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Worst Month Rain Rate Characterization for Line-of-Sight Link Performance in Tropical Locations

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ABSTRACT
Communication equipment operating in the 30 to 300GHz frequencies avails large bandwidth and high speed data transmission but suffers greatly from attenuation by rain. The design of radio communication equipment has been based on predicted rain rate from the International Telecommunication Union-Radio (ITU-R) recommendations. This equipment fails in the tropics due to the differences in tropical and temperate rainfall structure on which the ITU-R recommendation is based. Five minutes rainfall data from two tropical locations in Nigeria – Jos (9.93 ºN, 8.89ºE, 1280 m) and Minna (9.61 ºN, 6.56 ºE, 223 m) were analysed. The 1- minute and ITU-R predicted rain rate (RR) were obtained with the Lavergnat and Gole model and MatLab rain rate statistics respectively while the logarithmic scale was used to convert the RR to exceedance time percentages (0.001 to 1%). The two parameter conversion factors, Q_1 and β were generated with the ITU-R P. 841-6 recommendation; these were compared with the conversion factors recommended by ITU-R for global rain rate application. The results showed that at 0.01% exceedance, the ITU-R predicted rain rate for Jos and Minna were 87.1mm/hr and 91.6mm/hr respectively while the estimated rain rate from these locations were 84.5mm/hr and 110.0mm/hr respectively. The ITU-R conversion factor for the computation of the mean annual worst month from mean annual rain rate percentage exceedence were $Q_1 = 2.83$ and $\beta = -0.15$ while these parameters at Jos is, $Q_1 = 3.17$ and $\beta = -0.19$ and at Minna, $Q_1 = 3.12$ and $\beta = -0.18$. The results showed that there is a very strong relationship between the distribution of rain rate in the worst month and the annual rain rate distribution with coefficient of determination of 0.9994 and 0.9984 respectively. Thus for optimum link design budgeting, the modified values of Q and β should be adopted in these locations in order to enhance radio equipment performance in Nigeria.

Key words: Rain rate characterization, radio wave propagation, radio communication, propagation losses, tropical location.

1. INTRODUCTION

Rainfall is a natural and time varying phenomenon that varies from location-to-location and from year to year (Shebani *et al.*, 2017). Rainfall causes absorption and scattering of radio waves which results in the reduction of the received signal level, coverage area, overall system reliability and performance (Zheng et al., 2021). Rain attenuation has a serious impact on the availability and performance of radio communication services operating in the frequencies above 10 GHz especially in the tropical areas (Christofilakis *et al.*, 2020). The reference statistics for many radio-meteorological data and propagation prediction methods is the long term average annual distribution (ITU-R P. 841-6, 2019). However, Radio wave propagation conditions vary considerably from month to month (Ukhurebor and Azi, 2019). This presents the radio communications system designer and engineers the challenge of ensuring at least 99% of the systems availability and performance for the worst months of the year (ITU-R P. 837-7, 2017). The worst month of a year for a preselected threshold for any performance degrading mechanism is the month in a period of twelve consecutive calendar months during which the threshold is exceeded for the longest time (ITU-R P. 581-2, 1990). To ensure accurate radio-meteorological data and propagation conditions for the worst months, the pre- selected threshold for any performance degradation threshold should be specified (ITU-R P. 581-2, 1990).

2. PROBLEM STATEMENT

The major challenge confronting engineers working on higher frequency bands is the attenuating effects of rain on radio waves and bandwidth availabilities (Shrestha and Choi, 2019). Though a methodological approach has been developed by the ITU-R (Radio Communication Sector of the ITU) which is useful for radio signal attenuation prediction due to rain on any terrestrial paths, however, in the tropical climate, the ITU-R model does not perform well (Samad *et al.*, 2021). As opined by Ajayi *et al.* (1996) the rain in the tropics are more intense, more frequent and are of larger drops as against what obtains in temperate climates on which ITU methodology is based. In order to reliably predict rain attenuation for a given location, there is a need for studying monthly and seasonal rainfall variability, worst month and average worst month statistics of rain, and rainfall rate distribution models for the site under study (Owolawi and Afullo, 2007; Samad *et al.*, 2021).

3. METHODOLOGY

3.1 Data Collection

The data used in this study was sourced from the Tropospheric Data Acquisition Network (TRODAN), a project put forward by the Nigerian Centre for Atmospheric Research (CAR). The project was designed to collect and provide real-time meteorological data from different locations across Nigeria for monitoring the lower atmosphere, which covers the region from the surface of the Earth to the altitude of about 11km. The equipments used are of Campbell Scientific specifications. Tipping bucket rain gauge with a resolution of 5 minutes update cycle was used for rainfall data collection. The specification of the tipping bucket rain gauge used at each TRODAN station was TE525WS. The orifice is 20.3 cm and the resolution is 0.254 mm. The accuracy is up to 25.4mm/hr: ±1% while the operating temperature is from 0° to +50°C. The study area is Jos, the mid altitude and Minna, the southern guinea savanna climate regions of North Central Nigeria. The duration of the study was nine years. Figure 1 is a 3D plot showing the geography of the study locations while Table 1 shows the climatological parameters of the locations which includes the coordinates, height above sea level (altitude), the average annual rainfall (mm/year) and the climate region.

3.2 Data Analysis

3.2.1 Rain Rate Integration Time Conversion

The Lavergnat and Gole (LG, 1998) model (1) which is an application of stochastic process for rain drops time intervals was used for the conversion from 5 minutes to 1-minute integration time.

$$Q_c(r,t) = K^{\xi-1} Q_c\left(rk^{\xi-1}, kt\right) \qquad (1)$$

Where $Q_c(r,t)$ is the cumulative probability function of rain rate r that would be obtained with a rain gauge having an integration time t. Equation (1) thus allows a rain rate distribution observed using an integration time kt to be changed into one that would have prevailed for an integration time t. The parameters and ξ and k are constants. The 1- and 5-minute rain rates were accumulated over the periods of observation and converted to 0.01% exceedance by using logarithmic scale.

3.2.3 Conversion from Average Annual to Average Worst Month Time Percentage of Excess

The International Telecommunications Union (ITU-R P. 841-6, 2019) recommended method for the conversion of the average annual time percentage of excess to the average worst month time percentage of excess are as follows:

The average annual worst-month time percentage of excess, P_w, is calculated from the average annual time percentage of excess P by the use of the conversion factor Q, where

$$P_w = QP \qquad (2)$$

Where $1 \leq Q \leq 12$

and P and P_w refers to the same threshold levels, Q is a two parameter (Q_1 and β) function of P (%):

$$Q_p = Q_1 p^{-\beta} \qquad (3)$$

$$\text{for } \left(\frac{Q_1}{12}\right)^{\frac{1}{\beta}} < p \leq 3\% \ .$$

The calculation of the average annual time percentage of excess from the given value of average annual worst month time percentage of excess is done through the inverse relationship:

$$P = \frac{P_w}{Q} \qquad (4)$$

The dependence of Q on P_w can be easily derived from the given dependence of Q on P (4). The resulting relationship is (5)

$$12\, p_o < p_w (\%) < Q_1^{3(1-\beta)} \qquad (5)$$

where

$$p_o = \left(\frac{Q_1}{12}\right)^{\frac{1}{\beta}} \quad (6)$$

and

$$Q = \frac{1}{Q_1^{(1-\beta)}} \frac{-\beta}{p_w^{(1-\beta)}} \quad (7)$$

According to ITU-R P. 841-6 (2019), for global rain rate application, the following values for the parameters Q_1 and β should be used for tropical, subtropical and temperate climate regions with frequent rain.

Q1 = 2.82. β = 0.15

Substituting these values to (7) gives,

$$Q = 3.384 p_w^{-0.176} \quad (8)$$

Substituting (8) to (4) and approximating to 2 –decimal places,

$$p_a = 0.30 p_w^{1.18} \quad (9)$$

Changing subject and deriving P_w from (9),

$$p_w = 2.77407 p^{0.84746} \quad (10)$$

Equation (8) is for the computation of Q-values, (9) is for the calculation of ITU percentage annual rain rate exceedance while (10) is for the ITU average worst month rain rate exceedance computation.

3.2.4 ITU-R Rain Rate Prediction

4. RESULTS AND DISCUSSION

4.1 Cumulative Distribution Function of Rain Rates Based on Different Integration Times

Rainfall rate distribution is a function of sampling interval of rain gauge. Higher rain gauge sampling interval causes the under estimation of measured rain rate (Chun and Mandeep, 2013). One minute accumulation removes the fluctuations caused by the rain gauge measurement process and maintains the important geophysical variations (Crane, 1996). Figure 2 and 3 presents the results of 1- and 5- minutes rainfall rate distributions at Jos and Minna respectively. As shown from the figures, the higher the rainfall rate, the lower the percentage of exceedance. At Jos, it was observed that at 0.01% of exceedence, about 59.5mm/hr rainfall rate was continually exceeded at 5-minutes integration time while at 1-minute integration time the equivalent rain rate was about 70mm/hr. At Minna, about 81.5mm/hr rainfall rate was exceeded at 5-minutes integration time while at 1-minute integration time, about 116.7mm/hr was continually exceeded at 0.01 percentage of exceedence. Hence, at 5 minutes integration time, rainfall rate was under-estimated in all the locations.

4.2 Accumulated rainfall Distribution

The cumulative rainfall distribution (mm) was deduced throughout the duration of the study in all the locations under investigation. Figure 4 and 5 presents the accumulated monthly and annual rainfall amount over the observed 9 year period for Jos and Minna (2008-2016) respectively. As shown from the figures, the cumulative monthly rainfall distribution was highest (522.30mm) in Minna for the month of September while for Jos location, July witnessed the highest (477.80mm) cumulative monthly rainfall distribution. This is at variance with the findings of Akinbobola *et al.* (2018) that the peak of rainfall in Northern Nigeria occurs in August.

4.3 Rain Rate percentage Exceedance

The 1- minute estimated rain rate was obtained from the locations and these were compared with the predicted rain rate by the ITU-R. The result showed that at 0.01% exceedance, the ITU-R predicted rain rate for Jos and Minna were 87.1mm/hr and 91.6mm/hr respectively while the estimated rain rate from these locations were 84.5mm/hr and 110.0mm/hr respectively. Hence, the rain rate in Jos was over-estimated by the ITU-R while at Minna, it was under-estimated. These are shown in figure 6 and 7.

4.4 Worst Month Rainfall Rate Distribution

4.4.1 Deduction of Worst Months

Worst months scenario in Minna and Jos were captured in figure 8 and 9. As shown by the figure, six months (April to September) stood out as the months of intense rainfall at Jos location while five months (May to September) were the most with intense rainfall in Minna. The worst months rain rate at 0.01% of time were about 140mm/hr in Jos while others were below 120mm/hr at the location. In Minna, worst months have rain rate close to about 330mm/hr while others were below 250mm/hr. The average of the rain rate distribution for all the calendar months of the years gives the value for the average year (AY) as shown in fig. 8 and 9 for each location. These values were used to derive the worst months statistics. The cumulative distribution of rainfall rates for all years and the worst months in Jos and Minna (fig. 8) shows that in worst months at 0.01% of time , rain rate of 225mm/hr was exceeded as against 170mm/hr in average year for Minna. Similarly, Jos shows worst month exceedance of 120mm/hr as against 100mm/hr for average year.

4.4.2 Relationship Between Average Year (AY) and Average Worst Month (AWM)

The procedure in (10) which was defined in (4) was employed in deriving the power law relationship between the AY and AWM percentages (Figure 10). The correlation result from Fig. 10 shows that there is a very strong relationship between the distribution of rain rate in the worst month and the annual rain rate distribution in Jos and Minna with coefficient of determination of 0.9994 and 0.9981 respectively (Figure 11). The slope of the rain rate suggests that the dependence of rain rate characteristics is stronger in Minna than Jos. The power law relationship for the probability distribution over Jos and Minna is given in (11) and (12).

$$p_a = 0.7062\, p_w^{0.9471} \quad \text{(Jos)} \qquad (11)$$

$$p_a = 0.6387\, p_w^{0.9618} \quad \text{(Minna)} \qquad (12)$$

These varies remarkably with the ITU recommended universal power law relationship in (13) with regression coefficients a and b shown in Table 2

$$p_a = 0.300\, p_w^{1.180} \qquad (13)$$

4.4.3 Performance of ITU-R 841-6 Recommendation

The performance of ITU-R 841-6 Recommendation was evaluated between 0.001% to 3% mean annual rain rate exceedance. The values were applied to (10) to obtain the AWM percentages. The AWM value obtained when applied to (8) yielded the ITU-R 841-6 Q-value for the locations. Similarly, the AWM values obtained from (11) and (12) when applied to (8) yielded the Q-values from measurements at Jos and Minna. Figure 11 shows the relationship between the mean annual rain rate exceedance and the Q-values. As shown in Figure 11 and 12 and Table 2, some discrepancies exist between the ITU-R proposed Q-values and values obtained from measurements. Table 2 gives the Q-values (Q_1, β) and regression coefficients (a, b) for Jos and Minna as compared with other tropical locations and ITU-R. As can be inferred from the Table, the recommended Q-values parameters, Q_1, β, are at variance with the values obtained at the locations studied and other tropical and subtropical locations.

5. CONCLUSION

The worst month characteristics of rainfall rate have been investigated for radio wave propagation in tropical locations. The results obtained showed that it varies annually and at 0.001% to 1% time. There is a very strong relationship between the distribution of rain rate in the worst month and the annual rain rate distributions. The ITU-R proposed regression coefficients (a, b) and parameters of Q (Q_1 and β) varies remarkably from the measured values in the tropics. Hence line of sight links designed with the ITU-R worst month rain rate characterisation would perform below optimum in the tropics. These results serve as a guide to system engineers in designing for worst rainfall scenarios inorder to enhance system availability and performance in the tropics.

6. FIGURES/CAPTIONS

Table 1: Climatological parameters of the stations for this study

Sites	Coordinates	Altitude (m)	Average Annual rainfall (mm/yr)	Climate region
Jos	9.93 °N, 8.89°E	1280	812.40	Mid Altitude
Minna	9.61 °N, 6.56 °E	223	910.08	Southern Guinea Savanna

Table 2: Worst months parameters for Jos and Minna in comparison with ITU-R and other tropical locations

Locations	Q_1	β	a	b
Jos	3.173	-0.186	0.706	0.947
Minna	3.119	-0.183	0.638	0.962
Indonesia (Yagasena, 2000)	1.700	0.220	-	-
Kototabang (Marzuki et al., 2016)	1.390	0.240	-	-
ITU	2.828	-0.149	0.300	1.180

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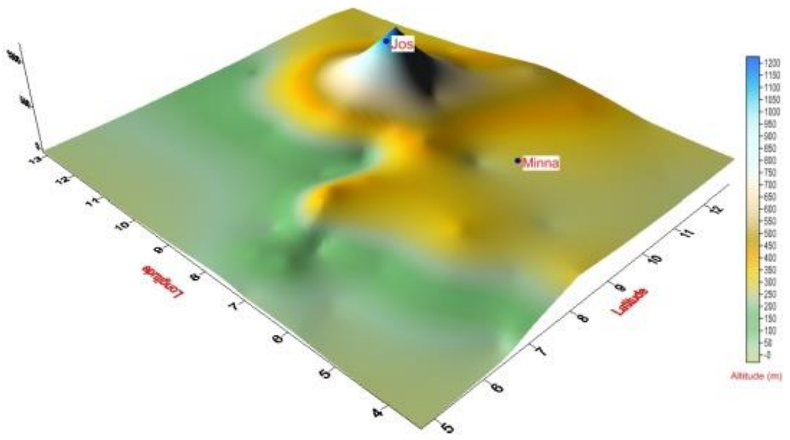

Figure 1: 3D plot of the study locations

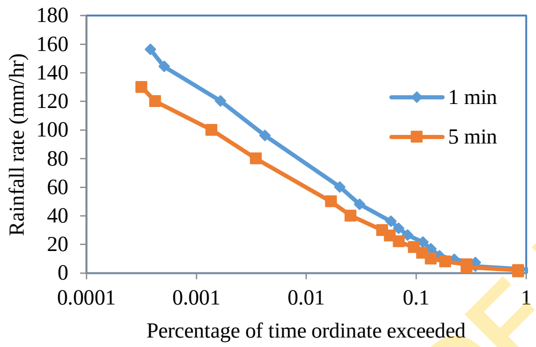

Figure 2. Rain rates distribution at 5-minutes and 1-minute integration time at Jos

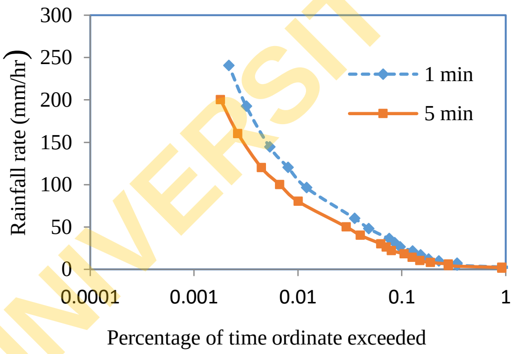

Figure 3. Rain rates distribution at 5-minutes and 1-minute integration time at Minna

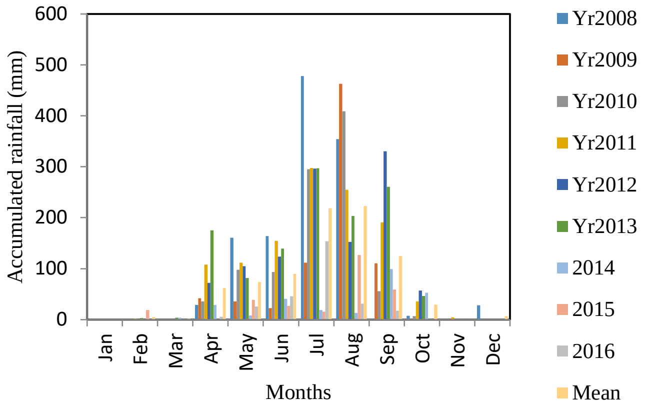

Figure 4. Cumulative monthly rainfall distribution for Jos (mm)

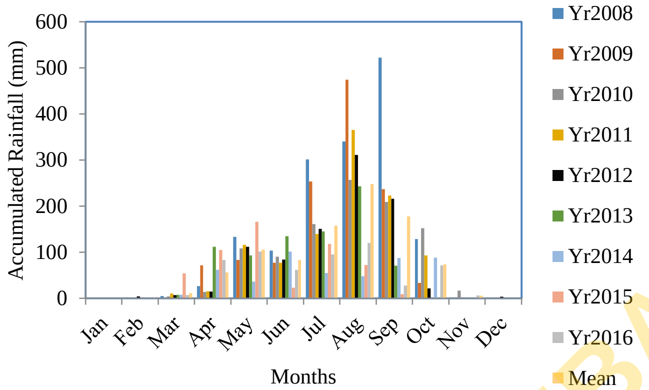

Figure 5. Cumulative monthly rainfall distribution for Minna (mm)

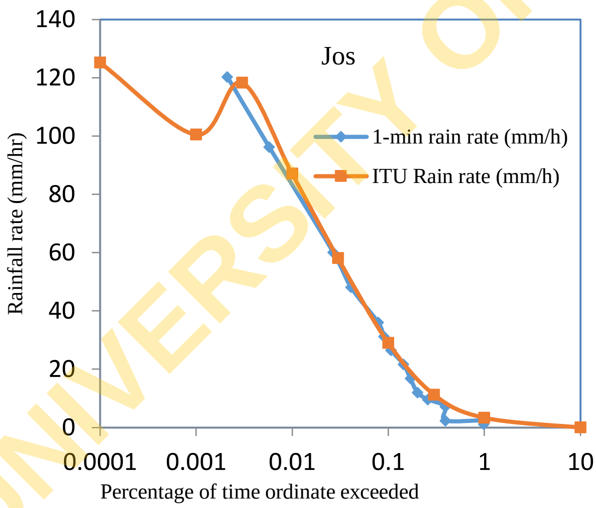

Figure 6: Percentage exceedance of rain rate in Jos

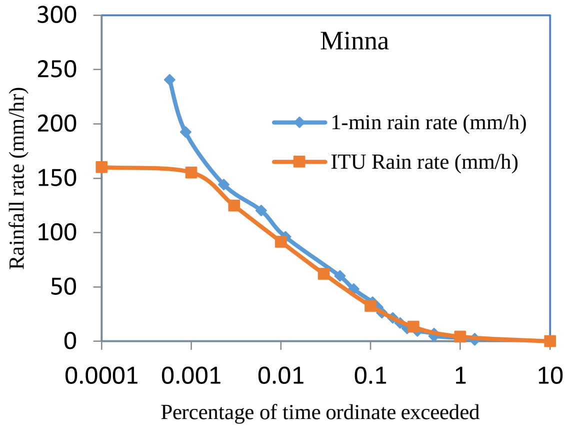

Figure 7. Percentage exceedance of rain rate in Minna

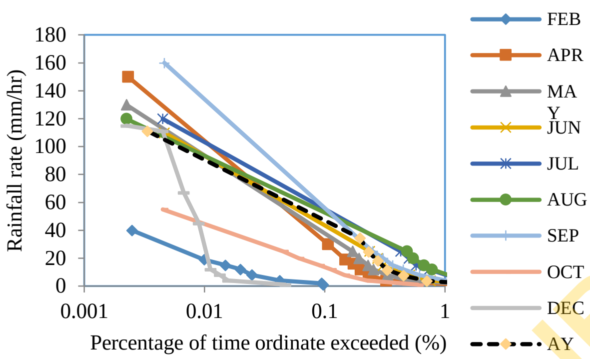

Figure 8. Monthly variation of rainfall rate distribution for Jos

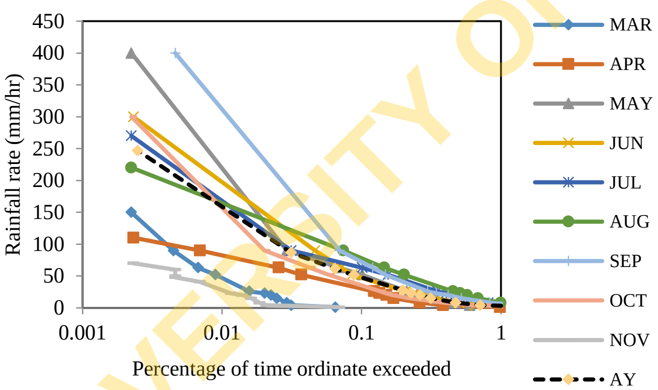

Figure 9. Monthly variation of rainfall rate distribution for Minna

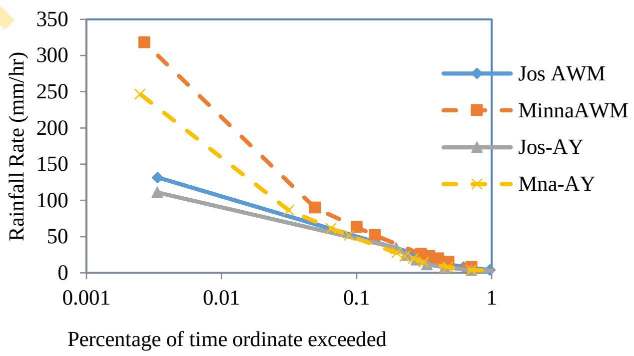

Figure 10. Cumulative distribution of rain rates in average year and worst months for Minna and Jos

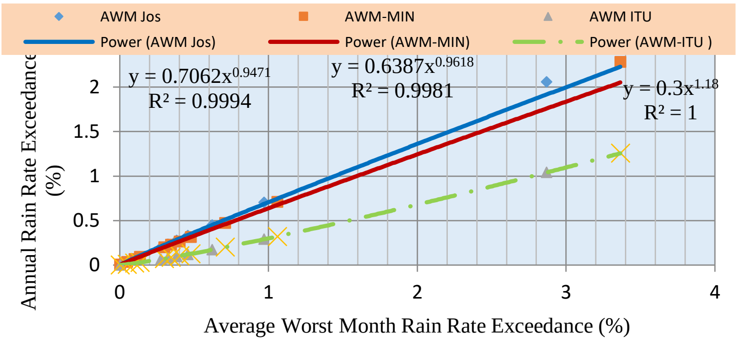

Figure 11. Worst month model compared with ITU-R

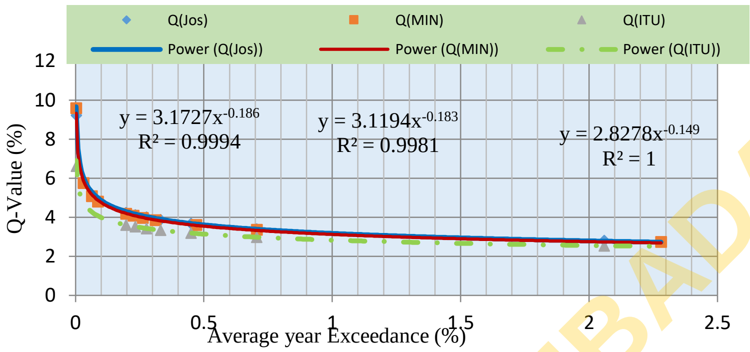

Figure 12. Determination of conversion factors β and Q_1

7. ACKNOWLEDGMENTS

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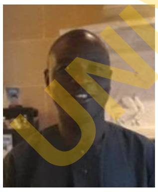

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