A Review of Weather Radar System for Rainfall Induced Disaster Preparedness

Nooradilla Abu Hasan, Masa Goto, Kuniaki Miyamoto

Abstract*: Rainfall is one of the major causes of natural disasters such as flood, landslide, debris flow and flash flood. Monitoring of rainfall is one of the main issues to be addressed for avoidance or mitigation of such disasters. The rainfall monitoring has been typically done by rainfall gauges for many years, but since the mid-20th century, radar technologies have also been applied for rainfall monitoring. Recently X-Band Polarimetric that uses the dual polarisation technique radar technology has been developed and investigated by several countries such as Japan and the USA for the disaster preparedness application. However, the application of this weather radar is still limited in developing countries such as Malaysia where the floods, flash floods and landslide keep happened during the heavy rainfall. Meteorological Department of Malaysia is effectively using C-Band and S-Band radars for weather forecast and warning. Meanwhile, the Department of Irrigation and Drainage of Malaysia uses the network of the rain gauges for monitoring the rainfall at the ground level and issues an alert or warning regarding the hazard. Under such circumstances, through the systematic reviewed approach, the current status of rainfall monitoring systems and weather forecast applications included the disaster caused by heavy rainfall in Malaysia was reviewed. Further, the characteristics of weather radars of different bands that focused on wavelengths and analysis methods are also been studied. Case studies on X-Band Polarimetric radar applications in the disaster area are included to identify the information needed for the utilisation of the X-Band Polarimetric radar in Malaysia.

Keywords : disaster, polarimetric radar, rainfall, weather radar, X-Band.

I. INTRODUCTION

Rainfall induces disasters such as floods, flash floods, debris flows and landslides. Flood disasters can happen due to a long duration of rainfall with high intensity. On the other hand a flash flood occurs when intensified downpour occurs within a short period of time especially in urban area [1, 2]. Thus, for the disaster preparedness and prevention activities (against rainfall induced disasters), the rainfall monitoring is indispensable.

For many years, rain gauge has been one of the traditional methods to measure the rainfall. There are several types of rain gauges which capture raindrops on the ground level [3-5]. A rain gauge is placed in an open area with no obstacle such as building or trees, which can cause inaccurate readings. A technician needs to regularly visit the rain gauge locations for maintaining the rain gauges and to collect the data if the data are not transmitted automatically. Any type of rain gauge, however, measures the amount of rainfall at the point, not an area. Therefore, in order to measure rainfall distribution, the density of rain gauge stations must be high enough to collect planar data.

Meanwhile, weather radar offers the capability to measure the precipitation intensity distribution over some distance, which is the covering range of the radar. Radars have been employed as a method for rainfall monitoring since the Second World War. The technology for rainfall monitoring radar has been developed from the usage of reflectance/reflectivity of the emitted wave in Doppler analysis, and more recently, the newly-developed Polarimetric analysis. The conventional radar, which uses reflectivity, mainly uses C-Band or S-Band. However, the radars for Doppler or Polarimetric analysis usually uses X-Band.

In Malaysia there are two government agencies to be responsible to monitor rainfall events that are the Department of Irrigation and Drainage (DID) of Malaysia and the Meteorological Department of Malaysia (MetMalaysia). The DID is responsible to prepare the information regarding hazard level and disseminate it to the government, private sectors and publics [6]. Meanwhile, MetMalaysia is responsible to report current weather conditions and issues based on weather forecast. MetMalaysia are currently using the long range data by conventional C-Band and S-Band weather radars [7, 8]. In 2009 MetMalaysia had introduced an X-Band mobile radar system, which transmits radio wave of 3 cm wave length. The X-Band mobile radar was used to obtain accurate data and information on potential rain for the cloud seeding activities in 2010. At that time, Malaysia was being hit by El Nino phenomenon. The radar system was also used to provide special meteorological services for International Maritime and Langkawi Air Show -LIMA 2009 [9, 10]. However, there is no available official report or technical papers discussing the application of X-Band radar in Malaysia especially in disaster area. Apart from that, there is no X-Band Polarimetric radar system available in Malaysia as of today.

The driving research question is "How should we implement the latest rainfall monitoring system in Malaysia?" especially by using the new radar system. For this purpose, it was started to review and evaluate the current status of weather radars in Malaysia followed by basics of radar analysis methods

Revised Manuscript Received on May 10, 2019

Nooradilla Abu Hasan, Disaster Preparedness and Prevention Center, Malaysia Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia.

Masa Goto, Disaster Preparedness and Prevention Center, Malaysia Japan International Institute of Technology, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia.

Professor Emiratus Kuniaki Miyamoto, University of Tsukuba, Tsukuba, Japan.

and the case studies in this study. The results of the review will provide basic knowledge for making a strategy or a concept to establish a rainfall monitoring network system, and will give practitioners the information of the characteristics of rainfall information.

The review is carried out by following the Bandara, et al. [11] method, which consists of four phases. The first phase is searching activities by setting up the keywords. In the second phase, the Analysis Preparation, which focuses on several issues, is conducted. The third phase is Actual Coding which is concerning on the rules of the author to achieve the goal of the study. The final phase is Analyses and Writing Up the results.

“Weather radar”, “X-Band MP radar”, “polarimetric radar”, “dual polarisation” “rainfall estimation” and “Malaysia” have been selected as the keywords for the searching activities in the first phase. The articles having any of the keywords have been collected with the publication period limited between 2010 and 2017. As a result, it has yielded 97 articles. In the second phase the Analysis Preparation was conducted. The issues on focus are; 1) major rainfall induce disaster in Malaysia, 2) Rainfall monitoring in Malaysia, 3) the basic characteristics of weather radar, especially the differences among the bands and wavelengths, 4) the methods to analyse the radar signal such as the conventional Z-R method and the Polarimetric methods, and 5) case studies or examples of implementation of weather radar and/or X-Band Polarimetric radar, and disaster. The goal of the review is to reveal the current status of weather radar monitoring systems and applications to discuss and to find suitable method/system which is to be introduced in Malaysia. To achieve it, the rule for the third phase was established to recognize and to compare the characteristics and the merits/demerits of weather radar monitoring methods, by using the key words selected in the first phase. In the final phase, according to the rules and through analysis, the suitable weather radar system for Malaysia is discussed and identified as a part of conclusion.

The results are stated in the following sections. In the next section, major rainfall-induced disasters and rainfall monitoring systems in Malaysia, that are the first and second issues in the second phase, are reviewed. In the section III, the characteristics of weather radar with emphases on wave bands as well as the analytical methods are summarized. In the section IV, applications for X-Band Polarimetric radar in the disaster area are discussed based on systems implemented in other countries. In the section V, the suitable weather radar system for Malaysia, based on the above results, is discussed and proposed as the conclusion in the section VI.

II. RAINFALL INDUCED DISASTER AND RAINFALL MONITORING IN MALAYSIA

Malaysia is located close to the equator that has a uniform temperature, high humidity and heavy rainfalls. The average annual rainfall for Peninsular Malaysia is approximately 2500 mm while in East Malaysia, the average annual rainfall is approximately 3500 mm in the north part of Kalimantan. In that sense, Malaysia is prone to various forms of disasters induced by rainfall such as flood, flash flood, landslide and debris flow. Flood events mainly take place in the Northeast monsoon season especially during November and December in Kelantan and Terengganu states on the east coast of peninsular Malaysia,. The flood disaster on December 2014 in Kelantan is one of the largest flood events in the past several decades, which had resulted in five deaths and 15,476 evacuated with damages estimated almost RM 1 billion [12, 13] . During the flood events, the number of downpours had increased from 18 December until 28 December 2014 with 507 mm daily average rainfall at 12 rain gauge stations. In addition, water levels increased from 5.80 m to 19.17 m in eight rivers in the state during the flood events. Besides that, the heavy rainfalls had caused the flash flood and landslide disasters in the surrounding areas of Kuala Lumpur such as the flash flood disasters at Ulu Klang since 1993 until 2012 as stated by Althuwaynee, et al. [14] and Mukhlisin, et al. [15]. On 30 June 1995, near the Karak tunnel, a landslide disaster took place [16]. The incident had caused 21 deaths and 23 injured. On 29 January 2011, the continued rain in Sandakan, Sabah had caused the landslide and flash flood at several places [16]. Besides that, in Hulu Langat, Selangor, the landslide happened due to constants rain lasted for a few days. The intensity of downpour extremely increased within 24 hours on 21 May 2011 [17].

The rainfall monitoring systems in Malaysia are managed by DID Malaysia and MetMalaysia. DID Malaysia have installed about 355 telemetric rain gauges and 208 telemetric water level gauges at 40 river basins in Malaysia by 2009. The non-telemetric rain gauges are manually read by technicians, but some have been replaced with or supplemented with automatic recording rain gauges for the rainfall data including time stamp [6]. The rainfall monitoring by radar is managed by MetMalaysia. The MetMalaysia has three types of weather radars which have been placed at 11 weather radar stations across the country. Four C-Band radars are located in East Malaysia (Sabah and Sarawak), six S-Band radars are located in Peninsular Malaysia and one in Miri (West Malaysia) and one Terminal Doppler Weather Radar (TDWR) in S-Band is placed in Kuala Lumpur International Airport (KLIA). In Malaysia, several studies have been published on the relationship between radar echo and rainfall intensity by using the existing weather radars. It is important for the meteorological officers to monitor the rainfall intensity and issue warning for any possibility of disaster.

The studies on Z-R relationship have been conducted to discuss the Marshall Palmer and Rosenfeld Tropical model for convective rain events in Malaysia [18, 19]. Meanwhile, Reba, et al. [20] study evaluated the Z-R relationship during flood events in December 2014 for different rainfall intensities. General issue relevant to Z-R relationship is how to improve the relationship of reflectivity and rainfall rate for the accuracy of rainfalls. On the other hand, according to Khairolanuar, et al. [21], in order to improve the attenuation model for Malaysia weather, it is important to study the rain classification in Malaysia. Generally, those studies used the radar data that have been processed by using

Interactive Radar Information Software (IRIS) system, which are provided and managed by MetMalaysia. This system has been applied for single polarisation weather radar only, especially for TDWR radar and S-Band radar. Both types of radars are installed in peninsular Malaysia while the C-Band radars are installed in East Malaysia. However, a study on the C-Band radars is still not reported so far. Table 1 below summarizes the studies conducted on weather radar and rainfall intensity estimation in Malaysia.

Table 1: Study topics related to weather radar in Malaysia

Type of radar	Study Topics	Source
TDWR (KLIA)	Z-R Relationship	Sobli, et al. [18], [19], Suzana, et al. [22]
	Attenuation of rain signal due to rain	Khairolanuar, et al. [21]
S- band	Z-R Relationship	Reba, et al. [20], Adam and Moten [7], Mahyun, et al. [8]
	Attenuation of rain signal due to rain	Lam, et al. [23], [24]

III. CHARACTERISTICS OF WEATHER RADAR

A. Wavelength

For rainfall monitoring, X-, C- and S-Bands radars are usually used. The wavelengths of X-, C-, and S- Bands are approximately 2-3 cm, 5-6 cm and 10-11 cm, respectively [25, 26]. The wavelength closely relates to detectable drop size. There is a linear relationship between the detectable drop size and the wavelength. Therefore, radar with shorter wavelength can monitor rainfall distribution in more detail than the one with longer wavelength. And the size of the radar antenna is also related to the wavelength. Shorter wavelength radar must be smaller than the longer wavelength one. On the other hand, shorter wavelength wave tends to attenuate in the space more easily compared with longer wavelength wave. Therefore the monitoring range of shorter wavelength radar is shorter than longer wavelength radars [27, 28].

Due to the two reasons described above, X-Band radar, which uses the shortest wavelength among the three bands, is suitable for high temporal- and spatial-resolution monitoring of rainfall [4, 5, 29]. On the other hand, the C-Band and S-Band radars, which use longer wavelengths, are suitable to monitor moderate to heavy rain with relatively large size rainfall drops. These are also suitable to a long range observation because of the relatively less back scatter effects and attenuation [30].

Besides that, longer wavelength also can cause problems from radar beam interaction with objects on the ground and from the variation of vertical reflectivity [28], which cause the lack of rain information in detail on local rainfall intensity. When a weather radar system is to be selected, the necessary frequency of scanning, which is the time resolution, the spatial resolution and the range should be considered based on the characteristics above for the proper selection, in addition to the cost of the installation and operation. Cost of radar would increase with the size of antenna, which increases with the length of wavelength [31]. These factors are summarized in Fig 1.

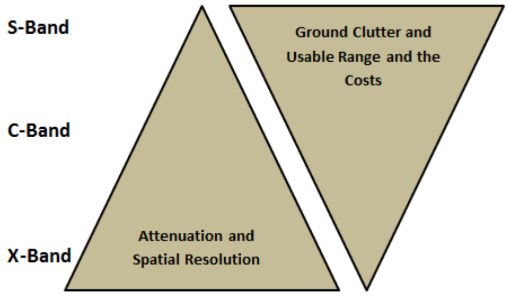


Fig 1: Different of aspects of bands [27]

In the 1990s, X-Band radar revolutionised weather radar systems because of its short wavelength. More sophisticated analytical methods were also developed as mentioned later. Today, X-Band radar is recognized as one of the most suitable monitoring systems for local, small area rainfalls with high temporal and spatial resolutions. Table 2 summarizes the differences among X-, C- and S-Bands.

Table 2: The differences among 3 bands [27, 30, 32]

	X-Band	C-Band	S-Band
Wave Length (λ)	2-3 cm	5-6 cm	10-11 cm
Frequency	8-12 GHz	4-8 GHz	2- 4 GHz
Observation radius	30-80 km	200 - 480 km	200 - 480 km
Spatial Resolution	250 m/ mesh	1 km/ mesh	1 km/ mesh

Due to the high spatial resolution provided by X-Band radar, X-Band weather radar provides detailed information on rainfall intensity on the selected area of interest. However, heavy rainfalls sometimes cause the disruption of echo behind of heavy rainfall or dense cloud due to the attenuation. To overcome this shortcoming of X-Band radar, the radar network concept has been applies by placing two or more radars in the observation areas [26].

B. Analytical Method

There are three methods that have been developed to analyse the signals from weather radars as shown in Fig 2. The first one is conventional method called *Z-R* method, which uses correlation between wave reflectivity (factor), *Z*, and rainfall intensity, *R*. The 'a' in the figure denotes the amplitude of the emitted wave for the reflectivity. The second is Doppler method, which detects the radial direction component of wind or rainfall drop velocity. The 'f_d' is the frequency of the Doppler and the 'f_e' is the frequency of emitted wave, however, Doppler method does not measure rainfall intensity. Therefore, to analyze rainfall

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

intensity, *Z-R* method is usually employed. Both of *Z-R* and Doppler methods usually use only horizontal polarization wave.

The third method uses not only horizontal polarimetric wave but vertical polarimetric wave as well. This method can measure the raindrop size by identifying the raindrop shape, which depends on the size of raindrop. There are two ways to analyze the raindrop shape. One is to use the difference between the reflectivity of horizontal (Z_h) and vertical (Z_v) polarization waves where a/b in Fig 2 is the Z_h/Z_v ratio. The other way is to measure the difference of phase shifts (φ_{DP}) of both polarization waves. These methods are called Multi Parameter (MP) methods.

Radar scanning is done in two- or three-dimensional way. Two- or three-dimensional scanning provides two- or three-dimensional profile, respectively. On the other hand, rainfall intensity is defined at points on two-dimensional plane, that is, on the ground surface. To use *Z-R* method, the empirical relationship between reflectivity and rainfall intensity is needed. Between both of two, one to one correspondence is necessary, and the relationship of Eq. (1) is usually employed.

$$Z = A\,R^{\,b} \tag{1}$$

In which, *A* and *b*, are empirical constant, which are called radar coefficient parameters. To fix the radar coefficients, because of two-dimensional observation of rainfall intensity by using rainfall gauges, two-dimensional horizontal reflectivity profile is necessary. Therefore, it is enough to do two-dimensional scanning. In order to use the three-dimensional scanning instead, it is necessary to convert from the three-dimensional reflectivity profile to the two-dimensional, plane profile. The two-dimensional scanning may be conducted at certain fixed vertical angle. In this case, it is needed to take into account the elevation observed by radar are different by the distance from the radar site. The accuracy of *Z-R* method depends on such monitoring data.

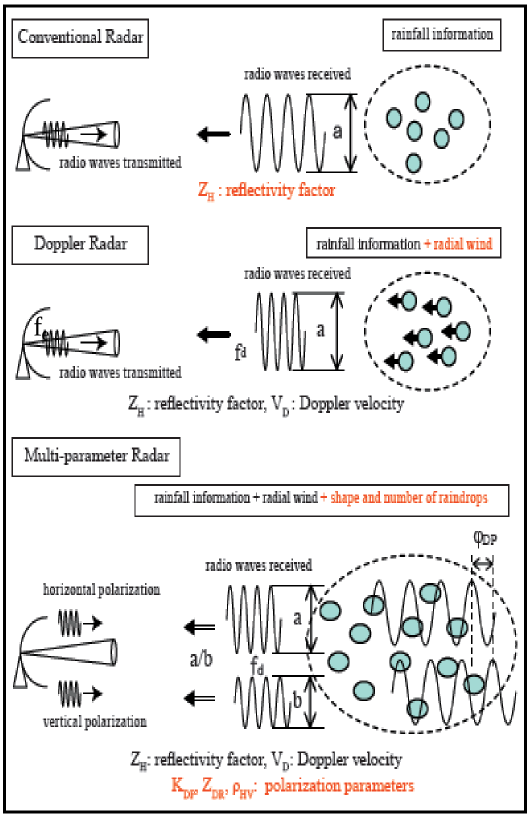
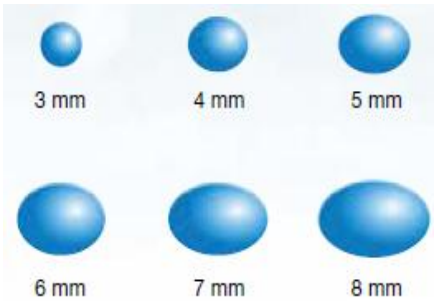


Fig 2: Three methods to analyze the signals from weather radar [26]

One of the two MP methods is based on the ratio of the reflectivity of both waves, as mentioned before. The reflectivity of horizontal and vertical polarisation waves, Z_h, and Z_v, are expressed as below [33, 34].



$$Z_h = \frac{\lambda^4}{\pi^5\,|K_w|^2} \int_{Dmin}^{Dmax} \sigma_h\,(D)\,N\,(D)\,dD \tag{2}$$

$$Z_v = \frac{\lambda^4}{\pi^5\,|K_w|^2} \int_{Dmin}^{Dmax} \sigma_v\,(D)\,N\,(D)\,dD \tag{3}$$

where, λ is wave length, σ_h and σ_v are horizontal and vertical radar cross sections, respectively, $N(D)$ is drop size distribution, D is diameter of a drop, and K_w is dielectric factor of water, which is defined as,

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

$$Kw = (\varepsilon_r - 1) / (\varepsilon_r + 2) \quad (4)$$

in which ε_r is the complex dielectric constant of water

The ratio of both σ_h and σ_v depends on the drop size, the diameter, as shown in Fig 3, therefore, the ratio of both Z_h and Z_v, Z_{dr} does not take the value 1, but depends on drop size distribution.

Fig 3: Raindrop shape [26]

The Z_{dr} can be expressed as the ratio of horizontal (Z_h) reflectivity and vertical (Z_v) reflectivity as below:

$$Z_{dr} = 10 \log_{10}(Z_h / Z_v)$$
(5)

N(*D*) in Eq.(2) and Eq.(3) used to be evaluated by using exponential distribution [33-35]

$$N(D) = N_w E(D/D_0)$$
(6)

$$E(D/D_0) = f(\mu)\left(\frac{D}{D_0}\right)^{\mu} e^{-\Lambda\left(\frac{D}{D_0}\right)} \quad (7)$$

where, N_w is the intercept parameter, μ is measure of the shape of drop size distribution, D_0 is the median volume diameter, and $f(\mu)$ and Λ in Eq.(7) are given by,

$$f(\mu) = \frac{6}{3.67^4} \frac{(3.67+\mu)^{\mu+4}}{\Gamma(\mu+4)} \quad (8)$$

$$\Lambda = \frac{3.67+\mu}{D_0} \quad (9)$$

where, Γ is gamma function.

The other MP method is to use phase shifts of both polarimetric waves. Both phase shifts while the waves are passing through a drop do not take the same value, if the shape of a drop is not spherical. The specific differential phase (K_{dp}) is define as below [36] .

$$K_{dp} = \frac{1}{2} \frac{d(\Phi_{DP})}{dr}$$
(10)

where, Φ_{DP} is the differential phase shift. K_{dp} is

$$K_{dp} = \frac{180}{\pi} \mathrm{Re} \int_{Dmin}^{Dmax} \Delta\Phi_{DP}(D)\, N(D)\, dD \quad (11)$$

where, $\Delta\ \Phi_{DP}(D)$ is the difference of both phase shifts,

$$\Delta\ \Phi_{DP}(D) = \Phi_h(D) - \Phi_v(D)$$
(12)

where, $\Phi_h(D)$ and $\Phi_v(D)$ are phase shifts of horizontal and vertical phase shift, respectively. Substituting Eq. (11) and Eq. (12) into Eq. (10) and integrating from $r=r_1$ to $r=r_2$, overall differential phase shift, Φ_{DP} , while the wave propagates from r_1 to r_2, is obtained as

$$\Phi_{DP} = 2\int_{r_1}^{r_2} K_{dp}\ dr$$
(13)

The overall differential phase shift while the wave propagates from r_1 to r_2, Φ_{DP}, is measured by polarimetric radar. Inclusively the differential phase shift does not depend on the signal amplitude or strength, that is, phase shift is not affected so much by attenuation. Therefore, multi-phase analysis by using phase shift is much better than the method by using reflectance.

When the drop size distribution is known or is assumed, that is, the suitable shape parameters for Eq. (8) and Eq. (9) are given, the back analysis can be conducted to obtain the drop size distribution, *N (D)*, and intercept parameter, N_w, which is raindrop content. Moreover, it is confirmed that the raindrop size distribution actually follows an exponential distribution [33, 37-40].

Once *N*(*D*) is obtained, rainfall intensity, R, can be calculated by,

$$R = \frac{\pi}{6}\int_0^{D_{Max}} D^3\, N(D)\, v(D)\, dD$$
(14)

or simply, by using N_w, which is obtained from Eq.(6) as follows,

$$N_w = \frac{\int_{Dmin}^{Dmax} N(D)\, dD}{\int_{Dmin}^{Dmax} E(D/D_0)\, dD}$$
(15)

$$R \doteqdot \frac{\pi}{6} D_0^4 N_w\, v$$
(16)

in which, *v*(*D*) is the terminal velocity of a rain drop with the diameter, *D*, and *v* is the average terminal velocity. Eq.(14) and Eq.(15) are based on an assumption that the measurement of the differential phase shift, Φ_{DP}, is done near the ground surface and horizontally. If the monitoring is conducted in three dimensions, it is needed to measure the altitude too, to evaluate the travel time of rain drops onto the ground surface.

IV. THE APPLICATION OF X-BAND POLARIMETRIC WEATHER RADAR

A. Detection of Heavy Rainfalls

X-Band Polarimetric radars are widely used for detection of heavy rainfall in the world. In 2008, the National Research Institute for Earth Science and Disaster Resilience [26], Japan had successfully monitored and

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

detected the detailed structure of heavy rainfall at Ebina City, Kanagawa prefecture by using the X-band Polarimetric radar network (X-Net) [29]. On 5 August 2008, there was a heavy rainfall in Tokyo Metropolitan area, which had swayed five sewerage workers and flooding above floor level in 34 houses. Fig 4 shows the rainfall distributions observed by both of X-Band Polarimetric radar and JMA C-Band radar between 11:00 PM and 2:00 PM during the event. The X-Band Polarimetric radar detected the heavy rainfall in small area over short period as shown in Fig 5 (a) while C-band radar which is operated by Japan Meteorology Agency (JMA) could not detect the small area and intensive rainfall as shown in Fig 5 (b). The visualisations from both radar are taken from three different locations which are Toshima sub-branch of the Bureau of Sewerage of Tokyo Metropolitan (T), Edogawa Elementary School (E) and Daiichi Junior High School (D).

The size of pixel presented by X-Band Polarimetric Radar in Fig 4 (a) is 16 times smaller than that of JMA C-Band radar (b), which indicates that X-Band radar has much greater resolution than C-Band radar. Thus, the results show the localized heavy rainfall was clearly and precisely detected as shown in Fig 5 (a).

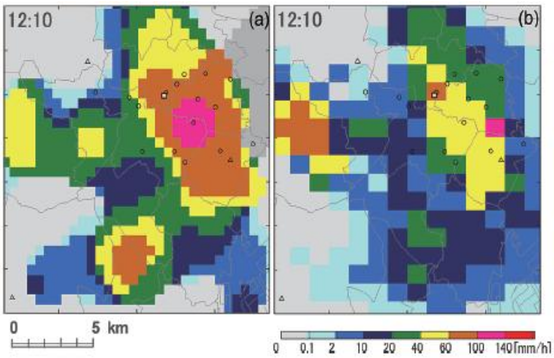
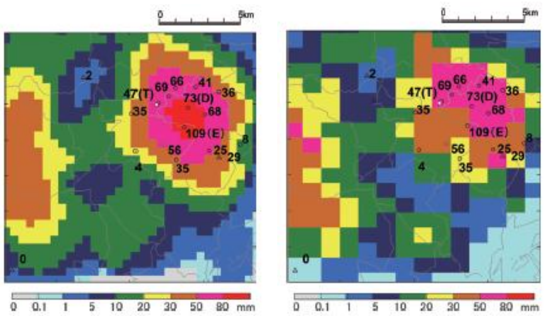


Fig 4: The echo cell distribution between (a) X-Band Polarimetric radar and (b) JMA C-Band radar at 12:10 on 5 August 2008 in Zoshigaya [29].



(a) (b)

Fig 5: The location of (T) is Toshima sub-branch of the Bureau of Sewerage of Tokyo Metropolitan (the nearest to Zoshigaya), (E) Edogawa Elementary School and (D) Daiichi Junior High School from the X-Band Polarimetric radar (a) and the JMA radar (b) visualisation [29] .

Fig 6 presents the comparison of temporal changes observed by X-Band Polarimetric radar, JMA C-Band radar and surface rain gauge at the three locations. There are obvious discrepancies in the observed temporal changes during the event. The distance between Toshima and Edogawa is about 2.2 km, while Daiichi and Edogawa is 1.2 km. It is shown that there is apparent disagreement between X-Band Polarimetric Radar data and the rain gauges data at Edogawa between 11:50 and 12:00 (10 minutes). The disagreement occurred due to the nature of vertical rainfall profile. Rainfall information from X-Band Polarimteric radar is originate from PPI scan at five elevation angles from 0.7° to 4.5° while the rain rate at certain grid point is calculated from the value in 3-D space of influence using Cressman interpolation method. Thus it is explained that X-Band Polarimetric radar has detected the upper rainfall surfaces that is not observed by rain gauges. JMA C-Band radar estimated that the rainfall was less than half of rain gauges measurement for the same location and time period.

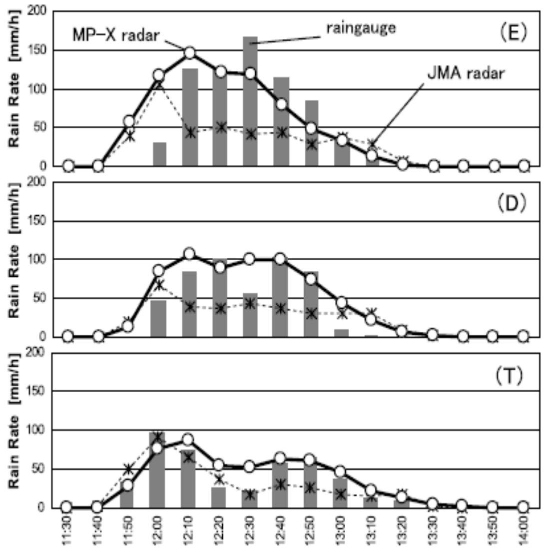


Fig 6: The temporal changes comparison for X-band Polarimetric radar by NIED, JMA radar and rain gauges [29].

Other than the above mentioned discrepancy in the rainfall rate (between 11:50 and 12:00), the X-Band Polarimetric radar was able to detect the heavy rainfalls for local areas, which were in good agreement with the rain gauge data. This implies that X-Band polarimetric data can be used to forecast the occurrence of disaster. For instance, debris flows disaster, that was caused by heavy rain in Hiroshima city, Japan, on 20 August 2014, has been extensively studied by Nishio and Mori [41]. The heavy rain and flood advisory was announced in Hiroshima city from the late evening on the 19 August until the dawn on 20 August 2014. In order to predict an occurrence of disaster in a localized area, hourly data on the amount of rainfall in the area are needed. It was known that hourly rainfall exceeding 20 mm/h in the area is potentially dangerous as shown in Table 3. Therefore, the accumulated rainfall data collected by X-band Polarimetric radar system located at Hiroshima city, which was managed by the MLIT, and the precipitation information provided by Automated Meteorological Data Acquisition System (AMeDAS), which covers the entire Japan and is managed by JMA, were compared and analysed.

Both data and information were input into GIS for rainfall analysis at Asakita and Asaminami wards in Hiroshima city. The result of rainfall analysis by using X-Band Polarimetric radar is shown in Fig 7. On 3 September 2014, the government of Hiroshima Prefecture announced that 36 % of damages were due to landslides and 64% damages were due to debris flows, and both disaster damages were caused by large amount of water accumulated in the earth during the preceding downpours.

Table 3: High intensity of hourly rainfall (mm/h) recorded by JMA AMeDAS [41]

Date, Time	Miiri	Tsushimi	Midori	Hiroshima
8/20 1:00	2	70	8.5	0.5
8/20 2:00	28	1.5	40	0
8/20 3:00	80	0	20	9.5
8/20 4:00	101	0	6.5	1

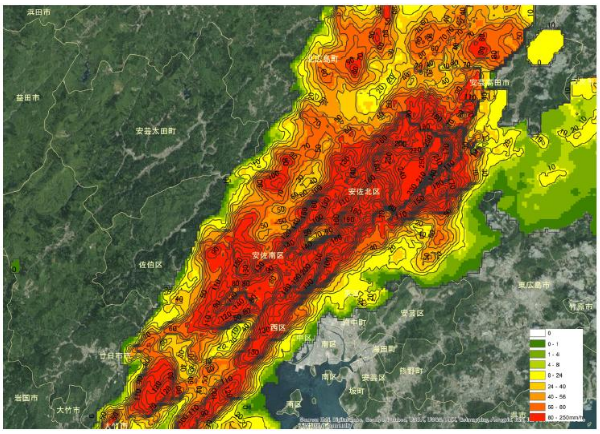


Fig 7: The analysis of rainfall data collected by X-Band Polarimetric radar on 20 August 2014 as at 4:00 [41]

X-Band Polarimetric radar data were also used in flood predictions through rainfall estimation by combining the rainfall data with flood alert criteria nomograph [42], developed for Toga River in Kobe, Japan. The flood alert criteria nomograph is a graphical representation of the peak flow that is estimated to occur during the flood event by based on the rainfall data in a small specific catchment area. It is based on rainfall intensity (y-axis) and its duration (x-axis) in Fig 8 to predict a flood event for each flood warning level that depends on the characteristics of river such as its cross section. Fig 8 presents the concept of nomograph where the flood is predicted to occur when the rainfall intensity and the duration exceed the reference flood hazard level.

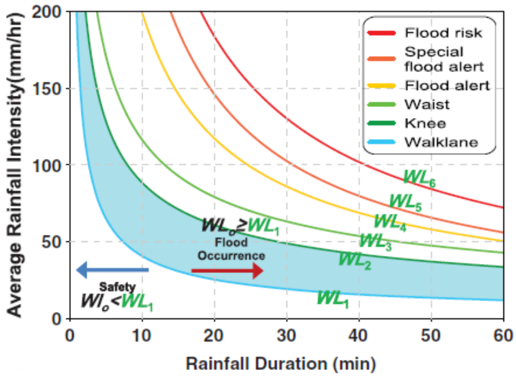


Fig 8: The Nomograph concept [42]

Therefore, in order to apply the nomograph concepts, the radar data, which provide information with high spatiotemporal resolution, are needed to estimate and predict the localized rainfall area. Since X-Band radar has the same beam width with a much smaller parabolic antenna, its data are more readily obtained in urban and mountainous areas. In Japan, the MLIT established the X-band Polarimetric radar network known as XRAIN which includes 38 X-Band Polarimetric radars as of 2017 and the operational data processing system has been developed by the National Research Institute for Earth Science and Disaster Prevention [26] to detect the torrential rainfall. In order to apply the nomograph concept to the Toga River basin in Kobe, four XRAIN radar sites shown in Fig 9 (Juubusan, Tanoguchi, Rokko, and Katsuragi) were selected to obtain the rainfall data.

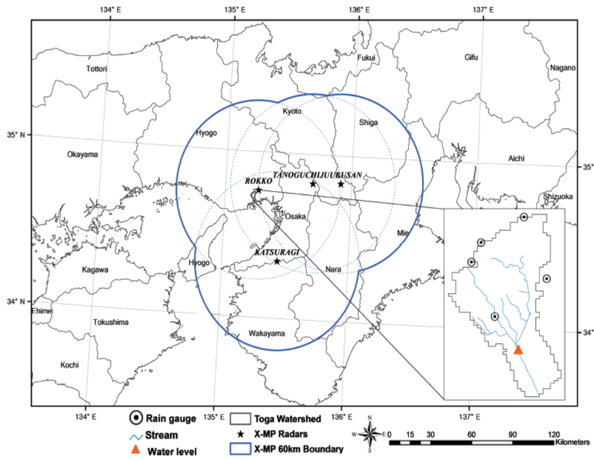


Fig 9: The composite radar network used in the Kinki area and Toga River basin [42]

Mean Areal Precipitation (MAP) was estimated by using the rain gauge data (GAUGE MAP) data and radar rainfall data (X-MP MAP, JMA MAP (C-Band radar) and MLIT C-Band MAP)). Theiessen polygons were used to estimate the MAP of rain gauge while arithmetic means were used for the radar rainfall data. The results showed that X-Band Polarimetric radar data provided more precise Quantitative Precipitation Estimation (QPE) for Quantitative Precipitation Forecasting (QPF) than C-Band radar data provided by JMA as shown in Fig 10. Thus the

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

results indicate that the nomograph concept is useful for flood forecasting as well as for urban flood management.

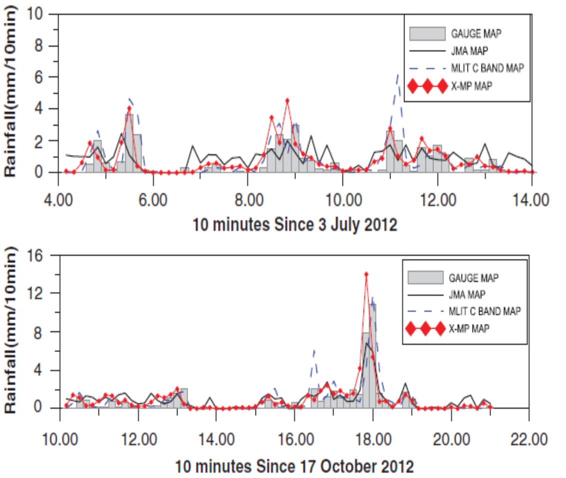


Fig 10: The rainfall results for Toga River basin for QPE using each radar type [42].

B. X-Band Polarimetric Weather Radar Systems

Nowadays, many countries have applied X-Band MP weather radars for disaster preparation purposes. Japan is the country that faces numerous disasters and adversities such as floods, landslides, and debris flow which are caused by heavy rainfall or extreme rainfall. They have operated the X-Band Polarimetric weather radars since 2000 [26]. The installed X-band Polarimetric radar network system in Japan provides crucial information for disaster preparedness and risk management. The features of radars and monitored events in Japan are;

i. Location: *The observation target areas.*
ii. Types of disaster: *Sort of tragedy.*
iii. Observation period: *The duration of X-Band Polarimetric radar data used for the case studies.*
iv. Wavelength: *The radar wavelength.*
v. Frequency: *The radar frequency.*
vi. Time interval of the observation: *The time taken to detect the precipitation. This will reflected to the time of observation scan by radar (Volume number of scan).*
vii. Number of rainfall event observed: *The total of rainfalls occurrences within the observation period.*
viii. Peak Events (Time/Date): *The highest incident during the observation period that cause the disaster*
ix. Spatial/ Temporal resolution: *The precision of a measurement with respect to time.*
x. Intensity of water: *The amount of downpour over time*
xi. Observation radius: *The range of areas covers by radar during the scanning operation*
xii. Number of radar used: *Total number of radar used for the observation project/ disaster area.*

Table 4 below, presents the examples of information gained from the installed X-Band Polarimetric radar in Japan known as X-rain system

Table 4: The X-Rain System in Japan and the information gained

Source / Types of Information	Kato and Maki [29]	Nishio and Mori [41]	Yoon and Nakakita [42]
Country	Japan	Japan	Japan
Location	Ebina City	Hiroshima City	Toga River, Kobe
Types of disaster	Flash Flood	Debris flow	Flood
Wavelength	3 cm	3 cm	3 cm
Frequency	8-12 GHz	8-12 GHz	8-12 GHz
Time interval of the observation	5 minute interval, 5 elevation angel (from 0.7^{o} to 4.5^{o})	1 minutes interval	10 minute interval
Observation period		19 Aug 2014 (10:00 am) – 20 Aug 2014 (15:00 pm)	2011 – 2012
Number of Rainfall Events Observed			10 event
Peak Events (Time/Date)	11:30 am – 14:00 pm / 5 Aug 2008	1:00 am – 4:00 am	
Spatial / Temporal resolution		250 m mesh / 1 min	250 m mesh / 1 min
Intensity of water / Hour	- 70 mm^{-h} (for 10 minutes) - the accumulate exceed 50 mm within 30 minutes	101.0 mm (first hours), 217.0 mm (3 hrs), 257.0 mm (24 hrs)	
Observation Radius		60 km	
Numbers of X-Band MP radar used		1 pcs	4 pcs

V. CONCLUSION

Through the systematic reviewed approach by following the Bandara, et al. [11], the following conclusions are obtained. In Malaysia, serious rainfall induced disasters have taken place very often. To understand disastrous situation, rainfall monitoring in Malaysia is conducted by MetMalaysia and DID by mainly using ground rain gauges and several weather radars, are installed by MetMalaysia. The Z-R relationship is used for analyzing rainfall intensity.

Weather radar can be characterized by the combination of the two key words which are wave band and analyzing method. Wave band determines minimum

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

detectable rain drop size, spatial resolution and attenuation. X-Band can detect smaller size of raindrops than C- and S-Bands. However, X-Band radar wave is more easily attenuated by cloud than C-Band and S-Band radars.

Analytical methods are mainly categorized into two groups, which are Z-R method and multi-phase method. Z-R method needs monitoring data on rainfall intensity to identify the relationship between reflectance and rainfall intensity. It means that Z-R is based on an empirical relationship between the two factors. The multi-phase method is based on the physics of radar wave. Therefore, it does not need any rainfall monitoring data. However, to calculate rainfall intensity, rain drop size distribution needs to be known or assumed. Therefore, to make sure the analysis is accurate, it is better to define the shape parameters in the distribution functions defined as Eq. (8) and Eq. (9), and by measuring the distribution in the equations Eq. (6) and Eq. (7). The multi-phase analysis uses reflectance or phase shift. The analytical method using reflectance is largely affected by attenuation, but the method using phase shift is not affected so much by attenuation. Therefore, the method using phase shift is much more suitable to rainfall monitoring than the method by reflectance.

Based on above analyses, the combination of X-Band and multi-phase analytical method using phase shift, is considered as the most suitable one to the weather radar system. Because it can detect much smaller size of raindrops and higher spatial and temporal resolutions than C- and S-Bands, and the method does not require rainfall intensity monitoring for calibration unlike Z-R relationship method.

From the review on practical use of X-band MP radar using phase shift, especially experiences in Japan, it is found that attenuation due to heavy rain and cloud affects the monitoring ability. The radar, sometimes, cannot detect the rain behind heavy cloud. To avoid it, network monitoring by using several X-band radars is necessary. Therefore, in order to discuss about suitable weather radar for Malaysia based on the results of the systematic review, the analytical method, wave band and the attenuation of signal need to be paid careful attention

Regarding analytical method, multi-phase analysis by using phase shift is the best. Regarding wave band, X-band is the best from the view point of resolution. However, X-band wave is easy to be attenuated by heavy rain and dense cloud. In Malaysia, rainfall intensity may be higher than in Japan. Therefore, attenuation could be a serious issue to be addressed in Malaysia. Network monitoring system may need to be employed. X-band wave is not easy to use in Malaysia by policy. To avoid the attenuation and conflict with policy, C-band multi-phase radar using phase shift may be one of the sensible alternatives. Especially, if the target of monitoring is relatively high-intensity rainfall, C-Band multi-phase radar might be a better solution. However, it is still a technology to be developed. Therefore, it is ideal and desirable, if possible, to conduct practical studies on both X-Band MP radars and C-Band MP radars concurrently.

REFERENCES

1. A. S. Farisham, "Landslides in the hillside development in the Hulu Klang, Klang Valley," in *Post-Graduate Seminar Semester*, 2007.
2. S. A. Anderson and N. Sitar, "Analysis of rainfall-induced debris flows," *Journal of Geotechnical Engineering*, vol. 121, pp. 544-552, 1995.
3. C. van de Beek, H. Leijnse, J. Stricker, R. Uijlenhoet, and H. Russchenberg, "Performance of high-resolution X-band radar for rainfall measurement in The Netherlands," in *Hydrology and Earth System Sciences* vol. 14, ed, 2010, pp. 205-221.
4. M. Allegretti, S. Bertoldo, A. Prato, C. Lucianaz, O. Rorato, R. Notarpietro, *et al.*, "X-Band Mini Radar for Observing and Monitoring Rainfall Events," *Atmospheric and Climate Sciences*, vol. 2, pp. 290-297, 2012.
5. S. Bertoldo, C. Lucianaz, M. Allegretti, and G. Perona, "Real Time Monitoring of Extreme Rainfall Events with Simple X-Band Mini Weather Radar," *Atmospheric and Climate Sciences*, vol. 6, p. 285, 2016.
6. DID, "Department of Irrigation and Drainage of Malaysia Manual - Hydrology and Water Resources," vol. Volume 4, D. i. I. a. Drainage, Ed., ed. Malaysia, 2009, p. 413.
7. [7] M. K. M. Adam and S. Moten, "Rainfall Estimation from Radar Data," *Research Publication of Malaysian Meteorological Department (MMD) & Ministry of Science, Technology and Innovation (MOSTI)*, vol. No.6 2012.
8. A. Mahyun, R. Abdullah, I. Abustan, M. Adam, and N. A. AA, "The Radar-Rainfall Relationship for Northern Region of Peninsular Malaysia," *International Journal of Innovation, Management and Technology*, vol. 5, p. 143, 2014.
9. MetMalaysia, "Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2009," Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI), Malaysia2009.
10. [MetMalaysia, "Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2010," Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI), Malaysia2010.
11. W. Bandara, S. Miskon, and E. Fielt, "A systematic, tool-supported method for conducting literature reviews in information systems," in *Proceedings of the19th European Conference on Information Systems (ECIS 2011)*, 2011.
12. W. Tahir, A. K. Aminuddin, S. Ramli, and J. Jaafar, "Quantitative precipitation forecast using numerical weather prediction and meteorological satellite for Kelantan and Klang river basins," *Jurnal Teknologi*, vol. 79, pp. 45-53, 2017.
13. M. B. Gasim, M. E. Toriman, M. K. A. Kamarudin, and A. Azid, "Fenomena Banjir Terburuk di Kelantan Sepanjang Musim Monsun di Pantai Timur Semenanjung," 2015.
14. [O. F. Althuwaynee, B. Pradhan, and N. Ahmad, "Estimation of rainfall threshold and its use in landslide hazard mapping of Kuala Lumpur metropolitan and surrounding areas," *Landslides*, vol. 12, pp. 861-875, 2015.
15. M. Mukhlisin, S. J. Matlan, M. J. Ahlan, and M. R. Taha, "Analysis of rainfall effect to slope stability in Ulu Klang, Malaysia," *Jurnal Teknologi (Sciences & Engineering)*, pp. 15-21, 2015.
16. Bernama, "Kronologi kejadian tanah runtuh di negara ini," in *Utusan Online*, ed. Malaysia: Utusan Melayu (M), 2011.
17. Bernama, "Hujan berterusan punca tanah runtuh," in *Utusan Online*, ed. Malaysia: Utusan Melayu (M), 2011.
18. N. H. Sobli, A. F. Ismail, F. N. Md Isa, and H. Mansor, "Assessment of radar reflectivity-rainfall rate, ZR relationships for a convective event in Malaysia," *International Journal of Electrical Energy*, vol. 1, pp. 239-243, 2013.
19. N. Sobli, A. F. Ismail, F. Isa, and H. Mansor, "Initial assessment of radar reflectivity-rainfall rate, ZR relationships for moderate rain events in Malaysia," in *Wireless Technology and Applications (ISWTA), 2013 IEEE Symposium on*, 2013, pp. 187-191.
20. M. Reba, N. Roslan, A. Syafiuddin, and M. Hashim, "Evaluation of empirical radar rainfall model during the massive flood in Malaysia," in *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International*, 2016, pp. 4406-4409.
21. M. H. Khairolanuar, A. F. Ismail, A. Z. Jusoh, and N. H. Sobli, "Classification of rain types for rain attenuation prediction method improvement based on radar information in tropics," *ARPN Journal of Engineering and Applied Sciences*, vol. 10, pp. 7202-7205, 2015.
22. R. Suzana, T. Wardah, and A. S. Hamid, "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*, vol. 5, pp. 684-688, 2011.
23. H. Lam, L. Luini, J. Din, C. Capsoni, and A. Panagopoulos, "Preliminary investigation of rain cells in equatorial Malaysia for propagation applications," in *RF and Microwave Conference*

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

(RFM), 2013 IEEE International, 2013, pp. 243-246.
24. H. Lam, J. Din, and S. L. Jong, "Evaluation of small-scale spatial distribution of rain cells in equatorial Malaysia for rain attenuation modeling," in *Applied Electromagnetics (APACE), 2014 IEEE Asia-Pacific Conference on*, 2014, pp. 12-15.
25. MetMalaysia, "Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2013," Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI)2013.
26. NIED, "Rainfall Observation by X-Band Multi-Parameter Radar," in *NIED*, N. R. I. f. E. S. a. D. P. (NIED), Ed., ed. Ibaraki, Japan: National Research Institute for Earth Science and Disaster Prevention, 2005.
27. [27] M. Quirmbach and G. Schultz, "Comparison of rain gauge and radar data as input to an urban rainfall-runoff model," *Water Science and Technology*, vol. 45, pp. 27-33, 2002.
28. [28] T. Einfalt, K. Arnbjerg-Nielsen, C. Golz, N.-E. Jensen, M. Quirmbach, G. Vaes, *et al.*, "Towards a roadmap for use of radar rainfall data in urban drainage," *Journal of Hydrology*, vol. 299, pp. 186-202, 2004.
29. A. Kato and M. Maki, "Localized Heavy Rainfall Near Zoshigaya, Tokyo, Japan on 5 August 2008 Observed by X-band Polarimetric Radar—Preliminary Analysis—," *SOLA*, vol. 5, pp. 89-92, 2009.
30. S. Y. Matrosov, K. A. Clark, B. E. Martner, and A. Tokay, "X-band polarimetric radar measurements of rainfall," *Journal of Applied Meteorology*, vol. 41, pp. 941-952, 2002.
31. P. Meischner, C. Collier, A. Illingworth, J. Joss, and W. Randeu, "Advanced weather radar systems in Europe: The COST 75 action," *Bulletin of the American Meteorological Society*, vol. 78, pp. 1411-1430, 1997.
32. MetMalaysia, "Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI) Annual Report 2013," Malaysia Meterology Department (MMD) & Ministry of Science Technology and Innovation (MOSTI), Malaysia2013.
33. V. Chandrasekar, E. Gorgucci, and L. Baldini, "Evaluation of polarimetric radar rainfall algorithms at X-band," in *Proceedings. ERAD 2002*, 2002, pp. 277-281.
34. S. Lim, D.-R. Lee, R. Cifelli, and S. H. Hwang, "Quantitative precipitation estimation for an X-band dual-polarization radar in the complex mountainous terrain," *KSCE Journal of Civil Engineering*, vol. 18, p. 1548, 2014.
35. D. Rosenfeld and C. W. Ulbrich, "Cloud Microphysical Properties, Processes, and Rainfall Estimation Opportunities," in *Radar and Atmospheric Science: A Collection of Essays in Honor of David Atlas*, R. M. Wakimoto and R. Srivastava, Eds., ed Boston, MA: American Meteorological Society, 2003, pp. 237-258.
36. V. Chandrasekar, S. Lim, and E. Gorgucci, "Simulation of X-band rainfall observations from S-band radar data," *Journal of Atmospheric and Oceanic Technology*, vol. 23, pp. 1195-1205, 2006.
37. M. N. Anagnostou, J. Kalogiros, E. N. Anagnostou, M. Tarolli, A. Papadopoulos, and M. Borga, "Performance evaluation of high-resolution rainfall estimation by X-band dual-polarization radar for flash flood applications in mountainous basins," *Journal of hydrology*, vol. 394, pp. 4-16, 2010.
38. M. N. Anagnostou, E. N. Anagnostou, and J. Vivekanandan, "Correction for rain path specific and differential attenuation of X-band dual-polarization observations," *IEEE transactions on geoscience and remote sensing*, vol. 44, pp. 2470-2480, 2006.
39. S. Park, V. Bringi, V. Chandrasekar, M. Maki, and K. Iwanami, "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*, vol. 22, pp. 1621-1632, 2005.
40. D. S. Kim and M. Maki, "Validation of composite polarimetric parameters and rainfall rates from an X-band dual-polarization radar network in the Tokyo metropolitan area," *Hydrological Research Letters*, vol. 6, pp. 76-81, 2012.
41. M. Nishio and M. Mori, "Analysis Of Debris Flow Disaster Due To Heavy Rain By X-Band MP Radar Data," presented at the The International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, Prague, Czech Republic, 2016.
42. S.-S. Yoon and E. Nakakita, "Application of an X-Band Multiparameter Radar Network for Rain-Based Urban Flood Forecasting," *Journal of Hydrologic Engineering*, 2015.

AUTHORS PROFILE

Nooradilla Abu Hasan is currently doing her PhD in Disaster Risk and Management area at Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia (UTM), Kuala Lumpur, Malaysia. She received her Master Degree in Information Technology Specialization in Information Technology Management from Universiti Teknologi Malaysia (UTM), Johor, Malaysia in 2016. Previously, she received her Bachelor Degree in Information Technology (E-Commerce) from Universiti Malaysia Sabah (UMS), Sabah, Malaysia in 2008. Experienced as a research assistant for one year while she studies her Master Degree. Her research interests are in Information System, Business Intelligence system and Disaster Preparedness and Prevention Management and Application.

Professor Dr Masa Goto is a Japanese Professor at Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia (UTM), Kuala Lumpur since 2013. He also is the director of Disaster Preparedness and Prevention Center (DPPC) at MJIIT, UTM, Kuala Lumpur. He received his PhD from Rice University, Houston, Texas, the USA in Environmental Science and Engineering field in 1985. Previously, he received his Bachelor Degree of Engineering in Environmental and Sanitary Engineering in 1976 and continue his Master Degree in 1978 at Kyoto University, Kyoto, Japan with his research in Municipal Solid Waste and Sewage Sludge Management. He is a member of the International Water Association and its ICA Specialists Group [IWA, SG on ICA], the Japan Society of Civil Engineers [JSCE], the Society of Environmental Instrumentation, Control and Automation [EICA, Japan] , the Licenced Professional Engineer, Japan, in two disciplines (i) Engineering Management and (ii) Environmental Engineering - Waste Management and Registered Graduate Engineer, BOE of Malaysia. He specially appointed as Professor of Shibaura Institute of Technology since 2013 until now and experienced as Visiting Professor of Hokkaido University form 2013- 2014 to manage the Biomass Waste Management Chair. Before joining MJIIT in 2013, he experienced working in the private sector as a senior research engineer and an executive research engineer for several multi-year national projects funded by the Japanese government or its subsidiary. He also is the inventor or co-inventor of more than 15 industrial patents, registered or pending, on bio-gasification, BDF production, wastewater treatment process and others and involved in establishing several ISO and JIS standards on biodegradable plastics. To date, he has more than 35 publication as author or co-author since he working with UTM. His research expertise and interests are in Solid Waste Management, Anaerobic Digestion and Fermentation, Wastewater Management, Renewable Energy (BDF, Bio-alcohol, Bio-hydrogen, Biogas) and Disaster Management.

Professor Emeritus Kuniaki Miyamoto is awarded as Professor Emeritus by the University of Tsukuba in 2018. Previously, he is an Associate Professor at the University of Tsukuba since 2000 and become a Professor in 2003. He has graduated his Bachelor Degree in Civil Engineering in 1979 and pursues his Master Degree in Civil Engineering, Graduate Course of Science and Engineering from Ritsumeikan University, Kyoto, Japan. Later, in 1984 he is graduated from Doctoral program in Civil Engineering, Graduate Course of Science and Engineering, from Ritsumeikan University also. He experienced working Researcher at Disaster Prevention Research Association Foundation of Kyoto University in1984 and as Senior Researcher at Sabo Technical Center Foundation in 1986. In 1994, he works as Associate Professor at Tottori University, Japan before joining the University of Tsukuba. His research expertise and interest are in Hydraulic Engineering, Forest Science, Natural Disaster and Prevention Sciences.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication