# FRAMEWORK FOR RAINFALL ESTIMATION USING X-BAND POLARIMETRIC RADAR

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FRAMEWORK FOR RAINFALL ESTIMATION USING X-BAND POLARIMETIRC RADAR

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# DEDICATION

This thesis is dedicated to my family, my daughter, Alya Afrina Dhuha and my best friend, Huzaifah.

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# ABSTRACT

Several countries, including Japan and the United States, have developed and researched X-Band polarimetric radar technology for disaster preparedness applications. However, this weather radar is still unavailable in tropical countries such as Malaysia, which has experienced flash floods and flood events, particularly during the monsoon season. The ability of X-Band polarimetric radar to observe rainfall for a localised area (30-60 km of observation radius) using a dual polarisation method can provide detailed and precise information to the disaster area in one or two minutes. Therefore, this research aimed to develop the framework of rainfall estimation by using X-Band polarimetric radar data. This research used Design Science Research (DSR) approach as the methodology. First, a systematic literature review was conducted to identify the current weather radar monitoring system in Malaysia and examine the theoretical background of X-Band polarimetric radar and its applications, as well as the components of the X-band polarimetric radar framework. Second, the DPPC server was set up with the study area and rainfall data of Kagoshima City. The study area data comprises Digital Elevation Model (DEM) and drainage area; whereas the rainfall data comprises X-Band polarimetric radar and AMeDAS ground data. Third, the framework components - storage, analysis tools and visualisation – were analysed using the X-Band polarimetric radar data to process the actual radar data and estimate the rainfall in four selected drainage areas. The analysis includes pre-processing raw data, clipping the DEM, selecting the drainage area, extracting rainfall data, and plotting the hyetograph. This is followed by the reliability analysis of the rainfall estimation from the extraction of X-Band polarimetric rainfall data analysed based on AMeDAS ground data. The validation results showed that there is a moderate positive correlation between X-Band polarimetric and AMeDAS with $R^2$ of 0.24 and $p = 0.009$. Further, the comparison of rainfall distribution results for both data by using QGIS showed that AMeDAS data was not reflecting actual rainfall monitored by X-Band polarimetric radar due to no AMeDAS stations in the drainage area and the distribution image from X-Band polarimetric radar was in real-time. All four drainage areas recorded heavy rain in the upper stream and showed the exact locations that had the highest intensity and the probability that the area closest to the drainage area would flood. In conclusion, it has been demonstrated that the newly developed framework translates real raw X-Band polarimetric radar data into accessible engineering data formats and that it can be used to estimate rainfall in a localised area.

# ABSTRAK

Beberapa negara, termasuk Jepun dan Amerika Syarikat, telah membangunkan dan menyelidik teknologi radar polarismetrik X-Band untuk aplikasi kesiapsiagaan bencana. Walaubagaimanapun, radar cuaca ini masih tidak tersedia di negara tropika seperti Malaysia, yang pernah mengalami banjir kilat dan kejadian banjir terutamanya semasa musim tengkujuh. Keupayaan radar polarismetrik X-Band untuk memerhati hujan bagi kawasan setempat (30-60 km jejari cerapan) menggunakan kaedah dwi polarisasi boleh memberikan maklumat terperinci dan tepat kepada kawasan bencana dalam satu atau dua minit. Oleh itu, penyelidikan ini bertujuan untuk membangunkan rangka kerja penganggaran hujan dengan menggunakan data radar polarismetrik X-Band. Penyelidikan ini menggunankan pendekatan Penyelidikan Sains Reka Bentuk (DSR) sebagai metodologi. Pertama, kajian literatur sistematik, telah dijalankan untuk mengenalpasti sistem pemantauan radar cuaca semasa di Malaysia, dan mengkaji latar belakang teori radar polarismetrik X-Band dan aplikasinya, serta komponen rangka kerja radar polarismetrik X-band. Kedua, pelayan DPPC telah disediakan dengan kawasan kajian dan data hujan bagi bandar Kagoshima. Data kawasan kajian terdiri daripada Digital Elevation Model (DEM) dan kawasan saliran; manakala data hujan terdiri daripada radar polarismetrik X-Band dan data tanah AMeDAS. Ketiga, kompenan rangka – penyimpanan, alat analisis dan visualisasi - dianalisis menggunakan data radar polarismterik X-Band untuk memprosess data sebenar dan menganggarkan hujan di empat kawasan saliran terpilih. Analisis termasuk pra-pemprosesan data mentah, memotong DEM, memilih kawasan saliran, mengekstrak data hujan dan memplot hyetograph. Ini diikuti dengan analisis kebolehpercayaan anggaran hujan daripada pengekstrakan data hujan polarismetrik X-Band yang dianalisis dengan berdasarkan data tanah AMeDAS. Keputusan pengesahan menunjukkan bahawa terdapat korelasi positif yang sederhana antara polarimetrik X-Band dan AMeDAS dengan dengan $R^2$ sebanyak 0.24 dan $p = 0.009$. Selanjutnya, perbandingan hasil taburan hujan untuk kedua-dua data menggunakan QGIS menunjukkan bahawa data AMeDAS tidak menggambarkan hujan sebenar yang dipantau oleh radar polarismetrik X-Band kerana tiada stesen AMeDAS di kawasan saliran dan imej taburan daripada radar polarismetrik X-Band adalah dalam masa nyata. Keempat-empat kawasan saliran merekodkan hujan lebat di bahagian atas saliran dan menunjukkan lokasi sebenar yang mempunyai keamatan tertinggi serta kebarangkalian kawasan yang paling hampir dengan saliran yang akan banjir. Kesimpulannya, telah ditunjukkan bahawa rangka kerja yang baru telah dibangunkan bagi menterjemahkan data mentah sebenar radar polarismetrik X-Band ke dalam format data kejuruteraan yang boleh diakses dan ia boleh digunakan untuk menganggarkan hujan di kawasan setempat

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| | | |
|---|---|---|
| ALOS | - | Advanced Land Observing Satellite |
| AMeDAS | - | Automated Meteorological Data Acquisition System |
| API | - | Application Program Interface |
| ASCII | - | American Standard Code for Information Interchange |
| AWS | - | Automatic Weather Station |
| CAPPI | - | Constant Altitude Plan Position Indicator |
| CRS | - | Coordinate Reference System |
| csv | - | Comma Separated Value |
| dBZ | - | Decibel Relative to Z |
| DEM | - | Digital Elevation Model |
| DID | - | Department of Irrigation and Drainage |
| DP | - | Dual Polarisation |
| DPPC | - | Disaster Preparedness and Prevention Centre |
| DRM | - | Disaster Risk Management |
| DSD | - | Drop Size Distribution |
| DSM | - | Digital Surface Model |
| DSR | - | Design Science Research |
| DSRP | - | Design Science Research Process |
| EPSG | - | European Petroleum Survey Group |
| FTP | - | File Transfer Protocol |
| GeoTiff | - | Geostationary Earth Orbit Tagged Image File Format |
| GIS | - | Geographic Information System |
| GUI | - | Graphical User Interface |
| gz | - | Gzip Utility |
| HDD | - | Hard Disk Drive |
| HSQ | | Horizontal Sequence Scan |
| IRIS | - | Interactive Radar Information System |
| JASTIP | - | Japan-Asean Science, Technology and Innovation Platform |
| JAXA | - | Japan Aerospace Exploration Agency |
| JMA | - | Japan Meteorological Agency |

| | | |
|---|---|---|
| KLIA | - | Kuala Lumpur International Airport |
| KML | - | Keyhole Markup Language |
| LIMA | - | Langkawi International Maritime and Aerospace Exhibition |
| LTS | - | Long Time Support |
| MAP | - | Mean Areal Precipitation |
| MetMalaysia | - | Malaysian Meteorological Department |
| MJIIT | - | Malaysia-Japan International Institute of Technology |
| MLIT | - | Ministry of Land, Infrastructure, Transport and Tourism, Japan |
| MP | | Multi Parametric |
| NAS | - | Network-Attached Storage |
| NEXRAD | - | Next-Generation Radar network (USA) |
| NIED | | National Research Institute for Earth Science and Disaster, Japan |
| OBS | - | Observation Segment |
| PC | - | Personal Computer |
| PPI | - | Plan Position Indicator |
| PRISM | - | Panchromatic Remote-sensing Instrument for Stereo Mapping |
| QPE | - | Quantitative Precipitation Estimation |
| QPF | - | Quantitative Precipitation Forecast |
| RHI | - | Range Height Indicator |
| RO | - | Research Objective |
| SAGA | - | System for Automated Geoscientific Analyses |
| scn | - | Scenario File format |
| SLR | - | Systematic Literature Review |
| SPU | - | Signal Processing Unit |
| SQL | - | Structured Query Language. |
| ssh | - | Secure Shell protocol |
| SVO | - | Sakurajima Volcano Observatory |
| TDWR | - | Terminal Doppler Weather Radar |
| U.S.A | - | United States of America |
| UPS | - | Uninterruptable Power Supply |

| | | |
|---|---|---|
| UTM | - | Universal Transverse Mercator |
| UTM-KL | - | Universiti Teknologi Malaysia – Kuala Lumpur |
| VPN | - | Virtual Private Network |
| X-RAIN | - | X-band polarimetric RAdar Information Network, Japan |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $A$ | - | empirical radar coefficient |
| $b$ | - | empirical radar coefficient |
| $D$ | - | diameter of drop |
| $D_0$ | - | median volume diameter |
| $E$ | - | Expectation value |
| $f_d$ | - | frequency of the Doppler |
| $f_e$ | - | frequency of emitted wave |
| GHz | - | Giga hertz |
| kB | - | kilo byte |
| $K_{dp}$ | - | specific differential phase |
| $Kw$ | - | dielectric factor of water |
| MB | - | Mega Byte |
| $N(D)$ | - | drop size distribution, |
| $N_w$ | - | intercept parameter |
| $R$ | - | rainfall intensity |
| $v$ | - | average terminal velocity |
| $v(D)$ | - | terminal velocity of a rain drops with the diameter $D$ |
| $Z$ | - | reflectivity (factor), |
| $Z_{dr}$ | - | ratio of horizontal reflectivity ($Z_h$) and vertical reflectivity ($Z_v$) |
| $Z_h$ | - | horizontal reflectivity of polarization wave |
| $Z_v$ | - | vertical reflectivity of polarization wave |
| $\Gamma$ | - | Gamma function |
| $\Delta\Phi_{DP}(D)$ | - | difference in both phase shifts |
| $\varepsilon_r$ | - | complex dielectric constant of water |
| $\lambda$ | - | wavelength |
| $\mu$ | - | measure of the shape of drop size distribution |
| $\sigma_h$ | - | horizontal cross sections |
| $\sigma_v$ | - | vertical radar cross sections |
| $\Phi_{DP}$ | - | difference of phase shifts |

| | | |
|---|---|---|
| $\Phi_h(D)$ | - | shift in horizontal phase |
| $\Phi v(D)$ | - | shift in vertical phase |

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Problem

Intense and localized rainfall can induce severe natural disasters such as flood, debris flow and landslide (Wang et al., 2019). These disasters usually happen due to the long duration of rainfall with a high intensity, however, in some cases such as flash flood, the disaster occurs when the amount of downpour is very intense even if it happens in a short period of time, especially, in the urban area (Anderson and Sitar, 1995, Farisham, 2007).Thus, for the disaster preparedness and prevention measures, an integrated high-resolution and real-time rainfall monitoring system is required. Such system is crucial for collecting information regarding the rainfall intensity and its attributes in high resolution on the potential hazards such as flood, debris flow, flash flood and landslide that are caused by the accumulation of precipitation in excess (Nishio and Mori, 2016).

For many years, the rain gauge is one of the standard tools to measure the rainfall with limited information on spatial rainfall variability. It captures the actual rainfall events on the ground level (van de Beek et al., 2010, Allegretti et al., 2012, Bertoldo et al., 2016). A rain gauge needs to be placed in the open area with no obstacle such as building or tree that may block the rain and result in inaccurate readings. Even though the rain gauge system can provide real-time cumulative information if connected by a network, its planar resolution depends on physical installation of devices and is naturally limited. Weather radar, on the other hand, offers the potentialities to estimate the precipitation in advance by monitoring movements of rain cloud before it reaches the area of interest. The advanced Nowcast models, which predict and estimate the near future event of a few hours from now, can be used to predict the precipitation intensity by using the rainfall motion detection (Hirano and Maki, 2010, Hirano et al., 2014). Moreover, the weather radar is capable of taking snapshots of the radar reflectivity above the ground (Nielsen et al., 2014, Reyniers, 2008). For that reason, the weather radar has been applied to monitor rainfall related disasters. The conventional radars such as C-Band and S-Band radars have been extensively operated as weather radars to perform rainfall monitoring over a long range while X-Band conventional radar, which has a shorter range but a higher resolution than C- and S-Band radars , has been used in the military, aviation and marine sectors (Arturi et al., 2016, Einfalt et al., 2004).

In recent meteorological research, some countries such as Japan, Indonesia and U.S.A. have been using X-Band polarimetric radars in disaster risk management. Use of X-Band radar and its integration with polarimetric techniques has also risen in a few European countries, including Italy, France, and Germany (Cremonini et al., 2012). Simply stated, X-Band polarimetric radar system is a combination of X-Band radar with multiparametric or dual polarization technique. The systems can provide the valuable data for meteorological and hydrological studies and analyses, especially in short range due to its wavelength (Zrnic and Ryzhkov, 1999, Chandrasekar et al., 2002). Examples of the valuable data available with X-Band polarimetric radar include Quantitative Precipitation Estimation (QPE), Quantitative Precipitation Forecast (QPF) and Drop Size Distribution (DSD). The application of this type of radar for rainfall monitoring is vital, since the information obtained (such as the amount of rainfall) is particularly useful for the government and private agencies to help each other to prepare for any circumstances of rainfall related disaster (Allegretti et al., 2012, Chandrasekar et al., 2012). However, there is no systematic and theoretical study conducted on X-Band polarimetric radar application in disaster risk management fields in Malaysia. Many researches have been made basically on the analytical method by weather radar and the rainfall estimation process in case studies, for instance, by Diss et al. (2009), Kurdzo et al. (2015) and Koffi et al. (2014). In addition, a limited number of researchers have discussed the desired structure of the monitoring and data management systems, especially, based upon X-Band polarimetric radars. There is no integrated rainfall monitoring system in operation in ASEAN based on the X-Band polarimetric radar data as pointed by Nishio and Mori (2018).

For the country like Malaysia to implement the application of rainfall estimation system by using X-Band polarimetric radar, the framework of the integrated radar and database system is needs to be established. Malaysia is in the tropical region a few degrees north of the equator in latitude that has a uniform temperature and high humidity throughout the year, and seasonal heavy rainfall in monsoon seasons. The average annual rainfall for Peninsular Malaysia is 2420 mm, while 2630 mm in Sabah and 3830 mm in Sarawak of rain per year (Ahmad et al., 2017). Due to the climatic conditions, Malaysia is prone to various forms of water-related disasters such as floods, flash floods, landslides, and debris flows. For example, Malaysia has been experiencing flood events during the north-east monsoon season, especially, in November and December every year. Recent severe disasters include the flood in Kelantan in December 2014 (Tahir et al., 2017, Gasim et al., 2015). Flash flood and landslide disasters have repeatedly occurred in the surrounding areas of Kuala Lumpur such as at Ulu Klang in 1993 (Althuwaynee et al., 2015, Mukhlisin et al., 2015).

In Malaysia there are two government agencies that are responsible to monitor rainfall events which are the Department of Irrigation and Drainage (DID) of Malaysia and the Malaysian Meteorological Department (MetMalaysia) (MMD, 2017). The DID is responsible to prepare the information regarding hazard level and disseminate it to the government, private sectors and publics sectors (DID, 2009). For this purpose, the DID monitors the rainfall events 24 hours a day. The MetMalaysia is responsible to report current weather conditions and issues weather for forecast. Currently, MetMalaysia operates long range, conventional C-Band and S-Band weather radars (Adam and Moten, 2012, Mahyun et al., 2014).

In 2009, an X-Band mobile radar which was not polarimetric system was introduced to Malaysia as the first X-Band weather radar in the country, which was demonstrated at Langkawi International Maritime and Aerospace Exhibition (LIMA). The same X-Band mobile radar was used by the MetMalaysia to evaluate the effects of cloud seeding experiments in 2010 when Malaysia was suffering from significant decrease in rainfall due to El Nino phenomenon off the coast of Peru in the eastern pacific (MetMalaysia, 2009, MetMalaysia, 2010). However, there has not been any additional project on X-Band weather radar conducted up to today.

## 1.2 Problem Statement

In the context of disaster preparedness, an early warning system is the fundamental means that has been implemented to prevent or mitigate damages and losses of property and life caused by disasters. Early warning systems can make big contributions to reduction in the burden of the response and recovery phases, if prompt and accurate (Khalid and Shafiai, 2015). As flood often occurs and become a major disaster in Malaysia, the studies on flood management system are actively in the centre. One of the demands in implementing the effective flood management system is the desire on processing and providing the disaster information such as rainfall data, the disaster area and many more (Khalid and Shafiai, 2015). Meanwhile, one of the strategies to acquire the knowledge for flood management system are by using the monitoring networks and information systems where it can provides the data related to the disaster in real time and accurate (Mansor et al., 2004). From the review of exploring and managing flood disaster from Malaysian perspective by Yusoff et al. (2018) saying that the utilization of technology in disaster will lead the effective and efficient problem solving.

However, disaster information such as rainfall data that commonly used and applied in Malaysia are using telemetric rain gauge that been handled by DID. Although, MetMalaysia have bought the 3 cm X-Band mobile radar, still there is no available official report or technical papers discussed regarding the application of X-Band radar in Malaysia. Apart from that, there is no X-Band polarimetric radar system available in Malaysia until today for a better nowcasting as well as for forecasting. Therefore, the aim of this research is to establish the X-Band polarimetric radar system framework for rainfall estimation in a selected local area, primarily intended for the applications in disaster risk management.

## 1.3 Research Objectives

Therefore, in this research to attain the aim, there are three specific objectives as follows:

1. To identify the X-Band polarimetric radar rainfall estimation system framework components as well as its approach in Disaster Risk Management (DRM) and evaluates the current weather radar monitoring systems in Malaysia.

2. To establish requirements of X-Band polarimetric radar rainfall estimation system framework for DRM.

3. To evaluate and analyse the X-Band polarimetric radar rainfall estimation system framework in selected localised area.

## 1.4 Scope of the Study

The research was conducted within the scope as follows:

1. This research was focused and designed to develop, evaluate, and propose a framework of X-Band polarimetric radar rainfall estimation system for Malaysia.

2. This research was focused on the X-Band polarimetric radar data conversion to readable format and its analysis for rainfall estimation. The system includes hierarchical data dissemination protocol and geographical presentation of the data.

3. Real X-Band polarimetric radar data collected in Kagoshima City, Japan, and actual rainfall data collected in the vicinity by Automated Meteorological Data Acquisition System (AMeDAS) stations were used in the study. There has been no X-Band polarimetric weather radar in operation in Malaysia until today.

4. The data collected in Japan were processed by using DPPC server that have been set up in Japan ASEAN Science and Technology Initiative Platform (JASTIP) office, at MJIIT-UTM-KL

## 1.5 Significance and Contribution of the Study

The significance and contributions in knowledge of this research are as follows.

1. Accumulation of more comprehensive knowledge to understand the advantages and disadvantages of X-Band polarimetric radar technology in rainfall estimation as well as the implementation requirements in Malaysia.

2. The research outcome presents the framework that processed the raw radar data and convert the data into rainfall intensity with high resolution which can be applied to Malaysia and elsewhere.

3. Once the X-Band polarimetric radar is installed in Malaysia, an integrated system of data acquisition, accumulation, and storage, conversion to engineering units, visual presentation, and appropriate accessibility classifications will be ready for use.

4. The processed rainfall data from this framework can be utilised for hydrological model development or improvement such as flood prediction model.

## 1.6 Thesis Structure

**Chapter 1** - This is the introductory chapter, and it provides an overview of the research. It starts with identifying the research context and research problem. Furthermore, the research's aim and objectives, as well as its scope, are identified. Before concluding with the Chapter Summary, the significance and contribution of the study are discussed.

**Chapter 2 -** This chapter contains an expanded section from the research background. This chapter's review began with a discussion of the importance of rainfall events in the disaster field. Following that, the cause of the rain-induced disaster and rainfall monitoring in Malaysia are discussed. There is also a review of a weather radar system available in Malaysia. The weather radar characteristics have been reviewed in order to gain a better understanding of weather application for disasters. In addition to the system, the use of X-Band polarimetric radar is demonstrated. The framework and components which are Storage Segment, Analysis Tools and Visualization of the X-Band polarimetric radar system are then examined. This chapter concludes with a summary of the chapter.

**Chapter 3 -** The chosen methodology and the steps involved in achieving the study's objectives is describe in this chapter. The method defines how the data are gathered, organized, and processed and produce the results. In this research, the author proposes the research approach which is Design Science Research Process (DSRP) that consists of six activities which are 1) Problem identification and motivation, 2) Define the for the solutions, 3) Design and development, 4) Demonstration, 5) Evaluation and 6) Communication. All the activities are following seven guidelines and the three-design cycle that have emphasis by DSR research communities to achieve research objectives.

**Chapter 4 -** This chapter first describes the rainfall data collected from the X-Band polarimetric radar and the ground data by AMeDAS system in Kagoshima city. Following, data collection analysis was demonstrated, which included rainfall analysis and reliability analysis. Further, the analysis result is validated to ensure that the results are effective. This chapter concluded with a summary of the chapter.

**Chapter 5 -** In this section, all the research objectives achievement for this research are concluded. Some recommendations of futures studies are elaborated and end with chapter summary.

## 1.7 Chapter Summary

This chapter provides an overview of the research in the field DRM. By focusing on rainfall estimation issues and the advancement of radar technology for disaster prevention, there is a need to apply the X-Band polarimetric radar for the localised area in estimating accurate rainfall data. However, because this is a new approach that has been studied for Malaysia, there are some limitations of this research that have been highlighted. This chapter also discussed the importance and contribution of this approach, particularly in Malaysia.

## REFERENCES


ADAM, M. K. M. & MOTEN, S. 2012. Rainfall Estimation from Radar Data. *Research Publication of Malaysian Meteorological Department (MMD) & Ministry of Science, Technology and Innovation (MOSTI),* No.6

AHMAD, F., USHIYAMA, T. & SAYAMA, T. 2017. Determination of ZR Relationship and Inundation Analysis for Kuantan River Basin. *Malays. Meterol. Dep. Res. Publ,* 2**,** 55.

ALLEGRETTI, M., BERTOLDO, S., PRATO, A., LUCIANAZ, C., RORATO, O., NOTARPIETRO, R. & GABELLA, M. 2012. X-Band Mini Radar for Observing and Monitoring Rainfall Events. *Atmospheric and Climate Sciences,* 2**,** 290-297.

ALTHUWAYNEE, O. F., PRADHAN, B. & AHMAD, N. 2015. Estimation of Rainfall Threshold and Its Use in Landslide Hazard Mapping of Kuala Lumpur Metropolitan and Surrounding Areas. *Landslides,* 12**,** 861-875.

ANAGNOSTOU, M. N., ANAGNOSTOU, E. N. & VIVEKANANDAN, J. 2006. Correction for Rain Path Specific and Differential Attenuation of X-Band Dual-Polarization Observations. *IEEE Transactions on Geoscience and Remote Sensing,* 44**,** 2470-2480.

ANAGNOSTOU, M. N., KALOGIROS, J., ANAGNOSTOU, E. N., TAROLLI, M., PAPADOPOULOS, A. & BORGA, M. 2010. Performance Evaluation of High-Resolution Rainfall Estimation By X-Band Dual-Polarization Radar for Flash Flood Applications in Mountainous Basins. *Journal of Hydrology,* 394**,** 4-16.

ANDERSON, S. A. & SITAR, N. 1995. Analysis of Rainfall-Induced Debris Flows. *Journal of Geotechnical Engineering,* 121**,** 544-552.

ARTURI, D., CROCCO, L. & SERAFINO, F. X band radar target tracking in marine environment: A comparison of different algorithms in a real scenario. Antennas and Propagation (EuCAP), 2016 10th European Conference on, 2016. IEEE, 1-3.

ASANOBU, K. 2021. *Weather Radar and AMeDAS Data* [Online]. Japan. [Accessed 8 August 2021].

BANDARA, W., MISKON, S. & FIELT, E. A systematic, tool-supported method for conducting literature reviews in information systems. ECIS 2011 proceedings [19th European conference on information systems], 2011. AIS Electronic Library (AISeL)/Association for Information Systems, 1-13.

BERNAMA. 2011a. Hujan Berterusan Punca Tanah Runtuh. *Utusan Online*.

BERNAMA. 2011b. Kronologi kejadian tanah runtuh di negara ini. *Utusan Online*.

BERTOLDO, S., LUCIANAZ, C., ALLEGRETTI, M. & PERONA, G. 2016. Real Time Monitoring of Extreme Rainfall Events with Simple X-Band Mini Weather Radar. *Atmospheric and Climate Sciences,* 6**,** 285.

CHANDRASEKAR, V., CHEN, H. & MAKI, M. Urban flash flood applications of high-resolution rainfall estimation by X-band dual-polarization radar network. *In:* HAYASAKA, T. & NAKAMURA, K., eds. Proc. SPIE 8523 Remote Sensing of the Atmosphere, Clouds, and Precipitation IV, 8 November 2012 2012 Kyoto, Japan. 85230K.

CHANDRASEKAR, V., GORGUCCI, E. & BALDINI, L. Evaluation of Polarimetric Radar Rainfall Algorithms at X-Band. Proceedings ERAD 2002, 2002. 277-281.

CHANDRASEKAR, V., LIM, S. & GORGUCCI, E. 2006. Simulation of X-Band rainfall Observations from S-Band Radar Data. *Journal of Atmospheric and Oceanic Technology,* 23**,** 1195-1205.

CHEN, H., LIM, S., CHANDRASEKAR, V. & JANG, B.-J. 2017. Urban hydrological applications of dual-polarization X-band radar: Case study in Korea. *Journal of Hydrologic Engineering,* 22**,** E5016001.

CHEN, R., SHARMAN, R., RAO, H. R. & UPADHYAYA, S. J. 2008. Coordination in Emergency Response Management. *Communications of the ACM,* 51**,** 66-73.

COLE, R., PURAO, S., ROSSI, M. & SEIN, M. 2005. Being Proactive: Where Action Research Meets Design Research. *ICIS 2005 Proceedings***,** 27.

CREMONINI, R., TABARY, P., SUGIER, J., FRECH, M., ALBERONI, P., BALDINI, L., HUUSKONEN, A., VOCINO, A., PIEMONTE, A. & TORINO, I. Evaluation of X-Band Radar Technologies within Opera 3 Project. 7th European Conference on Radar in Meteorology and Hydrology (Toulouse, France), 2012. 24-29.

CROWDER, M. J. 2017. *Statistical Analysis of Reliability Data*, Routledge.

DID 2009. Department of Irrigation and Drainage of Malaysia Manual - Hydrology and Water Resources. *In:* DRAINAGE, D. I. I. A. (ed.). Malaysia.

DIRAYATI, K. 2017. *Analisis Pengaruh Jarak Terhadap Perbandingan Hujan Radar dan Hujan Permukaan Studi Kasus: Wilayah Lereng Selatan Gunung Merapi.* Universitas Gadjah Mada.

DISS, S., TESTUD, J., LAVABRE, J., RIBSTEIN, P., MOREAU, E. & DU CHATELET, J. P. 2009. Ability of a Dual Polarized X-band Radar to Estimate Rainfall. *Advances in Water Resources,* 32**,** 975-985.

EINFALT, T., ARNBJERG-NIELSEN, K., GOLZ, C., JENSEN, N.-E., QUIRMBACH, M., VAES, G. & VIEUX, B. 2004. Towards a roadmap for use of radar rainfall data in urban drainage. *Journal of Hydrology,* 299**,** 186-202.

FAJRIANI, Q., JAYADI, R., LEGONO, D. & SUJONO, J. The Reliability of X-Band Multiparameter Radar Rainfall Estimates. IOP Conference Series: Earth and Environmental Science, 2021. IOP Publishing, 012060.

FARISHAM, A. S. Landslides in the Hillside Development in the Hulu Klang, Klang Valley. Post-Graduate Seminar Semester 2 Session 2006/2007, 2007. UTM.

FURUNO 2016. Operator Manual Compact Dual Polarimetric X-band Doppler Weather Radar - W2100. *In:* FURUNO (ed.).

GASIM, M. B., TORIMAN, M. E., KAMARUDIN, M. K. A. & AZID, A. 2015. Fenomena Banjir Terburuk di Kelantan Sepanjang Musim Monsun di Pantai Timur Semenanjung.

HAPSARI, R. I., OISHI, S., SYARIFUDDIN, M., ASMARA, R. A. & LEGONO, D. 2019. X-MP Radar for Developing a Lahar Rainfall Threshold for the Merapi Volcano Using a Bayesian Approach. *Journal of Disaster Research,* 14**,** 811-828.

HEVNER, A. & CHATTERJEE, S. 2010. *Design Research in Information Systems: Theory and Practice*, Springer Science & Business Media.

HEVNER, A. R. 2007. A three cycle view of design science research. *Scandinavian journal of information systems,* 19**,** 4.

HIRANO, K. & MAKI, M. 2010. Method of VIL Calculation for X-band Polarimetric Radar and Potential of VIL for Nowcasting of Localized Severe Rainfall : Case Study of the Zoshigaya Downpour, 5 August 2008. *Scientific Online Letters on the Atmosphere (SOLA),* 6**,** 89-92.

HIRANO, K., MAKI, M., MAESAKA, T., MISUMI, R., IWANAMI, K. & TSUCHIYA, S. Composite Rainfall Map from C-Band Conventional and X-Band Dual-Polarimetric Radars for the Whole of Japan. 8th European Conference on Radar in Meteorology and Hydrology, 2014.

HOLLEMAN, I. & BEEKHUIS, H. 2005. Evaluation of Three Radar Product Processors. Citeseer.

INAN, D. I. & BEYDOUN, G. 2017. Disaster Knowledge Management Analysis Framework Utilizing Agent-Based Models: Design Science Research Approach. *Procedia Computer Science,* 124**,** 116-124.

IWAMATSU, A. 1995. *Natural Disasters in Kagoshima Prefecture* [Online]. Kagoshima, Japan: Kagoshima University. Available: https://www.sci.kagoshima-u.ac.jp/oyo/natural_e.html [Accessed].

JAPAN, T. C. O. 2018. *White Paper on Disaster Management in Japan* [Online]. Japan. Available: http://www.bousai.go.jp/kaigirep/hakusho/pdf/H30_hakusho_english.pdf [Accessed].

JÄRVINEN, P. 2007. Action Research is Similar to Design Science. *Quality & Quantity,* 41**,** 37-54.

JAXA. 1997. *AW3D30 DSM Data Map* [Online]. JAXA. Available: https://www.eorc.jaxa.jp/ALOS/en/aw3d30/data/index.htm [Accessed 2019].

JOUSSET, P., PALLISTER, J., BOICHU, M., BUONGIORNO, M. F., BUDISANTOSO, A., COSTA, F., ANDREASTUTI, S., PRATA, F., SCHNEIDER, D. & CLARISSE, L. 2012. The 2010 Explosive Eruption of Java's Merapi Volcano - A '100-year' Event. *Journal of Volcanology and Geothermal Research,* 241**,** 121-135.

KATO, A. & MAKI, M. 2009. Localized Heavy Rainfall Near Zoshigaya, Tokyo, Japan on 5 August 2008 Observed by X-band Polarimetric Radar - Preliminary Analysis. *Scientific Online Letters on the Atmosphere (SOLA),* 5**,** 89-92.

KATO, A., MAKI, M., IWANAMI, K., MISUMI, R. & MAESAKA, T. 2009. Nowcasting of Precipitation Based on Complementary Application Of X-Band Polarimetric Radar and C-Band Conventional Radar. *Journal of Japan Society of Hydrology and Water Resources,* 22**,** 372-385.

KATO, A., MAKI, M., IWANAMI, K., MISUMI, R. & MAESAKA, T. 2012. Quantitative Precipitation Estimate by Complementary Application of X-Band Polarimetric Radar and C-Band Conventional Radar. *Wather Radar and Hydrology,* 351**,** 169-175.

KHAIROLANUAR, M. H., ISMAIL, A. F., JUSOH, A. Z. & SOBLI, N. H. 2015. Classification of Rain Types For Rain Attenuation Prediction Method Improvement Based on Radar Information in Tropics. *ARPN Journal of Engineering and Applied Sciences,* 10**,** 7202-7205.

KHALID, M. S. B. & SHAFIAI, S. B. 2015. Flood Disaster Management in Malaysia: An Evaluation of the Effectiveness Flood Delivery System. *International Journal of Social Science and Humanity,* 5**,** 398.

KIM, D. S. & MAKI, M. 2012. Validation of composite polarimetric parameters and rainfall rates from an X-band dual-polarization radar network in the Tokyo metropolitan area. *Hydrological Research Letters,* 6**,** 76-81.

KOFFI, A., GOSSET, M., ZAHIRI, E.-P., OCHOU, A., KACOU, M., CAZENAVE, F. & ASSAMOI, P. 2014. Evaluation of X-Band polarimetric Radar Estimation of Rainfall and Rain Drop Size Distribution Parameters in West Africa. *Atmospheric Research,* 143**,** 438-461.

KURDZO, J. M., BODINE, D. J., CHEONG, B. L. & PALMER, R. D. 2015. High Temporal Resolution Polarimetric X-Band Doppler radar Observations of the 20 May 2013 Moore, Oklahoma, Tornado. *Monthly Weather Review,* 143**,** 2711-2735.

LAM, H., DIN, J. & JONG, S. L. Evaluation of Small-Scale Spatial Distribution of Rain Cells in Equatorial Malaysia for Rain Attenuation Modeling. 2014 IEEE Asia-Pacific Conference on Applied Electromagnetics (APACE), 2014. IEEE, 12-15.

LAM, H., LUINI, L., DIN, J., CAPSONI, C. & PANAGOPOULOS, A. Preliminary Investigation of Rain Cells In Equatorial Malaysia for Propagation Applications. 2013 IEEE International RF and Microwave Conference (RFM), 2013. IEEE, 243-246.

LEE, A. S., THOMAS, M. A. & BASKERVILLE, R. L. 2013. Going Back to Basics in Design: From the IT Artifact to the IS Artifact.

LIM, S., LEE, D.-R., CIFELLI, R. & HWANG, S. H. 2014. Quantitative Precipitation Estimation for an X-Band Dual-Polarization Radar in the Complex Mountainous Terrain. *KSCE Journal of Civil Engineering,* 18**,** 1548.

LY, S., CHARLES, C. & DEGRÉ, A. 2013. Different Methods For Spatial Interpolation Of Rainfall Data For Operational Hydrology And Hydrological Modeling At Watershed Scale: A Review. *Biotechnologie, Agronomie, Société et Environnement,* 17**,** 392-406.

MAESAKA, T. Operational Rainfall Estimation by X-band MP Radar Network in MLIT, Japan. Proc. 35th Conf. on Radar Meteor., Pittsburgh, USA, Sep. 2011, 2011.

MAGNUSSON, M., NYBERG, L. & WIK, M. 2018. Information systems for disaster management training: investigating user needs with a design science research approach. *Proceedings ISCRAM2018*.

MAHYUN, A., ABDULLAH, R., ABUSTAN, I., ADAM, M. & AA, N. A. 2014. The Radar-Rainfall Relationship for Northern Region of Peninsular Malaysia. *International Journal of Innovation, Management and Technology,* 5**,** 143.

MAKI, M., IGUCHI, M., MAESAKA, T., MIWA, T., TANADA, T., KOZONO, T., MOMOTANI, T., YAMAJI, A. & KAKIMOTO, I. 2016. Preliminary Results of Weather Radar Observations of Sakurajima Volcanic Smoke. *Journal of Disaster Research,* 11**,** 15-30.

MAKI, M., IWANAMI, K., MISUMI, R., DOVIAK, R., WAKAYAMA, T., HATA, K. & WATANABE, S. Observation of Volcanic Ashes With a 3-Cm Polarimetric Radar. 30th International Conference on Radar Meteor, 2001.

MAKI, M., MAESAKA, T., KATO, A., KIM, D. & IWANAMI, K. 2012. Developing a Composite Rainfall Map Based on Observations from an X-Band Polarimetric Radar Network and Conventional C-Band Radar. *Indian Journal of Radio & Space Physics* 41 461-470

MANSOR, S., SHARIAH, M. A., BILLA, L., SETIAWAN, I. & JABAR, F. 2004. Spatial Technology for Natural Risk Management. *Disaster Prevention and Management: An International Journal*.

MARZANO, F. S., PICCIOTTI, E., VULPIANI, G. & MONTOPOLI, M. 2011. Synthetic signatures of volcanic ash cloud particles from X-band dual-

polarization radar. *IEEE transactions on geoscience and remote sensing,* 50**,** 193-211.
MATROSOV, S. Y., CLARK, K. A., MARTNER, B. E. & TOKAY, A. 2002. X-band polarimetric radar measurements of rainfall. *Journal of Applied Meteorology,* 41**,** 941-952.
MEISCHNER, P., COLLIER, C., ILLINGWORTH, A., JOSS, J. & RANDEU, W. 1997. Advanced Weather Radar Systems in Europe: The COST 75 Action. *Bulletin of the American Meteorological Society,* 78**,** 1411-1430.
METMALAYSIA 2009. Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2009. *In:* METMALAYSIA, M. (ed.). Malaysia: Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI).
METMALAYSIA 2010. Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2010. *In:* METMALAYSIA, M. (ed.). Malaysia: Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI).
METMALAYSIA 2013. Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2013. *Weather Observation And Monitoring.* Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI).
MMD. 2017. *Laman Web Rasmi Jabatan Meterologi Malaysia* [Online]. Available: http://www.met.gov.my [Accessed].
MUKHLISIN, M., MATLAN, S. J., AHLAN, M. J. & TAHA, M. R. 2015. Analysis of Rainfall Effect to Slope Stability in Ulu Klang, Malaysia. *Jurnal Teknologi (Sciences & Engineering)***,** 15-21.
NEELY III, R. R., BENNETT, L., BLYTH, A., COLLIER, C., DUFTON, D., GROVES, J., WALKER, D., WALDEN, C., BRADFORD, J., BROOKS, B., ADDISON, F. I., NICOL, J. & PICKERING, B. 2018. The NCAS Mobile Dual Polarisation Doppler X-Band Weather Radar (NXPol). *Atmos. Meas. Tech.,* 11**,** 6481-6494.
NEWKIRK, B. E. 2016. *Rainfall Estimation from X-band Polarimetric Radar and Disdrometer Observation Measurements Compared to NEXRAD Measurements: An Application of Rainfall Estimates.* Meterology Senior Thesis, Iowa State University
NIED 2005. Rainfall Observation by X-Band Multi-Parameter Radar. *In:* NIED (ed.) *National Research Institute for Earth Science and Disaster Prevention.* Ibaraki, Japan: National Research Institute for Earth Science and Disaster Prevention.
NIELSEN, J. E., THORNDAHL, S. & RASMUSSEN, M. R. 2014. Improving Weather Radar Precipitation Estimates by Combining Two Types of Radars. *Atmospheric Research,* 139**,** 36-45.
NIKAHD, A. 2018. Altitudes Effects in Calibration of Ground Doppler Radar for Rainfall Estimation.
NISHIO, M. & MORI, M. Precipitation Analysis by X-band MP Radar Sata Using Google Earth. 2013 IEEE International Geoscience and Remote Sensing Symposium-IGARSS, 2013. IEEE, 570-573.
NISHIO, M. & MORI, M. 2016. Analysis of Debris Flow Disaster Due to Heavy Rain by X-Band MP Radar Data *The International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences* Prague, Czech Republic

NISHIO, M. & MORI, M. 2018. The web‐based accumulated rainfall amount monitoring system by X‐band MP radar. *Journal of Flood Risk Management,* 11**,** S222-S232.
PALLISTER, J. S., SCHNEIDER, D. J., GRISWOLD, J. P., KEELER, R. H., BURTON, W. C., NOYLES, C., NEWHALL, C. G. & RATDOMOPURBO, A. 2013. Merapi 2010 Eruption - Chronology and Extrusion Rates Monitored with Satellite Radar and Used in Eruption Forecasting. *Journal of Volcanology and Geothermal Research,* 261**,** 144-152.
PARK, S., BRINGI, V., CHANDRASEKAR, V., MAKI, M. & IWANAMI, K. 2005. Correction of Radar Reflectivity and Differential Reflectivity for Rain Attenuation at X Band. Part I: Theoretical and Empirical Basis. *Journal of Atmospheric and Oceanic Technology,* 22**,** 1621-1632.
PEFFERS, K., TUUNANEN, T., GENGLER, C. E., ROSSI, M., HUI, W., VIRTANEN, V. & BRAGGE, J. The design science research process: A model for producing and presenting information systems research. Proceedings of the First International Conference on Design Science Research in Information Systems and Technology (DESRIST 2006), Claremont, CA, USA, 2006. 83-106.
PEFFERS, K., TUUNANEN, T., ROTHENBERGER, M. A. & CHATTERJEE, S. 2007. A Design Science Research Methodology for information Systems Research. *Journal of Mmanagement Information Systems,* 24**,** 45-77.
PUTRA, S. S., RIDWAN, B. W., YAMANOI, K., SHIMOMURA, M. & HADIYUWONO, D. 2019. Point-Based Rainfall Intensity Information System in Mt. Merapi Area by X-Band Radar. *Journal of Disaster Research,* 14**,** 80-89.
QUIRMBACH, M. & SCHULTZ, G. 2002. Comparison of Rain Gauge And Radar Data as Input to an Urban Rainfall-Runoff Model. *Water Science and Technology,* 45**,** 27-33.
RATIH INDRI HAPSARI, GERARD APONNO, ROSA ANDRIE ASMARA & OISHI, S. 2018. Rainfall Information System Based on Weather Radar for Debris Flow Disaster Mitigation. *International Journal of Engineering & Technology,* 7 165-171.
REBA, M., ROSLAN, N., SYAFIUDDIN, A. & HASHIM, M. Evaluation of Empirical Radar Rainfall Model During the Massive Flood in Malaysia. Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International, 2016. IEEE, 4406-4409.
REYNIERS, M. 2008. *Quantitative precipitation forecasts based on radar observations: Principles, algorithms and operational systems*, Institut Royal Météorologique de Belgique.
ROSENFELD, D. & ULBRICH, C. W. 2003. Cloud Microphysical Properties, Processes, and Rainfall Estimation Opportunities. *In:* WAKIMOTO, R. M. & SRIVASTAVA, R. (eds.) *Radar and Atmospheric Science: A Collection of Essays in Honor of David Atlas.* Boston, MA: American Meteorological Society.
SALEEM, I., ASLAM, M. & AZAM, M. 2013. The use of Statistical Methods in Mechanical Engineering. *Research Journal of Applied Sciences, Engineering and Technology,* 5**,** 2327-2331.
SANO, H., IKOMA, E., KITSUREGAWA, M. & OGUCHI, M. Implementation of Disaster Prevention Oriented Information Service Platform of XRAIN on

DIAS. 2017 IEEE International Congress on Big Data (BigData Congress), 2017. IEEE, 398-405.
SCHRYEN, G. & WEX, F. IS design thinking in disaster management research. 2012 45th Hawaii International Conference on System Sciences, 2012. IEEE, 4102-4111.
SEBASTIANELLI, S., RUSSO, F., NAPOLITANO, F. & BALDINI, L. 2013. On Precipitation Measurements Collected By a Weather Radar and a Rain Gauge Network. *Natural Hazards and Earth System Sciences,* 13**,** 605-623.
SIMON, H. 1996. The Sciences of the Artificial (Vol. 1). Cambridge, MA.: MIT Press.
SOBLI, N., ISMAIL, A. F., ISA, F. & MANSOR, H. Initial Assessment of Radar Reflectivity-Rainfall Rate, ZR Relationships for Moderate Rain Events in Malaysia. 2013 IEEE Symposium on Wireless Technology & Applications (ISWTA), 2013a. IEEE, 187-191.
SOBLI, N. H., ISMAIL, A. F., MD ISA, F. N. & MANSOR, H. 2013b. Assessment of Radar Reflectivity-rainfall Rate, ZR Relationships for a Convective Event in Malaysia. *International Journal of Electrical Energy,* 1**,** 239-243.
SUYONO, S. & TAKEDA, K. 2003. Hidrologi Untuk Pengairan. *Jakarta, Indonesia*.
SUZANA, R., WARDAH, T. & HAMID, A. S. 2011. Radar Hydrology: New Z/R Relationships for Klang River Basin Malaysia based on Rainfall Classification. *International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering,* 5**,** 684-688.
SYARIFUDDIN, M., HAPSARI, R. I., LEGONO, D., OISHI, S., MAWANDA, H. G., AISYAH, N., SHIMOMURA, M., NAKAMICHI, H. & IGUCHI, M. Monitoring the Rainfall Intensity At Two Active Volcanoes In Indonesia And Japan By Small-Compact X-Band Radars. IOP Conference Series: Earth and Environmental Science, 2020. IOP Publishing, 012040.
SYARIFUDDIN, M., OISHI, S., HAPSARI, R. I., SHIOKAWA, J., MAWANDHA, H. G. & IGUCHI, M. 2019. Estimating the Volcanic Ash Fall Rate from the Mount Sinabung Eruption on February 19, 2018 Using Weather Radar. *Journal of Disaster Research,* 14**,** 135-150.
SYARIFUDDIN, M., OISHI, S., LEGONO, D., HAPSARI, R. I. & IGUCHI, M. 2017. Integrating X-MP Radar Data to Estimate Rainfall Induced Debris Flow in the Merapi Volcanic Area. *Advances in Water Resources,* 110**,** 249-262.
SYARIFUDDIN, M., OISHI, S., NAKAMICHI, H. & IGUCHI, M. 2018. Spatiotemporal Distribution of Rainfall in Mount Sakurajima Based on Weather Radar. *水工学論文集 Annual Journal of Hydraulic Engineering, JSCE,* 63**,** I_187-192.
TAHIR, W., AMINUDDIN, A. K., RAMLI, S. & JAAFAR, J. 2017. Quantitative precipitation forecast using numerical weather prediction and meteorological satellite for Kelantan and Klang river basins. *Jurnal Teknologi,* 79**,** 45-53.
TOMASZEWSKI, B., JUDEX, M., SZARZYNSKI, J., RADESTOCK, C. & WIRKUS, L. 2015. Geographic Information Systems for Disaster Response: A Review. *Journal of Homeland Security and Emergency Management,* 12**,** 571-602.
TOSHIYA, T. 2011. Evolution of Debris Flow Monitoring Methods on Sakurajima. *International Journal of Erosion Control Engineering,* 4**,** 21-31.
ULRICH, P., BECKER, W., FIBITZ, A., REITELSHÖFER, E. & SCHUHKNECHT, F. 2018. Data Analytics Systems and SME Type- A Design Science Approach. *Procedia Computer Science,* 126**,** 1162-1170.

VAN DE BEEK, C., LEIJNSE, H., STRICKER, J., UIJLENHOET, R. & RUSSCHENBERG, H. 2010. Performance of High-Resolution X-Band Radar for Rainfall Measurement in The Netherlands. *Hydrology and Earth System Sciences,* 14**,** 205-221.

VOM BROCKE, J., HEVNER, A. & MAEDCHE, A. 2020. Introduction to Design Science Research. *Design Science Research. Cases.* Springer.

VOM BROCKE, J. & SEIDEL, S. Environmental sustainability in design science research: direct and indirect effects of design artifacts. International Conference on Design Science Research in Information Systems, 2012. Springer, 294-308.

VON ALAN, HEVNER, R., MARCH, S. T., PARK, J. & RAM, S. 2004. Design Science in Information Systems Research. *MIS quarterly,* 28**,** 75-105.

VULPIANI, G., MONTOPOLI, M., PICCIOTTI, E. & MARZANO, F. S. On the Use of Polarimetric X-Band Weather Radar for Volcanic Ash Clouds Monitoring. AMS Radar Conference, Pittsburgh (PA–USA), 2011.

WANG, H., ZHUANG, X., MENG, Q., CHEN, Y., LI, J. & ZHANG, F. 2019. Observational Analysis of X-band Dual-Polarization Radar for Beijing-Mentougou Debris-Flow Event. *2019 International Conference on Meteorology Observations (ICMO)***,** 1-4.

YONESE, Y., KAWAMURA, A., AMAGUCHI, H. & TONOTSUKA, A. 2018. Study on the precision of 1-minute X-Band MP radar rainfall data in a small urban watershed. *International Journal of Sustainable Development and Planning,* 13 614-625.

YOON, S.-S. & NAKAKITA, E. 2015. Application of An X-Band Multiparameter Radar Network for Rain-Based Urban Flood Forecasting. *Journal of Hydrologic Engineering,* 22

YUSOFF, I. M., RAMLI, A., ALKASIRAH, N. A. M. & NASIR, N. M. 2018. Exploring the Managing of Flood Disaster: A Malaysian Perspective. *Geografia-Malaysian Journal of Society and Space,* 14.

ZRNIC, D. S. & RYZHKOV, A. V. 1999. Polarimetry for Weather Surveillance Radars. *Bulletin of the American Meteorological Society,* 80**,** 389-406.

## LIST OF PUBLICATIONS

### Indexed Journal

1. **Hasan, N.A.**, Goto, M. & Miyamoto, K. 2019, A review of weather radar system for rainfall induced disaster preparedness, International Journal of Innovative Technology and Exploring Engineering, vol. 8, no. 7, pp. 268-277 **(Indexed by Scopus)**

2. **Hasan, N. A.**, Goto, M., & Miyamoto, K. (2019). The web-based framework of X-band polarimetric radar system. International Journal of Recent Technology and Engineering, 8(2), 4165-4169. doi:10.35940/ijrte. B3213.078219 **(Indexed by Scopus)**

### Indexed Conference Proceeding

1. **Hasan, N. A**., Goto, M., & Miyamoto, K. (2020). Analytical method on reliability of rainfall data from X-band polarimetric radar. Paper presented at the IOP Conference Series: Earth and Environmental Science, 479(1) doi:10.1088/1755-1315/479/1/012011. **(Indexed by Scopus)**

### Book Chapter

1. **Hasan, N. A.**, Goto, M., & Miyamoto, K. (2021), The Significance of X-Band Polarimetric radar in Disaster Risk Management, BOOK CHAPTER VOLUME 2, Understanding System Risk, Investing in Disaster Resilience, UTM Press **(In Press)**