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AREA-BASED RAINFALL RATE MODEL FOR SPECIFIC ATTENUATION IN THE EQUATORIAL REGION

YASSER ASRUL AHMAD[1*], AHMAD FADZIL ISMAIL[1], MUHAMMAD NASRIN AQIL ABDUL HAMID[1], MOHD FAIZAL JAMLOS[2,3]

[1]*Dept. of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University of Malaysia, Kuala Lumpur, Malaysia*

[2] *Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan, Malaysia*

[3] *Centre for Automotive Engineering, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan, Malaysia*

**Corresponding author: yasser@iium.edu.my*

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ABSTRACT: The advent of new telecommunication systems with large bandwidths like 5G/6G and satellites operating at higher frequency bands such as Ku, Ka-band, and even Q/V bands, has brought to the forefront the issue of rain attenuation, particularly in equatorial and tropical regions. Many existing models developed to address these inaccuracies in the rainfall rate prediction rely on a single rain gauge measurement, which still can lead to inaccuracy when the model is generalized for a larger area. This research, therefore, is of utmost importance as it aims to develop an area-based rainfall rate model using multiple rain gauges spread across many locations in a specific area. The area of focus for this research is the Klang Valley area, a crucial economic territory that includes the capital city, Kuala Lumpur, in Malaysia. Five rain gauges distributed in Klang Valley were chosen to measure the rainfall rate. The rainfall rate model was then developed based on the data from these five rain gauges. The results indicate that each rain gauge's rainfall rate at $R_{0.01\%}$ exceedance level varied greatly from 102 mm/hr to 138 mm/hr and exceeded Malaysia's recommended ITU-R at 100 mm/hr. The new model, presented herein, accounts for the variation of rainfall rate across a larger area, which can provide accurate modeling of specific attenuation and rain attenuation in the equatorial regions, thereby enhancing the reliability of communication systems.

ABSTRAK: Kemunculan sistem telekomunikasi jalur lebar baru seperti 5G/6G dan satelit yang beroperasi pada jalur frekuensi tinggi seperti Ku, Ka-band, dan jalur Q/V, menyebabkan penurunan ketara amplitud gelombang akibat hujan, terutamanya di kawasan khatulistiwa dan tropika. Kebanyakan model sedia ada yang dibangunkan bagi menangani ketidak tepatan ramalan kadar hujan hanya berdasarkan pengukuran dari satu tolok hujan, ini menyebabkan ketidaktepatan model itu apabila digeneralisasikan bagi kawasan lebih luas. Oleh itu, kajian ini adalah amat penting kerana ia bertujuan bagi membangunkan model kadar hujan berasaskan kawasan menggunakan beberapa tolok hujan yang tersebar di pelbagai lokasi pada satu kawasan tertentu. Kawasan tumpuan kajian ini adalah kawasan Lembah Klang, sebuah wilayah ekonomi penting yang melingkupi ibu negara, Kuala Lumpur, Malaysia. Lima tolok hujan yang tersebar di Lembah Klang dipilih bagi mengukur kadar hujan. Model kadar hujan kemudiannya dibangunkan berdasarkan data dari kelima-lima tolok hujan ini. Dapatan menunjukkan kadar hujan $R_{0.01\%}$ bagi lima tolok hujan adalah antara 102 mm/jam hingga 138 mm/jam dan melebihi kadar cadangan ITU-R Malaysia iaitu pada 100 mm/jam. Model baru yang mengambil kira variasi kadar hujan pada suatu kawasan lebih luas menggunakan banyak tolok hujan, di mana dapat memberikan pemodelan amplitud gelombang yang lebih tepat bagi hujan di kawasan khatulistiwa, dengan itu meningkatkan kebolehpercayaan sistem komunikasi.

KEYWORDS: *Rain gauge network, Areal rainfall analysis, Equatorial climate dynamics, Rainfall rate modeling, and Satellite communication attenuation.*

1. INTRODUCTION

New telecommunication systems such as 5G, 6G, and high throughput satellites (HTS) employ a higher frequency band such as Ku, Ka, and above. These microwave and millimeter frequency bands are well known to be highly susceptible to rain attenuation, which is a greater issue in the rainy tropical and equatorial regions. Not much research distinguishes the tropical region from the equatorial region, which can significantly affect the rain attenuation model. In a tropical region, the climate typically exhibits two distinct seasons: a dry season and a wet season. During the dry season, the average rainfall is approximately 50 mm/hr, whereas the wet season experiences significantly higher rainfall rates [1,2]. The equatorial region has a hot and wet season throughout the year with an average rainfall value of at least 60 mm/hr, with heavy rainfall usually occurring in the afternoon throughout the year [1,2]. Thus, the equatorial region also has heavy rainfall but with a well-distributed rainfall rate throughout the year. The rain formation and raindrop sizes exhibit similar features for the equatorial and tropical regions. As a comparison, temperate regions have a smaller raindrop size and a lower rainfall rate of around 25 mm/hr for an annual average with an interval not exceeding one hour [3].

The rainfall rate in equatorial regions greatly varies according to different geographical areas [4]. Therefore, understanding the characteristics of an area-based rainfall rate is imperative and should be based on local areas and climatic conditions. Malaysia is unique as it experiences an equatorial climate with tropical monsoons [5].

Malaysia has a very high rainfall rate that can exceed 200 mm/hr with an equatorial climate mixed with tropical monsoon [6]. The seasons in Malaysia are generally divided into two main seasons: heavy rainfall rate is typically distributed throughout the twelve months of the year, and heavy rainfall rate occurs in the afternoon [7]. Malaysia faces two monsoon seasons, namely, the Southwest Monsoon, which occurs from late May to September, and the Northeast Monsoon, occurring from November to March. During the monsoon regime in the East peninsular, heavy showers are expected to pour for an hour or so. Rain patterns are usually consistent and can be predicted for about a week before changing. In the Western peninsular, nonstop rain could occur for weeks at a time [8].

From the point of view of electromagnetic wave propagation, precipitation can be divided into two types, specifically stratiform rain and convective rain [9]. Stratiform rain is a product of stratus clouds. The stratiform rain features light rainfall intensity and limited vertical extent of rain height, spread over a large area. Whereas the cumulus clouds produce convective rain with high rainfall rates and extensive rain height that covers a smaller area [9]. Convective rain is the major cause of communication link outages in the equatorial region and Southeast Asia region [4].

The stratiform and convective rain can be discriminated or differentiated based on the rainfall rate. In the Equatorial region, stratiform rain has a rainfall rate of less than 10 mm/hr while convective rain can be considered above 10 mm/hr [10]. Rainfall rate can be obtained from the rainfall rate distribution model or direct measurement using an instrument such as a rain gauge. One of the major issues in predicting the rainfall rate in the tropical region is that most of the rain models are developed in the temperate climate [10].

The rainfall rate model is the major parameter in determining specific attenuation based on the power law relationship [11]. The ITU-R P.837-7 [12] provides a global rainfall rate model for exhibiting the propagation of electromagnetic waves under the condition of precipitation. However, the ITU-R rainfall rate model developed in temperate regions tends to underestimate the rainfall rate in other areas with heavier rainfall [13]. The ITU-R P.837-7 and the Singh & Acharya model focus on predicting the rainfall rate at $R_{0.01\%}$ to be suitable with the ITU-R 618 rainfall rate prediction model. However, rainfall rate distribution <1% is more critical due to the variation in rainfall rate in the equatorial climate [14]. Intriguingly, there is a developed model based on the local area, the Moupfouma model for Southern India [15].

The most common and direct way to measure rainfall rate is to use a rain gauge. Rain gauge measures the point rainfall rate [16]. Classic rain gauges may have an issue in terms of accuracy, but over the years, rain gauge design has seen improvement in terms of accuracy [17]. A single rain gauge may not give accuracy over a large area. Thus, hydrologists have resorted to a network of rain gauges to improve area average rainfall estimates [18].

In analyzing communication links, the rainfall rate is analyzed to produce a cumulative distribution based on 1-minute rainfall rate in accordance with the standard set by ITU-R [12]. Recent measurement [7] shows a lower rainfall rate than the older measurement [6, 19, 20]. Thus, this research aims to achieve the following objectives: to revise, measure, and analyze the area-based rainfall rate exceedance in the Klang Valley, Malaysia, and to develop and propose a more accurate area-based rainfall rate model based on multiple rain gauges for the equatorial region.

2. METHODOLOGY

2.1 Rain Gauge Measurement Set Up

In Malaysia, the Department of Irrigation and Drainage (DID) owns and operates a meteorological standard hydrological station network all over the country, which accurately provides tropical rainfall rate information. Thus, rain data could be obtained from the DID rain gauge. Fig. 1 shows a DID rain gauge.

Figure 1. DID Rain Gauge

The DID rain gauge is a remote-sensing tipping twin bucket type, which is able to measure the volume of rainfall continuously, accurately, and reliably. It is a meteorological standard rain gauge with a portable, rugged, lightweight unit that is able to continuously measure the volume of rainfall using a twin bucket, hence providing highly accurate and reliable measurement. Each tip of the bucket can measure 0.5 mm of rainfall. The accuracy of the rainfall intensity is +/- 1% at 250 mm/hr. The diameter of the funnel is 200 mm with a sharply beveled edge in conformance with best meteorological practice. The funnel has a 0.09 m height to reduce sampling loss due to splashing. The data is recorded on an electromagnetic strip chart recorder in less than 120 msec. The data is recorded in each one-minute interval and sent via modem to the internet. Then, it is made available at the DID portal.

The specification of the tipping bucket rain gauge used by DID is listed below[21].

- The rain gauge shall be a remote-sensing tipping bucket type. It shall be a rugged, lightweight and portable unit, which can be used to measure continuously volume of rainfall with high accuracy and reliability.
- The `unit' of measurement shall be in the metric system, with an accuracy of ± 1% over a rainfall intensity of 250mm/hr and an accuracy of ± 3% to 300mm/hr. The rain gauge shall be calibrated against a rainfall intensity of 250mm/hr to 300mm/hr.
- The rain gauge collecting funnel shall have a sharply beveled edge that conforms with the best meteorological practice. The diameter of the funnel shall be 200mm ± 0.2mm.
- The funnel wall shall be a minimum of 0.09m high to reduce the sampling loss due to splashing.
- The funnel shall have a large round sieve to prevent falling leaves, debris, etc., from entering the measuring element of the rain gauge.
- The funnel shall have a siphon mechanism for the rainwater to constantly flow into the measuring element.
- The secondary funnel shall be provided to feed the rainwater to the measuring element. Its function is to stabilize the feed water and to allow dust to settle.
- The measuring element of the rain gauge shall be the twin bucket type. It shall be pivoted in the centre and so balanced that one of the buckets shall always be under the funnel, ready to be filled with water. When a given amount of water is collected the bucket shall tip and bring the second bucket into position under the funnel.
- The bucket and movable part shall be made of a metal base material (plastic base material shall not be accepted).
- Each tip of the bucket shall represent a measure of 0.5mm of rainfall, and every tip of the bucket shall also cause a make-and-break closure of two reeds or switches at the same time with a two-output terminal.
- Enough closure time of the switches shall be allowed for data to be recorded on an electromagnetic strip chart recorder, which should not be longer than 120 ms.
- The measuring element shall have two drainage openings, one for each bucket. The openings shall be covered with screens to prevent insects from entering the measuring element. The two openings shall have a facility to connect 4 to 10-mm diameter rubber tubing.
- All components of the rain gauge shall be made from corrosion-resistant materials.

2.2. Area-based Rainfall Rate

The rainfall rate measured by a single rain gauge will provide a point rainfall rate associated with the rain attenuation measurement. To obtain an area-based rainfall rate model in the surrounding area, multiple rainfall rate measurements at different places should be made. The surrounding area of this experiment is the Klang Valley in Malaysia. Inside the Klang Valley is Kuala Lumpur, the main capital of Malaysia, with surrounding urban areas from the state of Selangor adjoining Kuala Lumpur. As the most urban and important economic area in

Malaysia, a reliable communication link is critical in the Klang Valley. The areal rainfall rate information is critical to satisfy the specific attenuation accurately.

Fig. 2 shows a typical DID hydrological station. The DID rain gauge is used to obtain the rainfall data. The DID rain gauge is part of the DID Hydrological station network. DID has a network of Hydrological stations across Malaysia. DID Selangor's Hydrological Network includes Rain gauges, Water Level Stations, Evaporation stations, Suspended Sediment Stations, Stream of Flow Stations, and Water Quality Stations. The specification of the rain gauge is the same as the rain gauge described in the previous section. The hydrological station's database can be found at HydroNET [22]. However, not all DID rain gauge stations provide measurements at 1-minute intervals. Thus, only 1-minute interval stations are selected from the HydroNET database. Table 1 lists the selected rainfall stations from HydroNET for the Klang Valley area. The selected stations record rain data for every 1-minute interval. All the rain data will be used to obtain the rainfall rate. 1-minute interval rainfall data from all stations from Jan 2015 to Dec 2016 will be used based on the existing database. The average rainfall rate data from the five stations will be obtained, and the rainfall rate will be modeled from the average data to give the rainfall rate for the Klang Valley area.

Figure 2. DID Hydrological Station

Table 1. Rainfall Stations in Klang Valley Area

Station No	Station Name	Latitude [N]	Longitude [E]	Area
2816139	Payah Indah	02 52 44	101 37 09	Cyberjaya
2916001	Puncak Niaga	02 54 40	101 41 56	Putrajaya
2917002	Sungai Merab	02 56 43	101 44 60	Bangi
3211001	Taman Templer	03 17 49	101 37 58	Gombak
3214057	Bdr. Tasik Puteri	03 17 59	101 29 18	Rawang

The rainfall data collected by the rain gauge is measured in mm thus it has to be converted to mm/hr for an actual rainfall rate. [23] suggested that the rainfall rate can be determined using Eq. **Error! Reference source not found.**1), where L is the maximum rainfall (mm) and T is the time interval (min).

$$R(mm/h) = L * \frac{60}{T} \tag{1}$$

Table 2 shows a sample of the rainfall rate converted from the "rain rainfall" to "rainfall rate." It shows that the increment of 0.1 mm is equivalent to an increment of 6 mm/hr. The effect of the conversion will cause the cumulative distribution function graph to be staggered.

3. RESULT

3.1. Rainfall Measurement and Analysis

The rainfall measurement presented in this section is based on the Paya Indah rain gauge data. The Paya Indah station is used as a benchmark because it is near the Earth stations located in Cyberjaya Malaysia. Similar analyses were done for the other four rain gauge stations presented in Table 1, which will be plotted together with the developed model in Fig. 9. The rain gauge measures rainfall in mm for every minute. This section presents the results and findings for the monthly rainfall volume (mm), monthly rainfall rate (mm/hr) and annual rainfall rate (mm/hr) for the Paya Indah Station. Data availability for rainfall during the two years is 100%.

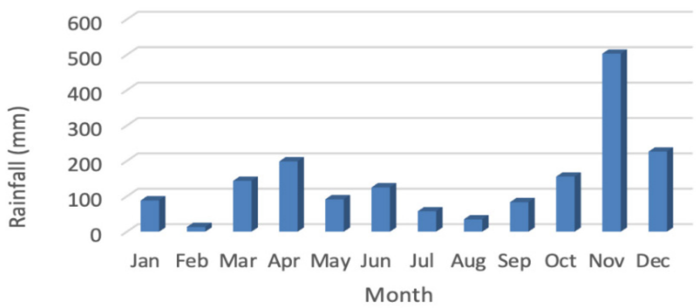

Figure 3. Monthly rainfall volume in 2015 for Paya Indah rain gauge

Table 2: Rainfall (mm) converted to rainfall rate (mm/hr)

Date	Time	Rainfall rate [mm/hr]	Rainfall [mm]
13/12/15	13:30:00	6	0.1
13/12/15	13:31:00	6	0.1
13/12/15	13:32:00	6	0.1
13/12/15	13:33:00	6	0.1
13/12/15	13:34:00	6	0.1
13/12/15	13:35:00	6	0.1
13/12/15	13:36:00	6	0.1
13/12/15	13:37:00	6	0.1
13/12/15	13:38:00	6	0.1
13/12/15	13:39:00	12	0.2
13/12/15	13:40:00	12	0.2
13/12/15	13:41:00	12	0.2
13/12/15	13:42:00	24	0.4
13/12/15	13:43:00	48	0.8
13/12/15	13:44:00	54	0.9
13/12/15	13:45:00	48	0.8

3.2 Equatorial Rainfall Volume

The measured rainfall was taken from the DID rain gauge in Paya Indah for two years, from 2015 to 2016. Fig 3 and Fig 4 present the rainfall recorded by the rain gauge. The rain volume or intensity collected annually for one year resembles the characteristic of an equatorial climate rain. It is observed that rain volume, on average, is higher throughout the year of 2016. In 2015, February and August presented lower rainfall values than March, April, May, October, November, December, and January. Rain volume provides a good idea of which month has higher rainfall. The rainfall volume in 2015 was much lower than in 2016 because of Malaysia's long dry season due to the El Nino phenomenon. The year 2016 shows typical equatorial rainfall for Malaysia, and the rainfall is well distributed throughout the year, which corresponds to the discussion based on the literature in the introduction section. The rainfall rate is required to provide valuable information associated with signal attenuation to analyze the satellite communication link. Thus, rainfall volume (mm) must be converted to rainfall rate (mm/hr).

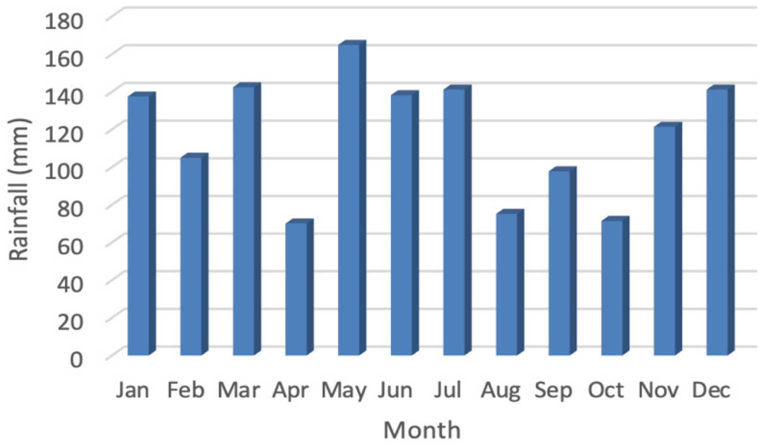

Figure 4. Monthly rainfall volume in 2016 for Paya Indah rain gauge

3.3. Rainfall Rate

Before analysis, the rainfall volume data were converted into rainfall rate. The rainfall rate, Probability Density Function (PDF), and Cumulative Density Function (CDF) were analyzed to produce the time exceedance on a monthly basis for the years 2015 and 2016. The monthly CDF for 2016 and 2015 are presented in Fig. 5 and Fig. 6, respectively. Fig. 7 presents the annual cumulative distribution of the average rainfall rate for 2015 and 2016. There is a small difference between the measurement of the average cumulative distribution for 2015 and 2016. The annual average rainfall rate measured at 0.01% of time exceedance for years 2015 and 2016 are 120 mm/hr and 96 mm/hr, respectively. Despite the dry season with lower rainfall volume, the average annual rainfall rate for 2015 was higher than in 2016. The average point rainfall rate measured at 0.01% of time exceedance was 108 mm/hr. The $R_{0.1}$ for 2015, 2016, and the two-year average were 48 mm/hr, 42 mm/hr, and 42 mm/hr, respectively. The rainfall rate was very high, reaching 222 mm/hr in 2015 and 174 mm/hr in 2016. Compared to the ITU-R P.837-7 [12] value, the measured local value of $R_{0.01}$ at 108 mm/hr is higher than the ITU-R $R_{0.01}$ which was 100 mm/hr for Peninsular Malaysia. The value of the typical time exceedance for the rainfall rate is presented in the next section.

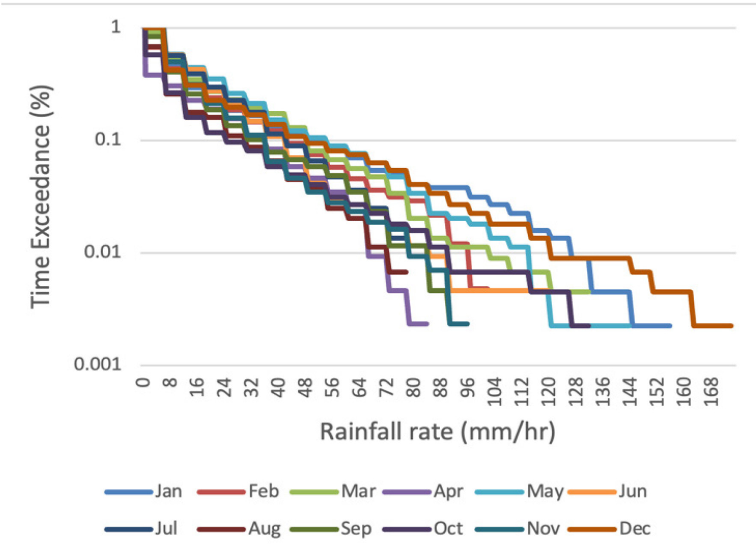

Figure 5. Monthly cumulative distribution of rainfall rate for year 2016

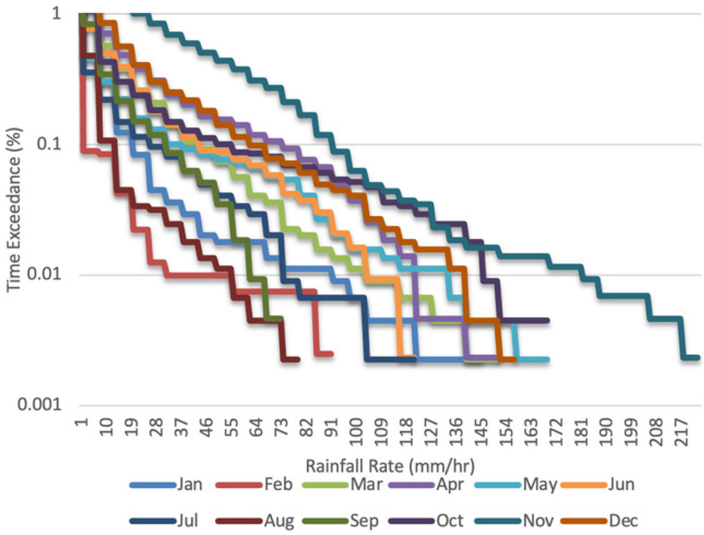

Figure 6. Monthly cumulative distribution of rainfall rate for year 2015.

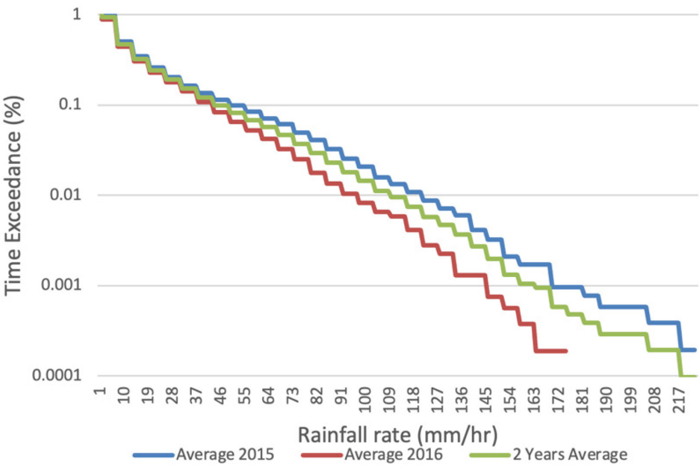

Figure 7. Annual cumulative distributions of rainfall rate for Paya Indah rain gauge

3.4. Rainfall Rate Model

This section presents the results to achieve the rainfall rate model, which will be the critical input to the specific attenuation and rain attenuation models. The specific attenuation is a function of rainfall rate and k and α coefficients. The rainfall rate measured in time exceedance for Paya Indah will be useful for finding the values of specific attenuation for Cyberjaya only. The rainfall rate model is derived based on steps similar to those of the Paya Indah Rain Gauge. In this section, another rainfall rate analysis was made from four different locations in the Klang Valley area. The additional rain gauges were located in Putrajaya, Sg Merab, Rawang, and Gombak. Together with Paya Indah, five measurements of rainfall rate areas are available. An area-based rainfall rate model based on the average rainfall rate could be derived for the two-year period from the five locations of rainfall rate. The average could be projected to provide a model for the rainfall rate in Klang Valley. The ITU-R model P.837-7 generalized the rainfall rate for the whole of Malaysia territory to be 100 mm/hr at 0.01% exceedance. The specific measurements made for the rainfall rate in five areas could potentially be referred to as the rainfall rate of Malaysia, replacing the ITU-R P.837-7 for a more accurate representation.

The CDF of the monthly rainfall rate for each of the five areas was established. Next, the annual averages were obtained. 10 measurements of rainfall rate annual averages were acquired for the two-year period. The average of these 10 measurements was then calculated in Microsoft Excel. The annual average was subsequently exported to Matlab Curve Fit Tool to obtain a suitable model of the Klang Valley's rainfall rate, which could be generalized as Malaysia's rainfall rate. Fig. 8 presents the curve fit for the average rainfall rate based on 2 years of rainfall rate from five combined areas. In the Y-axis, R_P represents the rainfall rate in mm/hr while p represents the probability or the time exceedance in %. The R^2 of the curve is 0.9832. Subsequently, Eq. (2) represents the derived rainfall rate model.

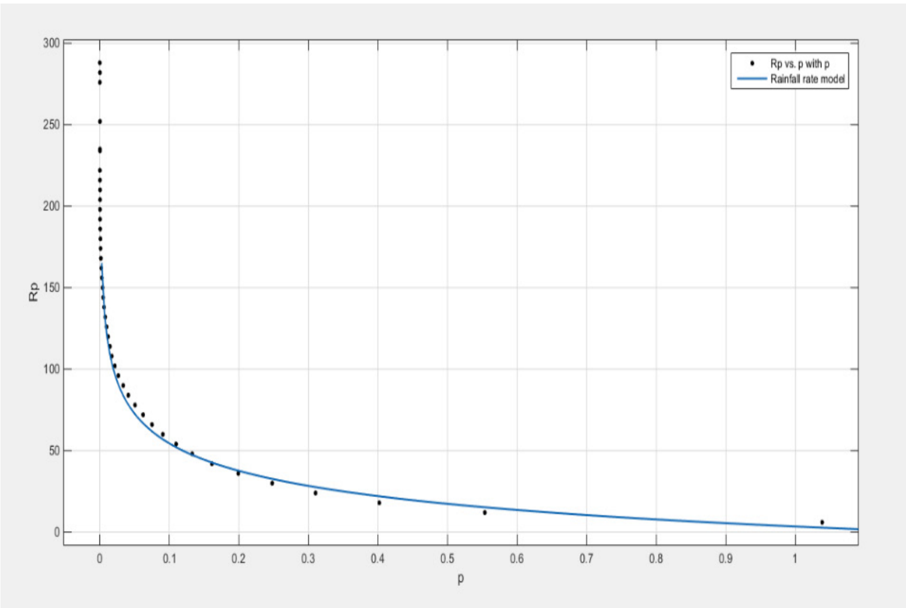

Figure 8. Rainfall rate curve fit for Klang Valley

$$R_{p\%} = 162p\%^{-0.12} - 158.6. \quad (2)$$

Eq. (2) is plotted together with the annual averages of the five rain gauges in the Klang Valley area for the years 2015 and 2016 in Fig. 9. The dots in the figure are the annual average rainfall rates for five different areas. The names of the areas are according to the legend and label in Fig. 9. The red line represents the Rp% model. The orange curve is the average of the dataset. Based on Fig. 9, the annual average rainfall rate varies from a minimum value of 96 mm/hr to a maximum value of 132 mm/hr. The measurement for 96 mm/hr at 0.01% time exceedance is from Paya Indah rain gauge data in 2016, while the Sg Merab rain gauges measured the maximum at 132 mm/hr in 2016. The average rainfall rate is 126 mm/hr, while the derived model produced 123 mm/hr for the annual rainfall rate average.

As a benchmark, other rainfall rate measurement studies in Malaysia also demonstrated that the annual average $R_{0.01}$ is typically 120 mm/hr with a monthly variation of 58 mm/hr to 136 mm/hr [7]. Thus, this model can be used to accurately obtain the time exceedance for Malaysian territory and equatorial regions. Considering the rainfall rate benchmark of 100 mm/hr at 0.01% by ITU-R, the rainfall rate model derived in this study could be considered a better approximation to the prediction of rainfall rate in Malaysia. The obtained $R_{0.01}$ is crucial for determining the specific attenuation and rain attenuation. This finding is valuable for defining a more accurate model of the rainfall rate in Malaysia, particularly for communication links.

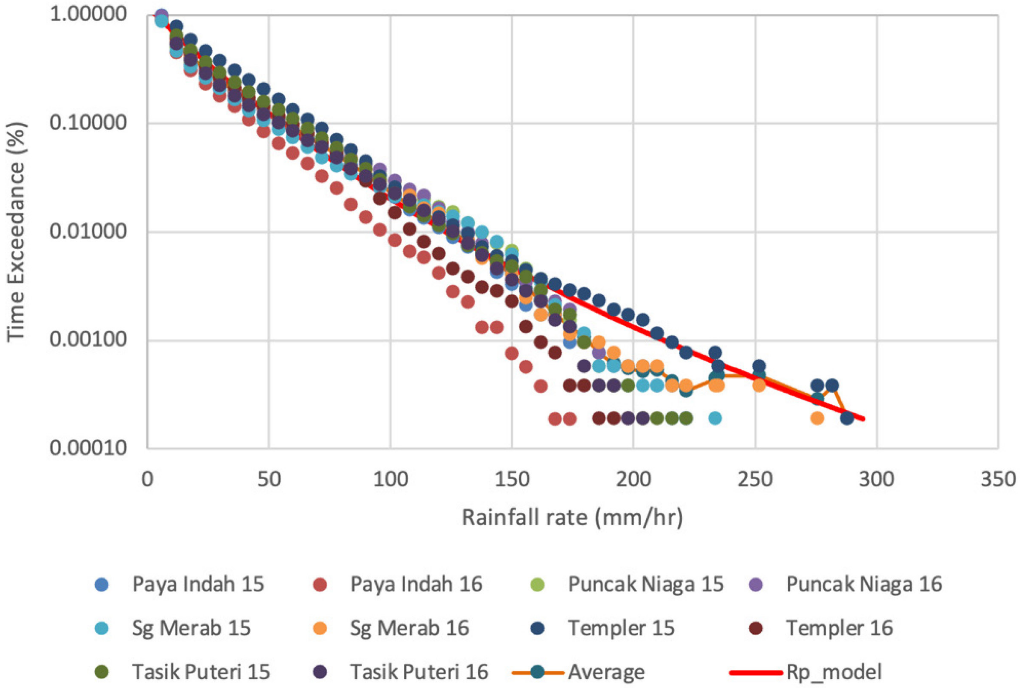

Figure 9. $R_{p\%}$ model plotted for 2 years average of rainfall rate from 5 areas.

4. CONCLUSION

The ITU-R stated that the rainfall rate for the region of Malaysia is 100 mm/hr [12]. Most measurements have shown that the ITU-R underestimated the rainfall rate distribution in equatorial regions, particularly in Malaysia [6], [19], [20], and newer measurements show that the measured rainfall rate is lower than the older one but still higher than the ITU-R model [7]. Most measurements, however, employed a single rain gauge to conclude that the ITU-R underestimated the predictions of rainfall rate. Multiple rain gauges should be used to obtain an accurate rainfall rate over a large area [18]. The methods of acquiring area-based rainfall rates using multiple rain gauges were discussed in the methodology section. As listed in Table 1, five rainfall stations provided rainfall data for the Klang Valley area. The results of the area-based rainfall rate measurements were discussed in the result section. The outcome from five rainfall stations indicates that the annual rainfall rate distribution for $R_{0.01}$ is from 96 mm/hr to

132 mm/hr, and the annual average is 126 mm/hr. From these findings, certain areas have a lower rainfall rate than 100 mm/hr, as recommended by ITU-R. However, most locations have shown results of higher rainfall rates than the ITU-R recommendation. Thus, the annual average is higher than the ITU-R recommendation. Based on the rainfall rate distribution of <1%, a rainfall rate model was developed and shown in Equation (2). The model produces a prediction for rainfall rate distribution exceedance of <1% for the Klang Valley in particular and Malaysia and equatorial regions in general. Thus, this model can contribute to a more accurate specific attenuation and rain attenuation model used in communication link modeling and analysis for the equatorial region.

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