006; Reinartz, 2016).

The rainfalls are classified based on the cloud types, such as convective and stratiform rain, or they could be classified based on the intensity, which are low, moderate and high rain intensity. On the other hand, although non-parametric regression through machine learning is a better alternative, this approach needs extensive training samples (Yen et al., 2019) to correlate the radar reflectivity with the rain gauge readings. However, existing training samples are unavailable for the rainfall types that Malaysia experiences. Radar data is generally used to present rainfall information rather than to assess the radar data’s quality and accuracy, both of which are very crucial for flood monitoring and modelling. The study on radar rainfall inversion focusing on systematic procedures that explain the geometry and radiometry qualities of the radar reflectivity is either limited or unavailable. Systematic radar inversion for single polarization S-band radar data is becoming more in demand in

Malaysia. This is because of the unavailability of systematic radar processing and data quality assurance routines. Ground meteorological radars produce complex radar data structures (Saltikoff et al., 2019) which makes the usage of radar data less favourable, in addition to the need for massive radar data sets to manage complicated data extraction in terms of the algorithm and processing time (Schleiss et al., 2019), as well as a large budget to purchase the processing tools such as IRIS.

1.3 Research Goal

The aim of this study is to design a systematic radar inversion framework for a single-polarisation weather radar based on developed geometric and radiometric correction and an intelligent *Z-R* model. This is to obtain accurate and robust rainfall estimations that are independent of spatio-temporal variabilities and heterogeneous rainfall intensities during flood events in Kelantan. Therefore, the following four objectives have been developed to accomplish the aim.

1.3.1 Research Objectives

The objectives of the research are:

(a) To calibrate geometric and radiometric errors in the reflectivity pixel to match with the gauge points using three-dimensional interpolation pixel matching and mean field bias adjustment.

(b) To quantitatively assess the spatial and temporal accuracies of different *Z-R* models in low, medium and high rain intensities using a non-linear optimization regression variant.

(c) To develop a neural network model using the radar reflectivity as the training network for a robust and accurate rainfall inversion model.

1. To evaluate the accuracy of the neural network inversion model and map the rainfall estimated from radar data during the 2014 Kelantan flood episode.

1.4 Research Questions

1. What is the technique to calibrate error in geometry and radiometry of radar reflectivity?
2. How the parametric *Z-R* model improves the accuracy of radar inversion in low, medium and high rainfall intensity?
3. Why different rainfall intensity and radar range measurement impact the quality of *Z-R* model?
4. How to determine the training network in machine learning from the radar reflectivity and rain gauge data?
5. What are the accuracy and the limitation of the artificial neural network in the radar inversion?

1.5 Scopes of the Study

The reflectivity data measured at Kota Bharu (KB) ground weather radar station using the lowest scanning angle at 0.7 degree and in data format of the Vaisala/SIGMET system are used for this study. The measurement at this scanning angle gives the minimum signal-to-noise ratio (SNR) from 3 dB and enables to cover the area up to 480 km radius. This setup also reduces the impact of ground clutter particularly at close range radars, provides rainfall information near to the surface and minimises temporal uncertainty in the Constant Plan Position Indicator (CAPPI) data (Seo *et al.*, 2011; Nielsen *et al.*, 2014a; Hadi *et al.*, 2019). The KB operates at 3 GHz S-band frequency and is a single horizontal polarization radar system. The data represented in the Plan Position Indicator (PPI) is acquired at every 10-minute interval with a radial resolution of 0.8 km by one-degree range bin. This data has been pre-processed at the MMD in which calibration for the ground clutter and beam blockage was applied. Uncertainties from rain attenuation were neglected following the

Rayleigh law that suggests that it is not significantly hampered at S-band. In addition, the systematic errors from instrument calibration have been corrected during the system maintenance every six months (Razak, 2016). The reflectivity data was collected during the wet season of the northeast monsoon from 2013 to 2015 (January, February, March, September, October, November and December). This data was selected to analyse the high intensity rainfalls during the flood episode in December 2014. The Sigmet radar data was converted to NetCDF file by Py-ART for further processing.

Disdrometers will not be discussed here, nor has it been used in this study, because no available data was ever measured in Kelantan. Thus, the ground truth measurements were collected by means of the rain gauge and used for the *Z-R* modelling. The gauge provided one-hour rain rate data collected from 58 rain gauge stations and was obtained from the DID Malaysia. The data was selected because the location of the rain gauge is acceptable within the radar maximum range. This data was ready to be used and needed no further manual filtering where the instrument error had been corrected by the DID. The gauge network is dense in the flat areas situated in the north of Kelantan but sparsely distributed on high terrains at the south of Kelantan. The digital elevation model (DEM) acquired from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 30 meter pixel spacing was used to extract the height of the rain gauge with a vertical accuracy of 6.2 m. This data was downloaded from the United States Geological Survey (USGS) website. The rain gauge height was needed to conduct the geometrical correction.

This study only focused on close-range radar (downstream) measurement, from 4 to 50 km radius, and less attention was given to intermediate and far range radar observations in order to minimize the impact of signal noise and maximize SNR. Besides, intense rainfall event had been recorded by the gauges at the downstream (Machang and Jeli), caused flooding within 16th to 24th December 2014 at the northern Kelantan. This scanning angle was selected to obtain the maximum SNR of above 3 dB to conform with Rosenfeld et al. (1994) who found low reflectivity for the same rainfall with a difference by 2 to 3 dB within the range of less than 48 km. Nearest neighbour interpolation (NN) was used in this study to calibrate geometric errors for rectification and resampling of the reflectivity pixel. This technique was selected because it minimizes uncertainties from the interpolation by preserving the reflectivity (radiometric) and the distortion in the resampling (Leclerc et al., 1994). Mean field bias was applied in the radiometric correction to correct the accumulated rainfall for hydrological purposes such as suggested by Kim *et al.* (2018). The statistical power-law model was used to estimate the *Z-R* model through the non-linear least square optimization by the Levenberg-Marquart (LM) method and to solve the non-linear relation between the radar reflectivity and the rain gauge. The LM optimization is effective in solving non-linear problems which need many parameters in the input model. It is also robust and has fast processing speed to converge the minimum values of mean square error (Nelles, 2013; Gavin, 2011) in the artificial neural network model.

1.6 Study Area

The study area is Kelantan, a state located in the northeast of Peninsular Malaysia within the latitude of 6.1254 °N and the longitude of 102.2381 °E (Figure 3.1) with an area of about 15099 km^2. The land is covered in 76 % forest, 22 % agricultural lands, and the rest buildings and infrastructures. Kelantan's topography consists of flat terrains with a mean elevation of less than 25 m above the mean sea level, as well as mountainous terrains with a mean elevation of more than 301 meters derived from the SRTM. The elevation surface is between -25 to 2183 meters above the mean sea level. The Kelantan river is the main river in the basin with 284 km of length flowing to the north into the South China Sea. There are four major basins in Kelantan which area; Golok River Basin, Kemasin River Basin, Semerak River Basin and Kelantan River Basin. This state experiences wet and humid tropical climate all year round with an average annual rainfall of 3689 mm/year and an annual temperature of 27.5 °C. The average humidity is 84 % and the average wind speed is 13.7 km/h. The northeast monsoon is accompanied by heavy to extreme rainfalls starting from November to January and the southwest monsoon (dry season) from May to end of August brings less rainfall and hot weather. The KB radar is located at the height of 13 meters above the mean sea level in the north of Kelantan (represented in Figure 3.1

by a red triangle whereas the location of the rain gauges is represented by dark-blue squares). This state has one operational weather radar system that operates with a maximum coverage radius of 512 km. There are 58 automatic tipping bucket gauges available in this study area, mostly located along the river.

1.7 Significance of the Study

This study presents a novel and almost universal *Z-R* model to estimate rainfall distribution for single polarization radars regardless of the rainfall intensity levels and radar measurements. The KB radar system in Kelantan would benefit from this study, as well as other radar systems similar to S-band single polarization radars such as those currently being operated at Butterworth (Penang), Kluang (Johor), Kuantan (Pahang), Subang (Selangor) and Alor Star (Kedah). In other words, the radar inversion model developed in this study is practical and applicable to other regions that have similar radar systems by offering guidelines on improvements. To achieve accurate radar rainfall estimations, this study provides more information on the quality and applicability of the reflectivity pixel to map rainfall in areas where there is a small gauge network installed. Thus, this study contributes to the meteorological and hydrological fields which currently have limited research on radar data processing due to the complexity of the radar data itself.

Radar rainfall data offers additional and complementary rainfall information for making decisions related to disaster mitigation in flood and climate modelling. By assessing the quality of the single polarization radar rainfall data with geometric and radiometric corrections, better comparisons with the data obtained from the gauge system can be achieved. Hence, this framework is beneficial for many weather-related local organizations such as the DID, MMD, National Disaster Management Agency (NADMA), National Hydraulic Research Institute of Malaysia (NAHRIM), and airports. Improvements on the radar rainfall system through this study are hoped to contribute towards the improvement of flood monitoring and risk assessment in line with SDG 11 and 13 by reducing the number of fatalities and property and infrastructure damages due to water disasters. The contribution of this study connects more directly with the Sustainable Development Agenda by providing regional rainfall information on Southeast Asia through the assessment and extraction of the Vaisala/SIGMET radar data product for the radar rainfall inversion.

1.8 General Methodology

Fast and straightforward data processing is required to process weather radar data. This is very useful for near real time weather forecasting as well as for flood inundation models and risk assessment. The methodology in this study is divided into five main parts, which are data acquisition, data pre-processing, data processing, validation and mapping of the rain rate during the Kelantan flood episode in December 2014. The flowchart of the general methodology used in this study which demonstrates all the processing stages is illustrated in Figure 1.1.

The first part is data preparation, starting with the conversion of the raw radar data's format and the collection of rain gauge and DEM data. These data would then be used as input in the pre-processing stage. Data format conversion through an open-source software, namely Python Atmospheric Radiation Measurement (ARM) Radar Toolkit (Py-ART) (Helmus et al., 2016), for reading, generating visualizations and writing the radar data from SIGMET into another data format (*.nc). Reflectivity data in NetCDF (*.nc) was used in this study.

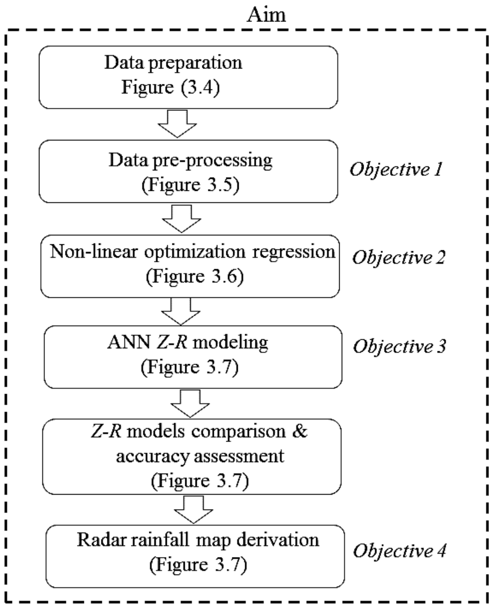

Figure 1.1 Flowchart of the general methodology

The pre-processing stage consists of geometric transformation, rain gauge interpolation, pixel matching and range (case I) and intensity (case II) classifications. This stage was conducted to achieve the first objective of the study: to minimize spatial bias through three-dimensional (3D) pixel matching between the 3D grid radar reflectivity and the corresponding rainfall gauge vector. To achieve the other objectives, major processing steps were conducted using the non-linear least square optimization, the artificial neural network (ANN) algorithm to derive the rainfall rate and accuracy assessment of radar inversion model then finally produce the map of ANN inverted rainfall for low to high rain rate during the specified Kelantan flood episode.

This thesis is divided into five chapters. Chapter 1 explains the background and objectives of this study. Chapter 2 reviews past studies to identify the state of the art of radar rain inversion with a focus on the Southeast Asian region, and to identify the research gaps from those studies. In estimating the rain rate from the reflectivity data, the assumption made was that the radar sampling volume measured is the same as the rainfall that vertically reached the ground (with reference to the rain gauge). This study delineates the pre-processing and processing schemes by specifying the criteria of the input, output and statistical assessments at every processing stage. Both parametric (empirical *Z-R* model) and non-parametric (machine learning) approaches for deriving the radar rainfall were performed in this study for the whole of Kelantan. These details on the methodology are described in Chapter 3. The results, analysis and discussion are assembled in Chapter 4, while Chapter 5 comprises the conclusion and recommendations of the study. The radar map produced by the proposed radar inversion model is included as an Appendix K, in which the weather radar data utilized were collected from the lowest elevation scanning angle of 0.7 degree at every 10-minute observation.

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