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Derivation of Regression Coefficients and Conversion Factors for 1-Minute Rain Rate Statistics in A Tropical Environment

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Abstract: An important characteristic of rainfall levels at a particular place is the statistical distribution of rainfall rate. In this paper, 1-minute, 5-minute and 30-minute integration time rainfall data were obtained from three different weather stations in Physics Department, Federal University of Technology, Minna, North Central Nigeria. The aim is to derive regression coefficients and conversion factors for predicting rainfall rate of 1-minute integration time from rainfall rates of other integration times. This was achieved by employing Segal, Flavin and Watson rain rate models. The results obtained revealed that there is a power law relationship between 1-minute rain rate (R_1) and the equiprobable 5-minute rain rate (R_5); and between 1-minute rain rate (R_1) and the equiprobable 30-minute rain rate (R_{30}). Also, it was observed that the values of regression coefficients *a* and *b*, and conversion factors C_e and C_R derived in Minna were different from values derived at other locations in and outside Nigeria when comparisons were made. These discrepancies are attributed to the differences in climatic conditions between the regions among other factors. Therefore, these findings have further corroborated claims by earlier researchers that different regression coefficients and conversion factors are needed for different locations for 1-minute rain rate conversion.

Keywords: Conversion factors, integration time, power law, rainfall rate, regression coefficients

1. Introduction

Rain rate is usually considered a very important parameter when analysing rain-induced attenuation [1, 2]. For effective and accurate analysis of rain-induced attenuation, conversion of rain rate from any integration time to 1-minute has been an important and accepted approach, especially when one-minute local data is not available [3, 4]. Recent efforts have been made in North Central Nigeria in this regard [5, 6].

Based on the different physical principles of measurement systems, whether it is direct or indirect or whether it is ground-based or space-based, a number of rainfall-measuring methods exist. Remote measurements by weather radars and weather satellites which fall under the indirect methods are broad but lack high accuracy, though with good spatial distribution of rainfall. In variance to the indirect methods, the direct methods which consist of rain gauges and disdrometers give the most direct and requisite accurate measurements, but are restricted to the point of measurement [7, 8]. A rain gauge, which consists mainly of a funnel with a specific diameter and a device that measures the volume of water collected over a specified amount of time, can be used to measure the intensity of rainfall. This instrument can either be a level detector (float or pressure sensor) in a cylindrical container or a calibrated bucket that tips up when it is full and emits an electric impulse. Weather stations frequently provide statistics at intervals of 5 to 10 minutes, which are too long for propagation requirements since heavy rainfall intensities are underestimated. Rain rate is normally expressed in mm/hr, and measurements need to be taken at one-minute intervals [9]. For the tipping bucket rain gauge, the amount of rainfall is measured by observing the volume increase and water weight in a collection container which has a mechanical part driven by a known amount of water [10].

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Given the variety of rain gauge types, understanding how changes in their integration times affect the probability distributions of rainfall rate is essential [11]. Everywhere in the world, the rate of rainfall varies greatly from place to place. The measurement and accuracy of empirical data enhance the development of rain attenuation for a specific location, which is also reliant on the understanding and accuracy of the rainfall rate [2, 12-17]. Due to the inherent enormous fluctuation of rainfall at a particular point, the cumulative distribution of the measured rain rate depends on the rain gauge's sampling time; and rain gauges with short integration time are recommended for radio-climatic observations because they account for these fluctuations on the communication links [18].

It has become necessary to predict 1-minute rain rate statistics by using conversion factors and the corresponding conversion coefficients, partly due to the dearth of 1-minute rain rate data needed for the estimation of rain-induced attenuation in this region of the world, and also due to the inherent errors in some rain rate models. Numerous efforts have been made in this direction, however significant discrepancies in the conversion factors obtained from different locations have also been noticed [19-25]. In the current work, conversion factors for Minna have been derived using the cumulative distribution of the available 30-minute, 5-minute, and 1-minute rain rate statistics.

2. Background

2.1 Segal and Flavin's Rainfall Rate Models

For converting data from a rain gauge with τ-minute integration time to an equivalent 1-minute integration time, Segal [26] suggested a model with a conversion factor ρ_τ. In terms of the ratio of the equiprobable rain rate, the model is represented as follows:

$$\rho_\tau(p) = \frac{R_T(p)}{R_\tau(p)} \tag{1}$$

where R_T and R_τ represent the rain rates exceeded with equal probability p, for the two integration times. It is beneficial to assume that τ is greater than T and that R_τ is the known rain rate, while R_T is the unknown.

Using the power law to estimate the empirical relation between the conversion factor and the independent variable, equation (1) can be expressed as:

$$\rho_\tau(p) = aR^b \tag{2}$$

where $0.001\% < p < 0.03\%$. The coefficients *a* and *b* may be climate dependent [27].
Taking the logarithm of both sides of equation (2) yields:

$$\log \rho_\tau = \log a + b\log R \tag{3}$$

Combining equations (1) and (3) becomes:

$$\log(R_T(p)/R_\tau(p)) = b\log R + \log a \tag{4}$$

where *b* is the slope and *a* is the intercept.

Flavin [20] had earlier established that there was a power law connection between the equiprobable rain rates of two integration times. This power law connection is given by:

$$R_\tau = aR_T^b \tag{5}$$

where R represents the rain rate, τ is the integration time for the required rain rate and T depicts the integration time of the available rain rate; *a* and *b* are the power-law coefficient and exponent respectively. The values of *a* and *b* are easily estimated between the rain rate of any integration time T and the desired integration time τ by taking the logarithm of both sides of equation 5 and plotting log (R_τ) against log (R_T). That is,

$$\log(R_\tau) = \log(a) + b\log(R_T) \tag{6}$$

2.2 Watson Rain Rate Model

Watson *et al*. [21] also considered the conversion factors Ce and C_R for rain gauge of different integration times. Both factors are given as:

$$C_e(R) = \frac{e_T}{e_\tau} \tag{7}$$

$$C_R(t) = \frac{R_T}{R_\tau} \tag{8}$$

where C_e (R) is the ratio of the exceedances for a specified rain rate R, determined from rain gauges of integration times T and τ, while C_R (t) gives the ratio of rain rates exceeded for a known percentage of time t exceedance. e_T represents the exceedance at R_T (rain rate) for T integration time, while e_τ depicts the exceedance at R_τ (rain rate) for τ integration time.

3. Methodology

3.1 1-Minute Integration Time Rainfall Measurement

A rain gauge and a data logger (Rain 101A) were used to measure the 1-minute integration time rainfall data. This is shown in Figure 1. The data logger was set to a reading interval of 10 seconds during the data collection. 2 years' rainfall data was measured and stored in the internal memory of the data logger. The stored data was downloaded and viewed in three different modes: graph, data table and statistical report. The downloaded data was then saved as Microsoft Excel spreadsheet.

Fig. 1 - Rain gauge and rain 101A data logger

3.2 5-Minute Integration Time Rainfall Measurement

Rainfall data of 5-minute integration time was measured using a rain gauge and a Campbell CR-1000 data logger as shown in Figure 2. Four years in-situ measurement of rainfall data was used for the analysis. The 5-minute integration time rainfall rate was computed from rainfall accumulation of 5-minute interval. The percentage exceedances were then computed from these measurements. These two computations are relevant input parameters for the 1-minute rain rate conversion. The weather station where this data was collected is called the Tropospheric Data Acquisition Network (TRODAN).

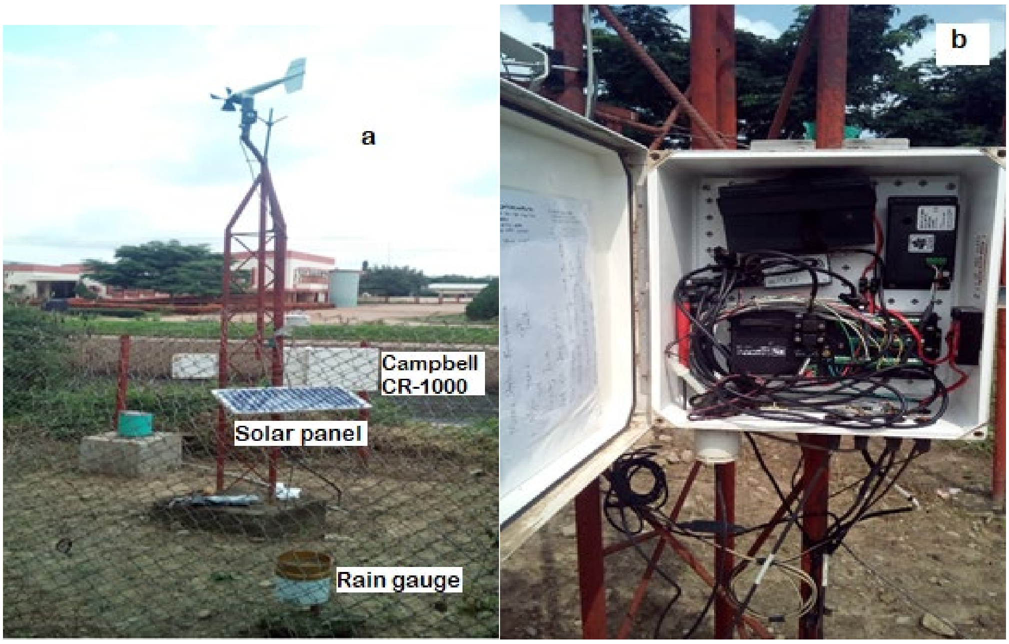

Fig. 2 - (a) TRODAN weather station; (b) Campbell CR-1000 data logger

3.3 30-Minute Integration Time Rainfall Measurement

30-minute integration time rainfall data was collected using a Davis vantage pro 2 automatic weather station equipped with an Integrated Sensor Suite (ISS) as shown in Figure 3. The block diagram of the equipment setup is shown in Figure 4. The ISS comprises the sensors for rainfall and other atmospheric parameters. It also consists of a Sensor Interface Module (SIM). The electronic devices that measure and record the values of weather parameters for onward transmission to the console via a radio are contained in the SIM. These measurements were taken at 30 minutes' intervals. Through wireless radio connection, the data is transmitted to the data logger which is attached to the console. The stored data is usually downloaded with a PC (personal computer). An inbuilt memory device with a capacity of 1 gigabyte enables the console to store data for about one month before downloading. Also, a software application called 'Weather link' which is installed in the PC enables the conversion of the stored data to Windows format.

Fig. 3 - The Davis vantage pro 2 automatic weather station

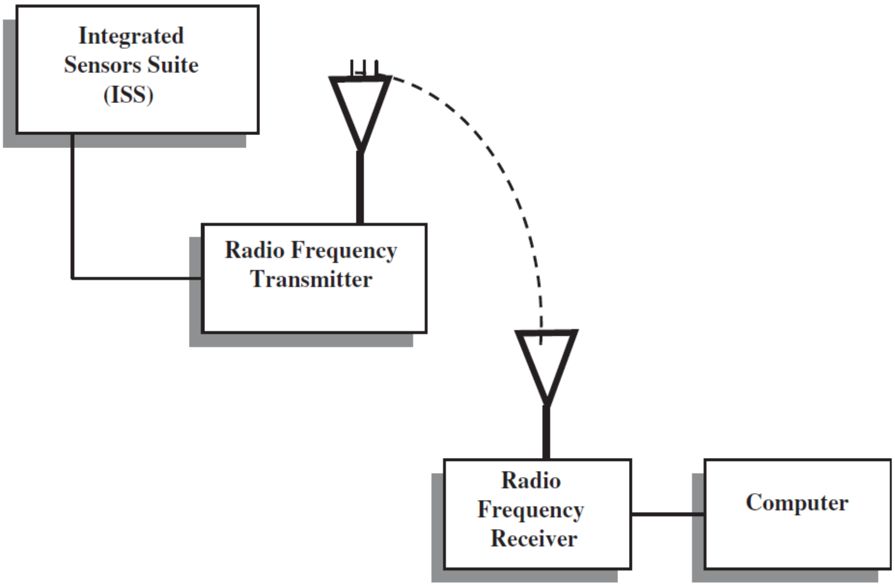

Fig. 4 - Block diagram of the integrated sensor suite

4. Results and Discussion

4.1 Derivation of Regression Coefficients for 1-Minute Rain Rate Prediction

The results of the rain rate statistics measured with different rain gauges at various integration times are shown in Figure 5. This depicts the relationship of the cumulative distribution of rain rate generated at 1-minute, 5-minute and 30-minute integration times.

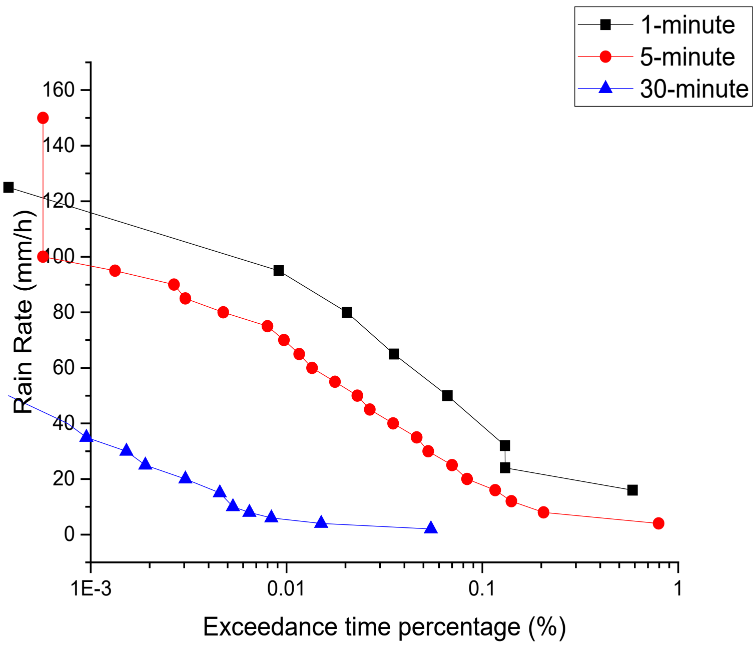

Fig. 5 - Cumulative distribution of rain rate

From Figure 5, at percentage time exceedance of 0.01%, 6 mm/h rain rate was measured at 30-minute integration time, while 70 mm/h rain rate was measured at 5-minute integration time, but the value of the rain rate recorded at 1-minute integration time is 95 mm/h. From this result, it is obvious that there are discrepancies at this very important percentage exceedance used for the computation of rain-induced attenuation at centimetric and millimetric wave frequencies. Hence, accurate derivation of the required conversion factors for the higher integration times (30-minute and 5-minute) is necessary.

The values of the equiprobable rain rate statistics at different integration times for exceedance probabilities of 0.001% - 1% are given in Table 1.

Table 1 - Equiprobable rain rates at different integration times

1-min (mm/h)	5-min (mm/h)	30-min (mm/h)	% Exceedances
20	-	-	0.5854
40	12	-	0.1309
60	25	2	0.0666
80	40	-	0.0356
95	70	6	0.0093
140	100	40	0.0006
200	-	-	0.0002

The values given in Table 1 show that equiprobable rain rates of different integration times are related. This relationship between rain rates of two different integration times is a power law relationship, which has already been established in equation (5) by [20].

Hence, Table 2 gives the values of coefficients a and b derived for rain rates at 5-minute and 30-minute integration times in Minna. These values were obtained from the regression equation derived when rain rate data of 1-minute integration time was fitted against those of 5-minute and 30-minute integration times.

Table 2 - Coefficients of $R_\tau = aR_T^b$ for τ = 1-min

T (min)	*a*	*b*
5	1.414	1.640
30	0.960	1.897

The regression equation was derived from equation (6) by plotting $\log(R_\tau)$ against $\log(R_T)$. The curve that resulted from this analysis yielded a straight-line equation given as:

$$y = 1.6401 \ln(x) + 0.3464 \tag{9}$$

Equation (9) represents conversion from 5-minute to 1-minute. When equation (6) was compared with equation (9), the coefficient *a* was obtained as 1.414 (by taking the exponential value of 0.3464), while the coefficient *b* was easily given as 1.640.

Following the same procedure for conversion from 30-minute to 1-minute, the straight-line equation that resulted is given as:

$$y = 1.8973 \ln(x) - 0.0418 \tag{10}$$

From equation (10), the coefficients *a* and *b* were derived as 0.960 and 1.897 respectively. The result in Table 2 expresses the relationships between rain rates of 1-minute and 5-minute integration times; and between rain rates of 1-minute and 30-minute integration times in Minna. These values were observed to be in conformity with the results obtained by [20] when he derived the following relationship:

$$R_1 = 0.990R_6^{1.054} \text{ mm/h} \tag{11}$$

where R_1 is the rain rate at 1-minute and R_6 is the equiprobable rain rate value at 6-minute integration time.

Therefore, from Table 2, the following relationships between rain rates at 1-minute and 5-minute integration times; and between those of 1-minute and 30-minute integration times in Minna were inferred:

$$R_1 = 1.414R_5^{1.640} \text{ mm/h} \tag{12}$$

$$R_1 = 0.960 R_{30}^{1.897} \text{ mm/h} \tag{13}$$

where R_1 is the 1-minute rain rate, while R_5 and R_{30} are the equiprobable values of 5-minute and 30-minute rain rates respectively.

The values of *a* and *b* derived in Minna were compared with values obtained at some locations in Nigeria and with those obtained at other locations outside Nigeria. This is given in Table 3.

Table 3 - Comparison of coefficients a and b obtained at other locations

In Nigeria	T (min)	*a*	*b*	Outside Nigeria	T (min)	*a*	*b*
Akure [28]	5	0.749	1.380	South Africa [29]	5	1.964	0.858
Ile-Ife [22]	5	0.991	1.098	Brazil [30]	5	0.929	1.036
Minna	5	1.414	1.640	China [30]	5	1.110	1.010
Ogbomoso [24]	5	0.797	1.195	Korea [30]	5	0.934	1.032
				Spain [31]	5	0.795	1.081
Akure [28]	30	2.566	0.871	Brazil [30]	30	0.554	1.331
Ile-Ife [22]	30	--	--	Korea [30]	30	0.723	1.062
Minna	30	0.960	1.897				
Ogbomoso [24]	30	--	--				

It is observed in Table 3 that the derived regression coefficients exhibited some discrepancies at the different locations considered. This confirms the observations of [26] and [31] that it is impossible to achieve a single regression coefficient for rain rate conversion from other integration times to 1-minute for all locations. Also, it has been observed that climate is responsible for the effect of integration time on rain rate [21]. Moreover, environmental differences and accuracy of rain gauge sampling frequency are additional factors that are responsible for these disparities.

4.2 Derivation of Ratio of Rain Rate Exceedances C_e (R) and C_R (t)

The comparison between the values of C_e for τ = 1-minute and T = 5-minute derived for different rain rate values in Minna and other locations within Nigeria is given in Table 4, while Table 5 shows the comparison of the derived values of C_R for τ = 1-minute for different exceedance time percentages in Minna and other locations in Nigeria.

Table 4 - C_e(R) for τ = 1-min and T = 5-min

Location	Rain rate (mm/h)							
	30	40	50	60	70	80	90	100
Akure [28]	0.11	0.04	0.03	--	--	--	--	--
Ile-Ife [22]	0.59	0.57	0.4	0.30	0.17	0.10	0.08	--
Minna	--	1.08	--	1.05	--	0.98	--	1.04
Ogbomoso [23]	0.37	--	--	0.28	--	--	0.16	--

Table 5 - C_R (t) for τ = 1-min

Location	T (min)	C_R (0.01)	$R_{0.01}$ (mm/h)	C_R (0.001)	$R_{0.001}$ (mm/h)	Remarks
Akure [28]	5	0.33	105	0.29	-	2 years data
Ile-Ife [22]	5	0.68	80	0.64	-	$2\frac{1}{3}$ years data
Minna	5	0.70	70	0.71	100	2 years data
Ogbomoso [23]	5	0.64	90	--	-	10 months data
Ogbomoso [24]	5	0.42	24	0.53	-	2 years data
Akure [28]	30	0.83	60	0.68	-	2 years data
Minna	30	0.06	6	0.25	35	2 years data

From Tables 4 and 5, it is observed that the values of C_e (R) and C_R (t) obtained in Minna are different from the values obtained at the other locations. The different geographic and climatic conditions of the two regions, as stated earlier, are responsible for these differences. Minna is situated in the North Central region of Nigeria with a guinea savannah vegetation, while Akure, Ile-Ife and Ogbomoso are situated in the South West region of Nigeria with moist/rain forest vegetation.

5. Conclusion

A power law relationship has been established between equiprobable rain rates of 30- minute, 5-minute and 1-minute integration times. Conversion factors for obtaining 1-minute rain rate statistics from higher integration times have been derived in Minna, North Central Nigeria. These values can be used to predict 1-minute rain rate when there is no rain gauge of 1-minute integration time in the region.

Also, the regression coefficients *a* and *b*, and the conversion factors C_e and C_R derived for 1-minute rain rate statistics in Minna have been found to vary from those derived for other locations in and outside Nigeria. This disparity is attributed to the differences in climatic conditions and sensitivity of rain gauge sampling frequencies between the two regions amongst other factors. With these findings, the present study has further attested to the assertions by earlier researchers that different regression coefficients and conversion factors are needed for different locations when converting rain rates of other integration times to 1-minute integration time.

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