An Experimental Study on The Correlation of Natural Rainfall Intensities and Raindrop Size Distribution Characteristics

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Abstract. This paper aims to study the natural raindrop size distribution characteristics based on the experimental works for three (3) different rainfall intensities, which are 32.41 mm/h, 56.84 mm/h and 85.73 mm/h. A tipping bucket rain gauge was used to record rainfall data during the field study and a professional DSLR camera (Sony α6000) was used to capture raindrop distribution during rainfall events. A sufficient number of photographs were taken with necessary adjustments on camera setting to produce the required sharpness of the images and to significantly reduce noise disturbances. Sharp images were selected for image segmentation using a customized coding script to further process the images on MATLAB. The segmented or processed images presented in the form of numerical data would provide the details on the number of drop counts in addition to the diameters of the individual drops captured. The raindrop sizes or diameters ranging from 0.5 mm to 4.5 mm were divided into group of 0.5 mm intervals. It is found that lower rainfall intensity at 32.41 mm/h has the highest volumetric drop distribution of 1.0–1.5 mm interval drop group 78.64%. The relatively higher rainfall intensity at 85.73 mm/h tends to produce higher counts in larger droplet sizes with increments of 6.90% for 2.5–3.0 mm and increment of for 3.45% 4.0–4.5 mm. The study also recorded a significant increment of median droplet sizes (D₅₀) ranging from 1.18 mm to 1.33 mm as the rainfall intensity increased from 32.41 mm/h to 85.73 mm/h, respectively.

Keywords. Rainfall Intensity, Raindrop Size Distribution, Volumetric Drop Distribution, Median Drop Size.

1. Introduction
Raining (precipitation) is a natural phenomenon in the water cycle process that composes parameters such as humidity, atmospheric pressure, temperature, etc. [1]. Formation of precipitation consists of two actions; the action of raindrop breaking apart (fragmentation) and combining of raindrop particles (coalescence) [2]. It is noted that the occurrence and frequency of coalescence and fragmentation of raindrops would deviate significantly in every rainfall event. Hypothetically, higher rainfall intensities would increase the chances of formation of larger raindrops and thus would increase the number of
The average raindrop size would be comparatively higher as rainfall intensity increases. Villermaux & Bossa [3] suggested that the formation of larger droplets are highly possible in the larger and deeper convective clouds.

The median drop size ($D_{50}$) is a common practice to be taken as a benchmark of the raindrop size distribution of a specific rainfall event. Several authoritative researchers in the field such as Mason & Andrews [4], Kelkar [5] and Laws & Parsons [6] published their research works on the relationship of $D_{50}$ and rainfall intensities that were presented in the form of empirical equations. Although numerous studies had been conducted to determine $D_{50}$, the studies were confined to investigate the different ranges of natural rainfall intensities at localised and regionalized areas. The studies were mainly carried out in the temperate region of the United States of America and negligible number of studies on the equatorial region.

Rainfall characteristics in the equatorial region are distinguished by extremely high rainfall volume in the range of 2,000–6,000 mm/yr [7], [8], which can be translated to rainfall intensities of approximately 50–200 mm/h [9], [10]. To date, there is a negligibly low number of studies conducted on the correlation of natural rainfall intensities and raindrop size distribution characteristics.

Table 1 shows the classification of rainfall intensities stated by several authoritative researchers, including Llasat [11], Yakubu, Yusop & Fulazzaky [12], Varikoden, Samah & Babu [13] and Yang [14]. As shown in Table 1, it is noted nearly all studies were conducted on the relatively low rainfall intensities that highly resembled the characteristics of rainfall in the temperate regions. This research looks into the rainfall intensities and drops size distribution for rainfalls experienced in the equatorial region. Literature reviews showed that there are very limited information or citations on high equatorial rainfall intensities. This paper aims to determine the raindrop distribution characteristics with respect to high rainfall intensities encountered in the equatorial zone.

| Source                        | Location | Low | Medium | High | Very High | Extreme High |
|-------------------------------|----------|-----|--------|------|-----------|--------------|
| Llasat [9]                    | UK       | 1 < 2 | 2 < I ≤ 15 | 15 < I ≤ 30 | 30 < I ≤ 60 | I > 60 |
| Yakubu, Yusop & Fulazzaky [10]| Malaysia | 1 < 4 | 4 < I ≤ 15 | 15 < I ≤ 30 | 30 < I ≤ 60 | I > 60 |
| Varikoden, Samah & Babu [11] | Malaysia | 1 < 4 | 4 < I ≤ 8 | 8 < I ≤ 12 | - | - |
| Yang [12]                     | Malaysia | 0 < I ≤ 10 | 10 < I ≤ 30 | 30 < I ≤ 60 | I > 60 | - |

Note: $I =$ Rainfall Intensity (mm/h)

2. Materials and Methods

In this study, natural rainfall characteristics with respect to intensity and size distribution patterns were investigated experimentally. The surroundings of the experimental site would require sufficient clearance and without high structures nearby. The selected site was located in Kuching (Sarawak), a city with tropical rainforest climate [15], which was approximately 2.46 km from Swinburne University of Technology Sarawak Campus (Figure 1).

This site is accessible by motor vehicles via Jalan Three Hills Park and Jalan Pending. The coordinates of the site are 1° 32’ 47.99” N and 110° 22’ 26.37” E. A standard tipping bucket rain gauge has a standard 350mm high with 200 mm diameter opening as shown in Figure 2 (a). It was installed onsite to collect rainfall data; rainfall duration and daily rainfall amount. The rain gauge was manufactured by Hydrological Services P/L at Liverpool, NSW, Australia. The requirements on the orientation of the tipping bucket rain gauge include its mounting on approximately 2 meters from the ground. For this study, three (3) different natural rainfall intensities of 32.41 mm/h, 56.84 mm/h and 85.73 mm/h were investigated for determination of the properties and characteristics of raindrop size.
distribution with respect to the three different rainfall intensity groups. The results were compared with the raindrop size classification put forward by Yakubu, Yusop & Fulazzaky [12] and Llasat [11].

![Map of Malaysia and Kuching](image)

**Figure 1.** Locality of Study Site.

A professional DSLR camera (Sony α6000) in Figure 2 (b) was used to capture the natural rainfall droplet distribution. High shutter speed with precise camera settings was chosen for the photo shooting on fast raindrop movements. Adjustments on camera settings (ISO, aperture, shutter speed, focal length, etc.) were performed during the photo shooting process in order to produce sharp images of raindrop sizes and to significantly reduce noise disturbances in the pictures. A larger number of photographs or pictures were taken for the individual rainfall events in order to capture representative raindrop distribution pattern. A customized rainfall photobooth (Figure 2 (c)) with a dark colour background was fabricated to capture the individual droplet sizes during a rainfall event.

![Figure 2](image)

**Figure 2.** (a) Tipping Bucket Rain Gauge, (b) DSLR Camera (Sony α6000), and (c) Customized Photobooth.
To determine raindrop size distribution properties, the selected images include the image of the droplet were processed by a customized coding script program and to be run in MATLAB for image segmentation. Based on the pixel measurements, the processed or segmented images provided the information on raindrop count, drop diameter, drop area, drop perimeter and coordinates of the raindrops. The numeral data were then extracted from MATLAB in Excel Format and the droplet sizes were subsequently categorised into several intervals for raindrop size distribution analysis. During the data sorting process, drop sizes below 0.3 mm were deemed as a cut-off point or considered negligible because of the misting effect for drop size <0.3 mm where are detectable during the image segmentation process. Hurley et al. [16] stated that misting particle sizes could range from 10 µm to 100 µm (0.01 mm to 0.10 mm), and even up to 300 µm (0.3 mm). The drop ranges are grouped at 0.5 mm intervals from 0.0 mm to 4.5 mm. The drop distributions and volumetric drop median in each of the groups with respect to different rainfall intensities were compared and analysed.

3. Results and Discussions

The three (3) rainfall intensities are plotted in bar chart format as shown in Figure 3, and the details on volumetric drop distribution, mean and standard deviations with respect to intensities are illustrated in Table 2. The results show similar trends for all intensities with the highest volumetric distribution mean (VDM) of 55.33% for 1.0–1.5 mm drop size and the lowest VDM of 1.66% for 4.0–4.5 mm drop size. Based on the results, the rainfall intensity of 32.41 mm/h was found to produce highest volumetric drop distribution of 78.64% for drop size of 1.0–1.5 mm, as compared to 56.84 mm/h of 47.69% and 85.73 mm/h of 39.66%. For the higher intensity at 85.73 mm/h, it is shown that there is a significant increase in the larger drop sizes of the 3.0–3.5 mm and 4.0–4.5 mm groups that constitute about 5.17% and 3.45%, respectively. From this study, it is also found that incremental of rainfall intensity from 56.84 mm/h to 85.73 mm/h would result in significant increase (15.52% increase) in larger drop sizes of 3.0–4.5 mm, as well as significant reduction (13.57% decrease) in the distribution of smaller drop sizes between 1.5–2.5 mm. Table 2 shows the details of volumetric drop distribution (%), mean and standard deviation.

![Figure 3. Natural Rainfall Intensities and Drop Size Distribution.](image-url)
Table 2. Rainfall Intensity Classification.

| Drop Size (mm) | 32.41 mm/h | 56.84 mm/h | 85.73 mm/h | Mean | St. Dev. |
|----------------|------------|------------|------------|------|---------|
| 0.5            | 0.00       | 0.00       | 0.00       | 0.00 | 0.00    |
| 1.5            | 78.64      | 47.69      | 39.66      | 55.33| 20.58   |
| 2              | 13.59      | 27.69      | 29.31      | 23.53| 8.65    |
| 2.5            | 5.83       | 15.38      | 15.52      | 12.24| 5.56    |
| 3              | 0.00       | 6.15       | 6.90       | 4.35 | 3.79    |
| 3.5            | 1.94       | 1.54       | 5.17       | 2.88 | 1.99    |
| 4              | 0.00       | 0.00       | 0.00       | 0.00 | 0.00    |
| 4.5            | 0.00       | 1.54       | 3.45       | 1.66 | 1.73    |

A comparison of the current findings on intensity versus drop size distribution with Elbasit, Yasuda & Salmi [17], a similar trend is noted with respect to incremental larger drop sizes and decreases in smaller drop sizes. It is noted that there are glaring or discernible differences between the findings of the current study conducted in the equatorial area and previous researches in the temperate zone. A comparatively higher volumetric drop distribution for smaller raindrop size (1.0–1.5 mm) is recorded in this (equatorial) as compared to the findings of Elbasit, Yasuda & Salmi [17], i.e., higher margin on the larger drop sizes of >4.0 mm. Because of the potential limitations, it is noted that rainfall distribution patterns and raindrop size distribution patterns are highly dependent on the regional locality in different parts of the world and climatic characteristics. Generally, this study shows rainfall intensities correlate well with raindrop size distribution patterns.

The best fit plots of cumulative volumetric drop of the three (3) different rainfall intensities are depicted in Figure 4 and the quantile regression details are shown in Table 3. It is shown that the overall cumulative distribution pattern versus intensity is consistent with respect to drop size distribution. It is also found that the median drop size increases as rainfall intensity increases. From the results, the median drop size (D_{50}) for intensities at 32.41 mm/h, 56.84 mm/h, 85.73 mm/h are 1.18 mm, 1.57 mm and 1.70 mm, respectively. As shown in Table 3, an increase in rainfall intensities would result in a general increase in drop sizes, as indicated in the percentile diameter (D_{10} and D_{90}) and quartile diameter (D_{25} and D_{75}) for all the 3 rainfall intensities understudy.

Table 3. Raindrop Size Distribution - Percentile and Quartile Drop Diameters.

| Intensity | 32.41 mm/h | 56.84 mm/h | 85.73 mm/h |
|-----------|------------|------------|------------|
| D_{10}    | 0.86       | 1.01       | 1.03       |
| D_{25}    | 0.92       | 1.28       | 1.33       |
| D_{50}    | 1.18       | 1.57       | 1.70       |
| D_{75}    | 1.49       | 2.14       | 2.37       |
| D_{90}    | 2.14       | 2.72       | 3.36       |
| Span (D_{90} – D_{10}) | 1.28 | 1.71 | 2.32 |
| Relative Span (Span / D_{50}) | 1.08 | 1.09 | 1.36 |
| Quartile Ratio (D_{75} / D_{25}) | 1.61 | 1.67 | 1.79 |
Based on the findings, it can be statistically be interpreted that higher rainfall intensities are always characterized by having closer distances among raindrop particles and thus higher chances for smaller raindrops to collide and to coalesce into larger droplets before falling from the cloud. Related studies conducted by Laws & Parsons [6], Zanchi & Torri [18] and Van Dijk, Bruijnzeel & Rosewell [19] in the temperate region at low rainfall intensities and different study approaches show that an increase of raindrop sizes with the increment of rainfall intensities.

4. Conclusion
The experimental outcomes of the study are summarized in Table 4 showing intensity versus drop size and volumetric drop weightage (%). To put the field study results in perspective, the drop sizes are simplified into 6 ranges or intervals from <0.3 mm to >4.0 mm (Table 4).

Table 4. Intensity Versus Volumetric Drop Weightage (%).

| Rainfall Intensity | I = 32.41 mm/h | I = 56.84 mm/h | I = 85.73 mm/h |
|-------------------|----------------|----------------|----------------|
| Drop Size (mm)    | Drop (%)       | Drop (%)       | Drop (%)       |
| d ≤ 0.3           | Negligible (Misting Effect) | 0.00 | 0.00 | 0.00 |
| 0.3 < d ≤ 1.0     | 92.23          | 75.35          | 68.97          |
| 1.0 < d ≤ 2.0     | 5.83           | 21.53          | 22.42          |
| 2.0 < d ≤ 3.0     | 1.94           | 1.54           | 5.17           |
| 3.0 < d ≤ 4.0     | 0.00           | 1.54           | 3.45           |
| d > 4.0           |                |                |                |

From this study, the following conclusions can be drawn with respect to rainfall intensities between 32.41 mm/h and 85.73 mm/h. Generally, it is confident to conclude that, about 95% of the cumulative volumetric drop tend to fall within the 1.0 mm and 3.0 mm, while the constituents of drop sizes of <1.5 mm and >4.0 mm are negligible. Drop sizes between 1.5 mm and 2.0 mm constitute for about 92.23%, 75.53% and 68.97% of the cumulative volumetric drop weightages for intensities at 32.41 mm/h, 56.84 mm/h and 85.73 mm/h, respectively. The 2.0 mm and 3.0 mm drop sizes account for approximately 5.83%, 21.53% and 22.42% of the total volumetric drop weightages for intensities at
32.41 mm/h, 56.84 mm/h and 85.73 mm/h, respectively. The 3.0 mm to 4.0 mm raindrop size particles recorded as low as 1.94%, 1.54% and 5.17% for intensities at 32.41 mm/h, 56.84 mm/h and 85.73 mm/h, respectively. The incremental number of drop sizes between 3.0 mm to 4.0 mm particles is not proportional to the increment of rainfall intensities.

5. References

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