CHAPTER 4

ANALYSIS OF RAIN INTENSITY IN SOUTHEAST ASIA

4.1 Introduction

Rain intensity or rainfall rate is one of the most significant meteorological parameters causing rain attenuation above frequencies 10 GHz and resulting degradation of a terrestrial and a satellite communication systems. Understanding statistical characteristics of rain-intensity is essential for planning telecommunication systems especially in the area of heavy rainfall of Southeast Asia.

This chapter presents statistical analysis of rain intensity measured in Southeast Asia over a three year period, 1/Mar/92 - 28/Feb/95. The statistical analysis includes cumulative distributions of rain intensity over a three year period, annual cumulative distributions, monthly cumulative distributions, year-to-year variations, seasonal and diurnal variations, and rain-intensity duration statistics. Measured results are used to develop a suitable rain intensity distribution and compared with various rain intensity models such as the ITU-R 836 [1988], the Rice and Holmberg [1973], and the Moupfouma and Martin [1995].Details of this study is also summarized in the open literature by R. Lekkla, P.Prapinmongkolkarn and K.S McCormick [1988]

4.2 Data Analysis

Tipping-bucket rain gauges with 8 inches in diameter and providing a contact closure for every rainfall accumulation of 0.2 mm, are used to measure rain intensity. This variation integration time rain gauge is recorded for each tip. The measured rain intensity can be calculated by equation (3.13) in chapter 3. It should be noted that due to loss accuracy of very high rain intensity (> 200 mm/h) measurement, rain intensity which is higher than 200 mm/h will not be analyzed and we will not apply any correction factor to all measured data. Measurement accuracy was also described in Chapter 3, section 3.5.

Data availability over a 3-year period is 93% for Bundung, 85% for Bangkok, 86% for Si-racha, and 96% for Singapore. Table 4.1 shows some information used for data analysis including the ratio of thunderstorm activity (β) proposed by Rice and Holmberg [1973], the ITU-R Rain Zone, 30 years average annual rainfall accumulation (M), an annual rainfall accumulation of year-1, year-2, and year-3 respectively.

4.3 Cumulative Distribution of Rain Intensity

A cumulative distribution of rain intensity is the probability distribution of measured rain intensity (R) exceeding the threshold (γ) during an long-term observation period which can be expressed by:

$$P(R > \gamma) = 1 - P(R \leq \gamma) \qquad \text{------------------------ (4.1)}$$

$$= 1 - F_R(\gamma) \qquad \text{------------------------ (4.2)}$$

where

γ is the threshold rain intensity (mm/h),

$P(R > \gamma)$ is the probability distribution of rain intensity (R) exceeding the threshold.

Table 4.1 Site characteristics of four locations in Southeast Asia.

Location	RH Model (β)	ITU-R Rain Zone	Average Annual Rainfall (mm/yr) (M)	Annual Rainfall (1992) (mm/yr)	Annual Rainfall (1993) (mm/yr)	Annual Rainfall (1994) (mm/yr)
Bangkok	0.5	N	1460	965	1591	1431.2
Si-racha	0.5	N	1340	904.2	764.6*	1062.4
Singapore	0.7	P	2285	2370	2405	2316.4
Bundung	0.7	P	2160	1782	2091	1529.8

* completely lost of data on April 1993 - July 1993

The measured cumulative distribution of rain intensity can be obtained by measuring the total accumulation time that rain intensity exceeds each threshold in a number of years. The measured cumulative distribution can be calculated by:

$$P(R > \gamma) = \frac{\Sigma T(R > \gamma)}{T_{total}} \qquad (4.3)$$

where

$\Sigma T(R > \gamma)$ is the total accumulation time in seconds that $R > \gamma$,

T_{total} is the total observation times in seconds.

In a telecommunication system design, an annual cumulative distribution of rain intensity requires the measured data over a given year, shown in Figure 4.1 - 4.4. In this case, the annual cumulative distribution can be acquired by applying equation (4.3) with the total observation time equals to one year. The seasonal or monthly cumulative distributions can also be obtained by adjusting an observation period.

1) Annual Cumulative Distribution of Rain Intensity

Figure 4.1 - 4.4 indicate the annual cumulative distributions of rain intensity of Bangkok (Figure 4.1), Si-racha (Figure 4.2), Singapore (Figure 4.3) and Bundung (Figure 4.4) respectively. The vertical axis is a probability or a percent of the measured rain intensity exceeding each threshold (the abscissa). The dotted curve belongs to year-1 (March 1, 1992 - February 28, 1993), the dashed curve belongs to year-2 and the solid curve belongs to year-3 .

As shown in Figure 4.1 and 4.2, the curves of Bangkok and Si-racha (ITU-R zone N) look similar. The uppermost curve belongs to the year-3 curve followed by year-2 and year-1 curves. Only at 80 kilometers site-separation, there is no significant difference of the annual cumulative distribution of Bangkok and Si-racha.

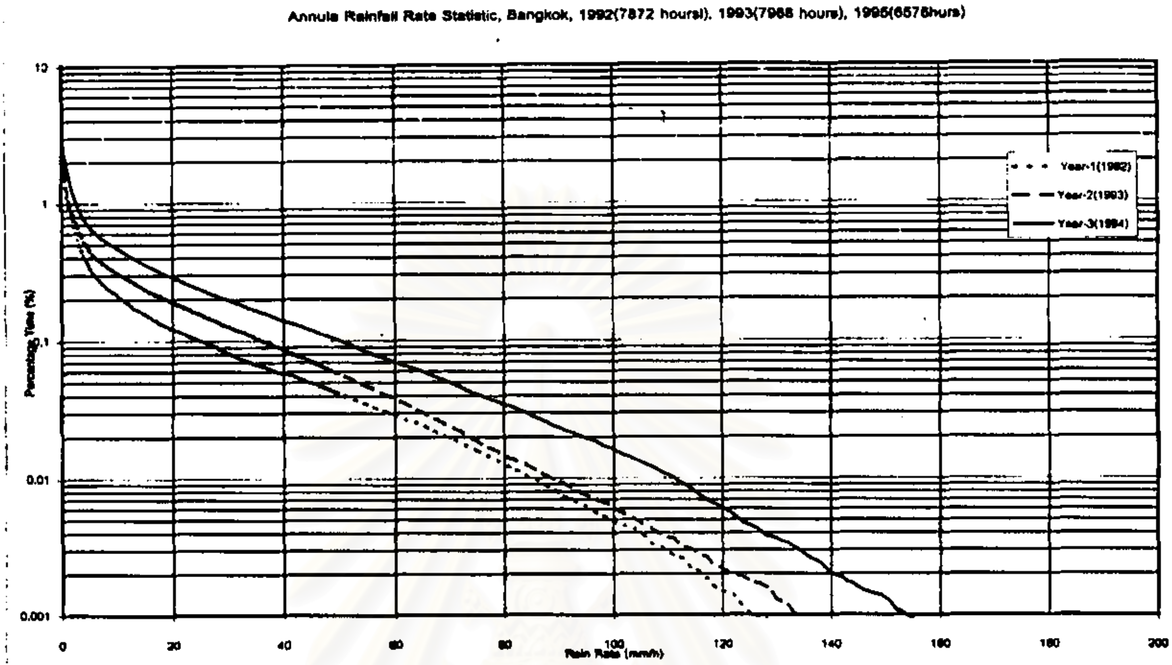

Figure 4.1 Annual cumulative distribution of rainfall distribution in Bangkok (ITU-R zone N) over 3-years

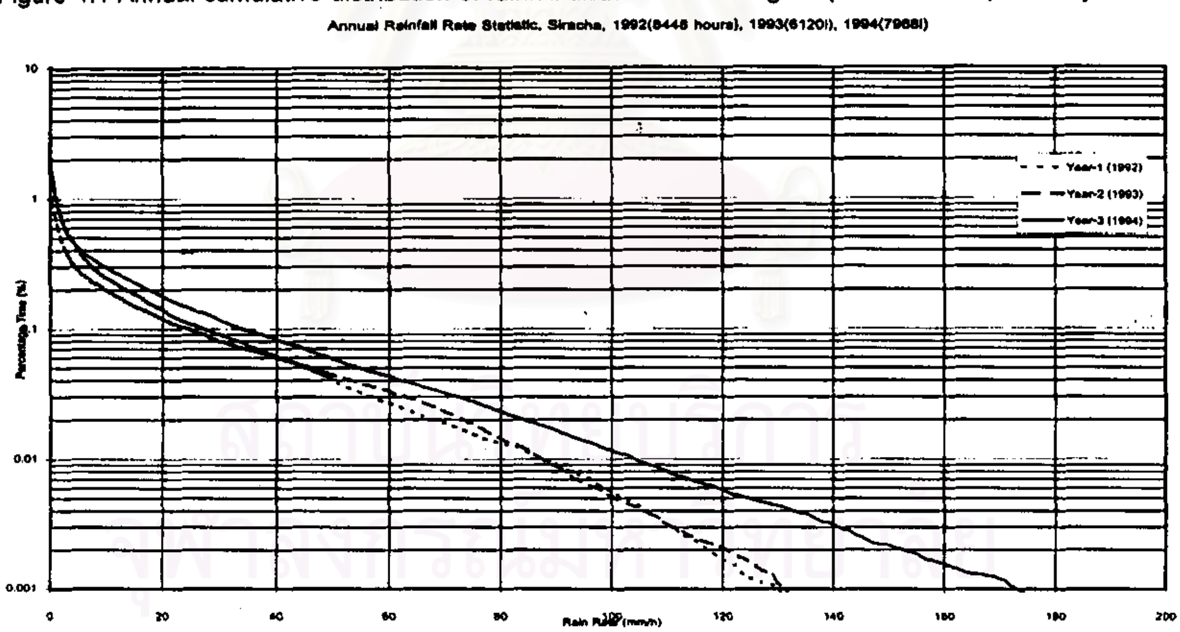

Figure 4.2 Annual cumulative distribution of rainfall distribution in Si-racha (ITU-R zone N) over 3-years

Figure 4.3 and 4.4, show the curve of Singapore and Bundung located in the ITU-R zone P. The Singapore curves (year-1, year-2 and year-3) have very similar distributions and have a small variation from year to year. Year-1 and year-2 curves of Bundung show very similar distributions, but year-3 curve shows the lowest distribution.

Annual Rainfall Rate Statistic, Singapore, 1992(8472 hour), 1993(8760 hours), 1994(7968 hours)

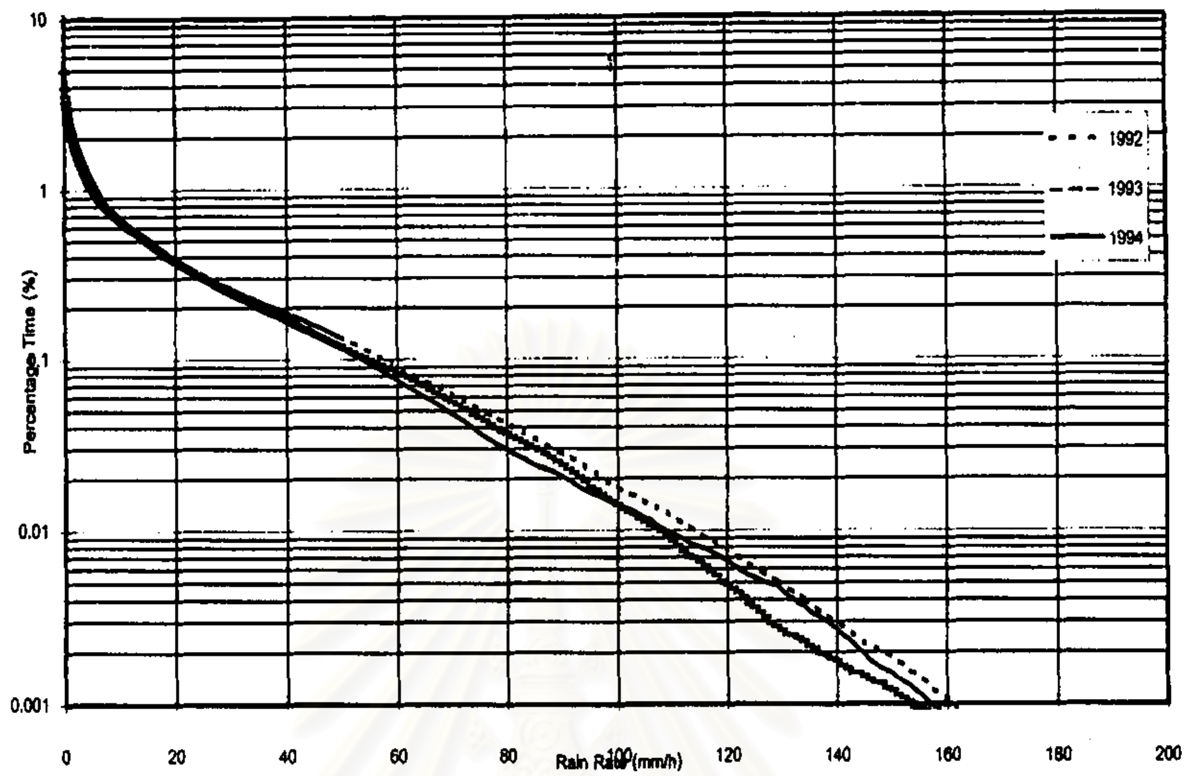

Figure 4.3 Annual cumulative distribution of rainfall distribution in Singapore (ITU-R zone P) over 3 years

Annual Rainfall Rate Statistic, Bundung, 1992(7224 hour), 1993(8688 hours), 1994(8520 hours)

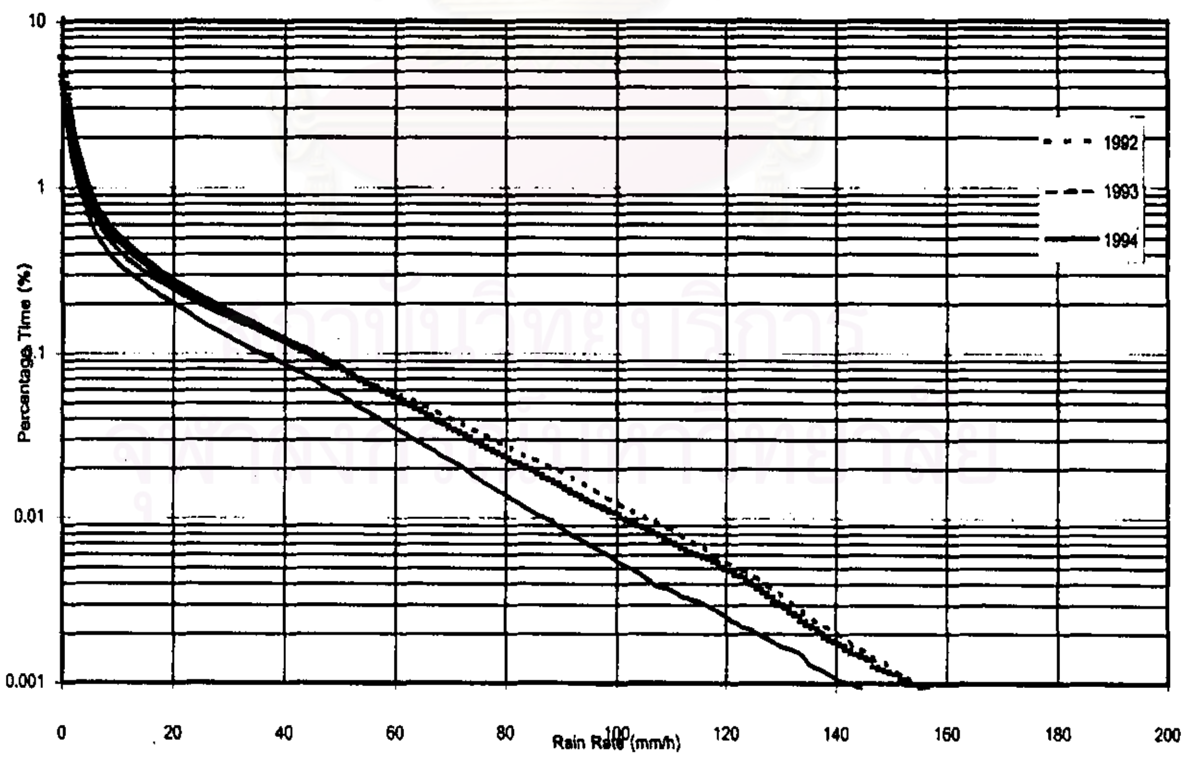

Figure 4.4 Annual cumulative distribution of rainfall distribution in Bundung (ITU-R zone P) over 3 years

2) Monthly Cumulative Distribution of Rain Intensity

A monthly cumulative distribution of rain intensity is also essential for the design of a millimeter wave communication system. Forty - eight pictures (144 curves) of the monthly cumulative distribution of rain intensity over three years in Southeast Asia are illustrated in Appendix B. It is remarkably indicated that there is relatively a larger variation of the monthly distribution from year to year especially in Bangkok and Si-racha. It is estimated that due to the large variation of the frequency of occurrence of the large weather patterns i.e., tropical storms. Singapore and Bundung do not show significantly variation than Bangkok and Si-racha. It may be estimated that rainfall in the ITU-R zone P is mainly due to effects of the local convectivity.

Table B1 - B4 in Appendix B summarized the percent exceedance probability of monthly, yearly, and 3-year cumulative distribution of rain intensity in Bangkok (Table B1), Si-racha (Table B2), Singapore (Table B3), and Bundung (Table B4) respectively. These information are useful for the design of radio communication link above 10 GHz in Southeast Asia. Each row shows the name of each month, each year, and average of 3 years, while each column shows the percent (probability) of rain intensity exceeding the thresholds. Due to a large variation of monthly rain intensity, it may not be appropriate to analyze each monthly cumulative distribution to obtain the statistical distribution unless the long term observation period is performed.

3) Cumulative Distributions of Rain Intensity

Figure 4.5 presents the cumulative distribution of rain intensity at four locations over a three-year period associated with a fitted statistical distribution. The highest rain intensity distribution belongs to Singapore followed by Bundung, Bangkok, and Si-racha respectively. Both curves are corresponding to an amount of rainfall accumulation shown in Table 4.1. It is clearly shown that the exponential distribution, similar to the gamma distribution with the shape factor = 1, is found to be the best fitted to all measured distributions especially over 5 mm/h threshold. The fitted distribution can be expressed by:

$$P(R > \gamma) = (\rho/\mu)\exp(-R/\mu) \qquad (4.4)$$

where

ρ is a constant that scales the curves,

μ is a constant that modifies the shape and the slope of the curve.

The fitted parameters ρ, μ, ρ/μ and correlation coefficient are shown in Table 4.2. The method to obtain the fitted parameters ρ, μ is indicated in Appendix B. The parameters ρ/μ have some correlations with the parameter β the ratio of thunderstorm activity of the Rice and Holmberg model.

Table 4.2 Parameters ρ, μ , ρ/μ and correlation coefficient for the exponential fit

Name	ρ	μ	ρ/μ (β)	Correlation Coefficient
Bangkok	12.17	23.585	0.5 (0.5)	0.9961
Si-racha	10.375	25.77	0.4 (0.5)	0.9976
Singapore	24.30	23.256	1.04 (0.7)	0.9982
Bundung	16.137	25.06	0.643 (0.7)	0.9959

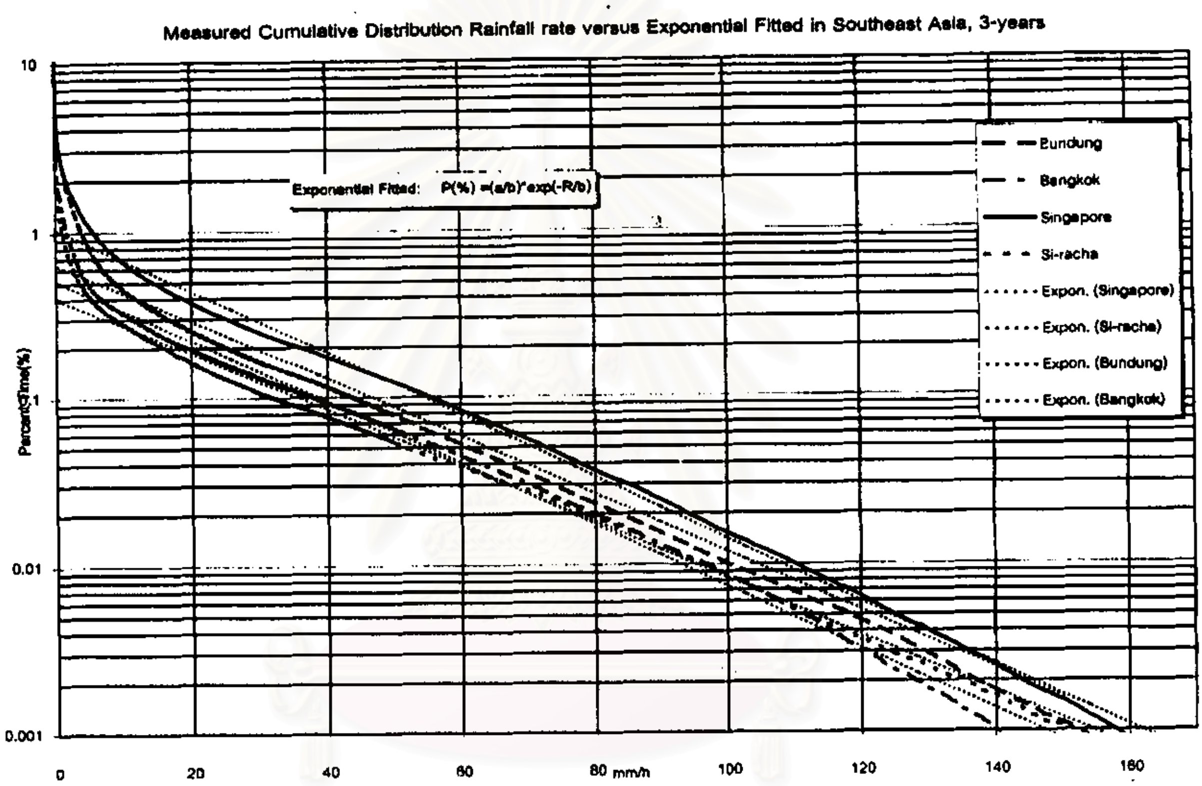

Figure 4.5 Cumulative distribution of rain intensity over 3 years and the exponential distribution.

4.4 Year-to-Year Variability

Figure 4.6 shows the plots of an annual cumulative distribution at four locations. It may be estimated that measured results reflect the local climates: a tropical moderate climate or the ITU-R zone N (Bangkok and Si-racha) and a tropical wet climate or the ITU-R zone P (Singapore and Bundung). The Singapore curves (SP92, SP93, SP94) and Bundung curves (BD92, BD93, BD94) show relatively small year-to-year variation whereas the Bangkok curves (BK92, BK93, BK94) and the Si-racha curves (SR92, SR93, SR94) show relatively large year-to-year variation especially in Year 3 (BK94, SR94). There is about 30 - 40 mm/h difference between the highest curve and the lowest curve.

Table 4.3 indicates values of an annual rain intensity distribution (BK92, BK93, ..., BD94, 3-year) corresponding to 1%, 0.5%, 0.1%, 0.05%,0.01%, 0.005%, 0.001% of the time. In addition, the "MAX Diff." represents the maximum difference between the smallest value and the largest value of each percentage time. The underlines emphasize the maximum values of rain intensity for each year. In Table 4.3, the maximum difference are found in Bangkok (39 mm/h at 0.1%), Si-racha (45 mm/h at 0.01%.), Bundung (19 mm/h at 0.01%), and Singapore (9 mm/h, 0.005%). Singapore has the smallest year-to-year variation (3.8% average) followed by Bundung (10% average), Si-racha (15% average), and Bangkok (19.8%average).

Results imply that rainfall in the tropical wet is mainly due to the local convectivity rather than the large weather patterns, but rainfall in the tropical moderate climate is influenced by both local convectivity and large weather patterns (i.g., monsoon, ITCZ, tropical storms) having large variation on the frequency of occurrence.

Table 4.3 Year-to-year variation of the annual cumulative distribution

Name	1%	0.5%	0.1%	0.05%	.01%	.005 %	.001 %
BK92	1.2	3.1	25.3	45.2	86	102	125
BK93	1.4	4.3	36.5	53	89	106	133
BK94	2.8	8.9	50	70	111	125	153
3-year	1.36	4.7	37.8	56	96	111	140
MAX Diff.	1.6	5.8	24.7	24.8	39	23	20
SR92	1.1	3.7	27.2	45.3	88	104	129
SR93	0.8	3.2	33.6	57	94	109	136
SR94	1.1	4	36.2	54	106	131	174
3-year	1	3.7	32	52	97	114	151
MAX Diff.	0.3	0.8	9	5	18	27	45
SP92	5.6	14.5	58	75	115	131	160
SP93	5.1	14.9	55	73	108	121	153
SP94	6.1	14.3	53	69	110	130	157
3-year	5.6	14.5	55	72	111	127	157
MAX Diff	1	0.6	2	4	3	9	7
BD92	3.4	8.1	45.3	64	107	125	153
BD93	4.3	10	44.7	62	102	122	152
BD94	3	6.5	36	52	88	104	142
3-year	3.9	8.6	43.9	61	101	120	152
MAX Diff.	1.3	3.5	9.3	10	19	16	11

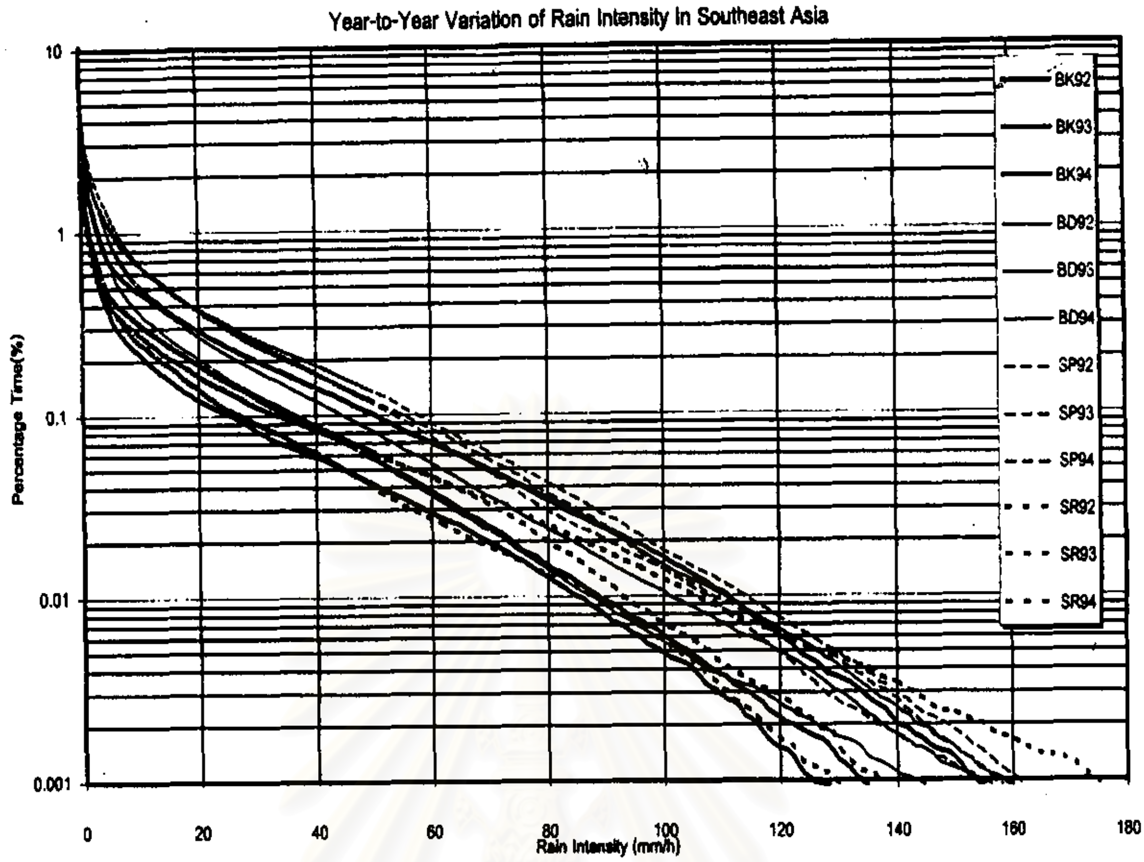

Figure 4.6 Year-to-year variability of measured annual cumulative of rain intensity, 1992-1995

4.5 Diurnal and Seasonal Variation of Rain Intensity

Figure 4.7 shows the diurnal variation pattern of one hour rainfall (the conditional probability of rainfall in each hour) derived by four tipping bucket rain gauges over the three year period. It shows a remarkable difference between a coastal area and a mountainous area. Bangkok, Si-racha, and Singapore are located in the coastal areas whereas Bundung is located in a valley surrounded by mountains at relatively high altitude of 870 meters. In Bundung the convective rain frequently occurs in the afternoon, between 1300LT to 1700LT, but at night almost no rain occurs. It is clearly noticed that rainfall in Bundung is mainly influenced by the local convectivity rather than by the large weather patterns.

Singapore shows a high probability of rainfall in the morning and in the afternoon (0700LT-1500LT). Bangkok has the highest rainfall in the evening (1700-19.00LT) while Si-racha does not show an outstanding rainfall pattern. *Three years of measurement imply that the diurnal variation of rainfall is dependent on the local geographical area. More detailed analysis is described in chapter 8.*

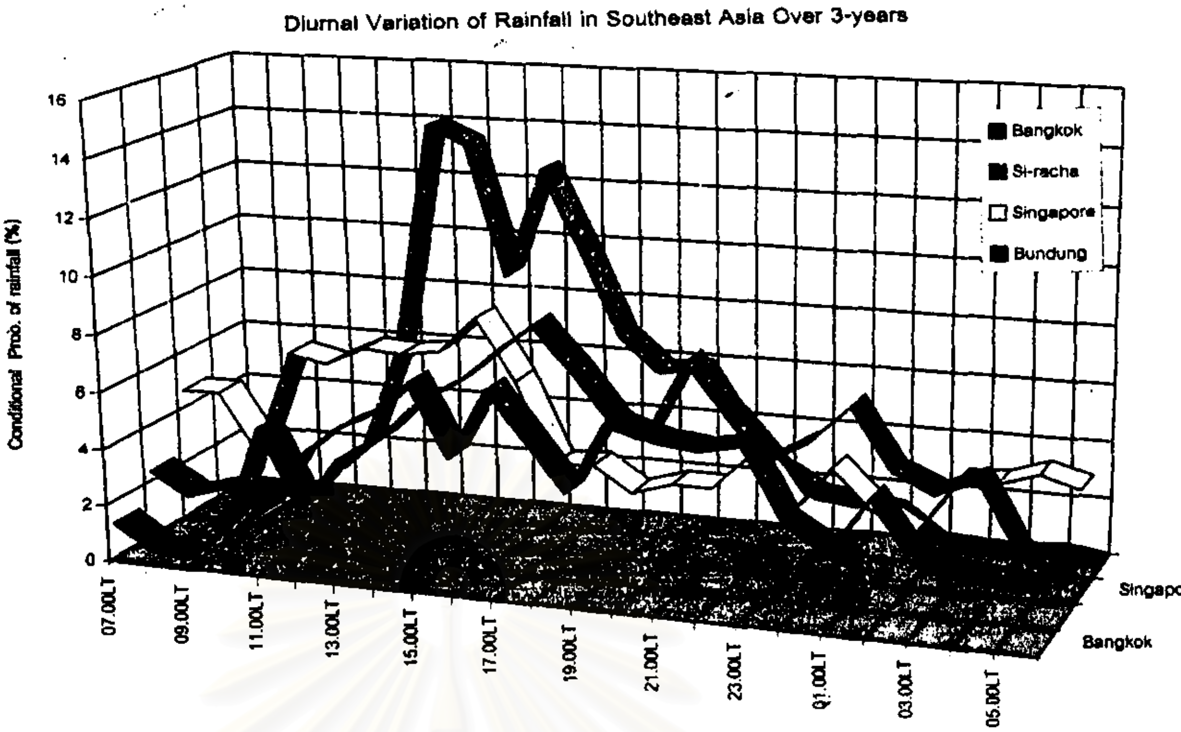

Figure 4.7 Diurnal variation of 1-hour rainfall in Southeast Asia, 1992-1995

An average seasonal variation of rain intensity for Bangkok (ITU-R zone N) and Singapore (ITU-R zone P) are shown in Figure 4.8. Effects of monsoon and ITCZ have major impact on the season variation in Southeast Asia which can be classified into two or three seasons (rainy, dry, and cold). When cold and dry seasons occur in the northern part of the region (Thailand, Laos, Vietnam), at the same time a rainy season occurs in the southern path of the region (Singapore, Indonesia, Malaysia). It is remarkably shown in Figure 4.8 that the average rain intensity distribution in Singapore has no effect on a seasonal variation while the rain intensity distribution of the ITU-R zone N is highly dependent on the season.

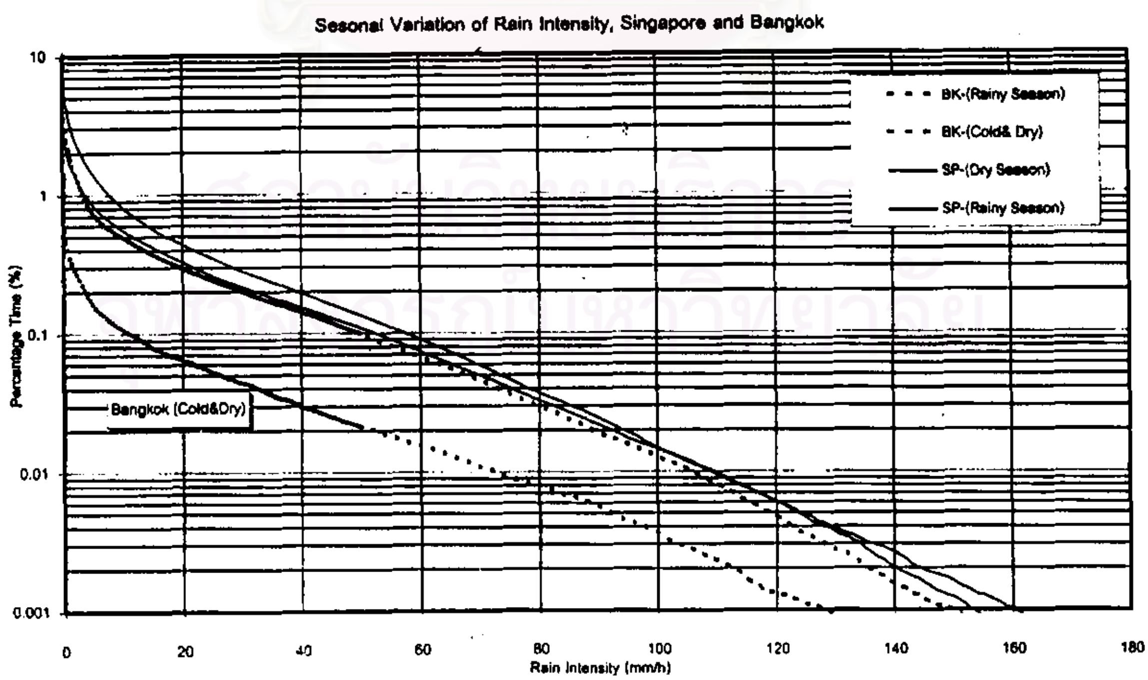

Figure 4.8 Seasonal variation of rain intensity in the ITU-R zone P (Singapore) and the ITU- zone N (Bangkok)

The seasonal cumulative distribution in the ITU-R zone N during the cold and dry season (November-May) has lower rain intensity distribution than during the rainy season (June - October) about 30-40 mm/h.

Results of measurement clearly show that the cumulative distribution of rainfall in the ITU-R zone N (Thailand) is highly reliable on the season. To design the radio communication link in the ITU-R zone N, the link margin in the cold and dry seasons can be decreased unless the link is located in ITU-R zone P.

4.6 Comparison of Measured Rain Intensity with Models

Many rain intensity models e.g. ITU-R [1990], Rice and Holmberg [1973], and Moupfouma and Martin [1995], were derived from the measured data in many parts of the world. From the previous studies, scientists found that at low-moderate rainfall distribution (< 25 mm/h), a log-normal distribution can be represented to the measured distribution while at higher rain intensity, a gamma distribution is well represented. Many rain intensity measurement in the tropics found that the classical Rice and Holmberg model using a double exponential distribution is more suitable than the ITU-R model using a log normal distribution rain intensity. Recently Moupfouma and Martin [1995] proposed an empirical model modified by the combination of the log-normal distribution for medium rain intensity and the gamma distribution for higher rain intensity for world wide usage.

In our analysis, the exponential distribution or a gamma distribution with a scale factor equals to 1 is the best represented to our experimental data and the shape parameter (ρ/μ) has some correlation with the Rice & Holmberg parameter (β) .

In Figure (4.9) - (4.12), the measured data associated with the curves fitted are compared among three models. The measured data of the ITU-R zone - N shown in Figure (4.9) - (4.10) indicate a well fitted with all models at the percentage time higher than 0.01%. However at the percentage time lower than 0.01%, all models tend to overestimate the measured distribution.

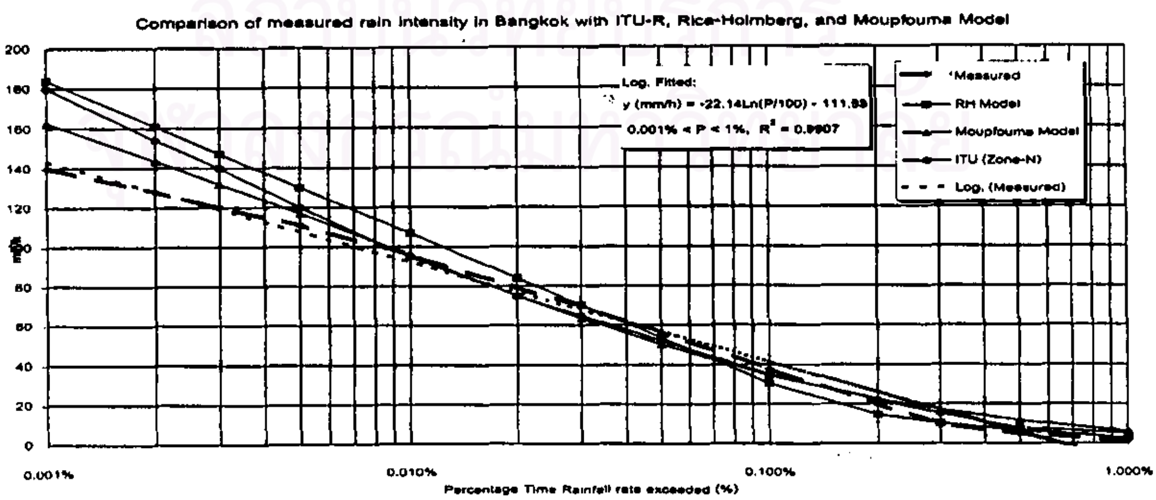

Figure 4.9 Comparison of measured rain intensity distribution in Bangkok with three models.

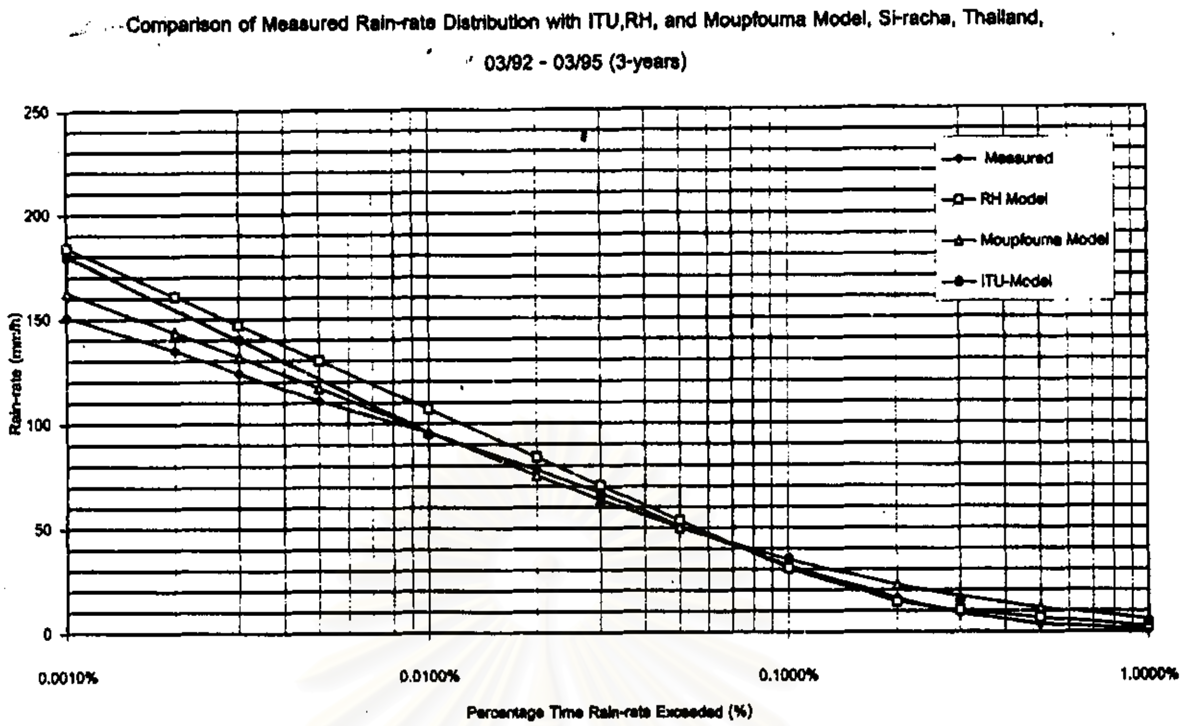

Figure 4.10 Comparison of measured rain intensity distribution in Si-racha with three models.

As shown in Figure (4.11) and (4.12), ITU-R zone P, all models do not show a good fit with the measured distribution. The ITU-R model P is the most overestimated followed by the Rice and Holmberg, the Moupfouma and Martin model. The ITU-R model N is underestimated and overestimates the measured distribution. The Moupfouma and Martin model with λ =1.066, and V =0.214 seem to be the nearest fit. At the percentage time lower than 0.01%, all four models overestimate the measured distribution.

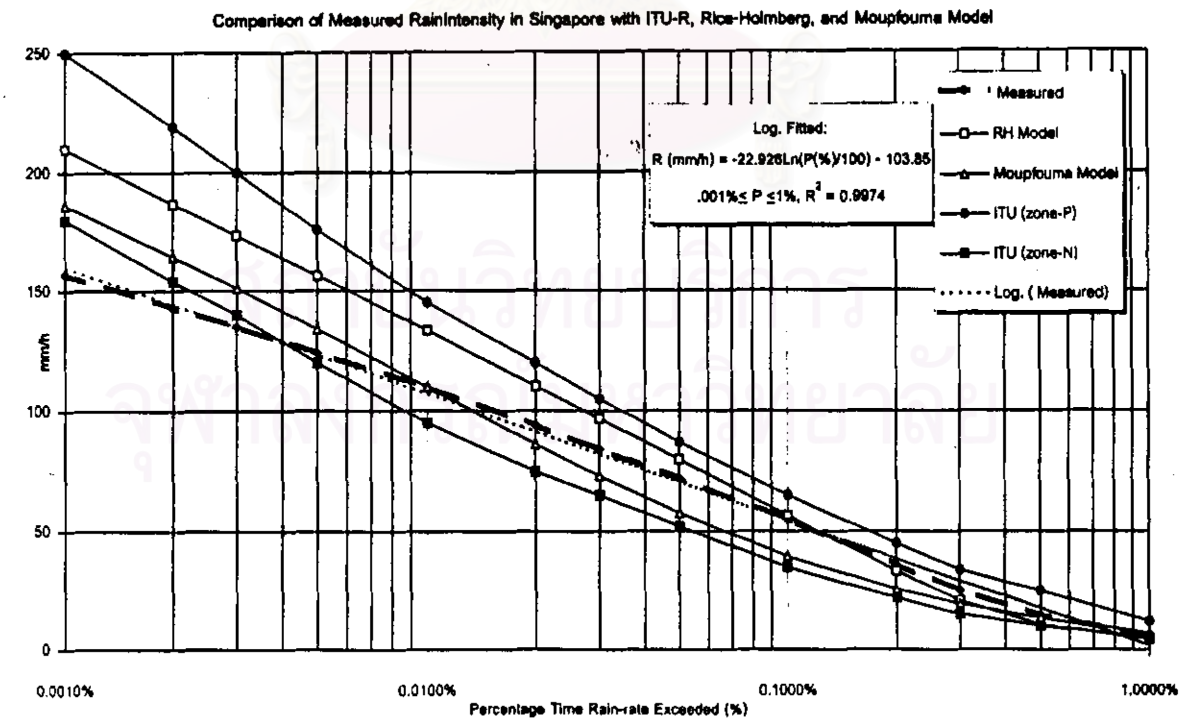

Figure 4.11 Comparison of measured rain intensity distribution in Singapore with three models

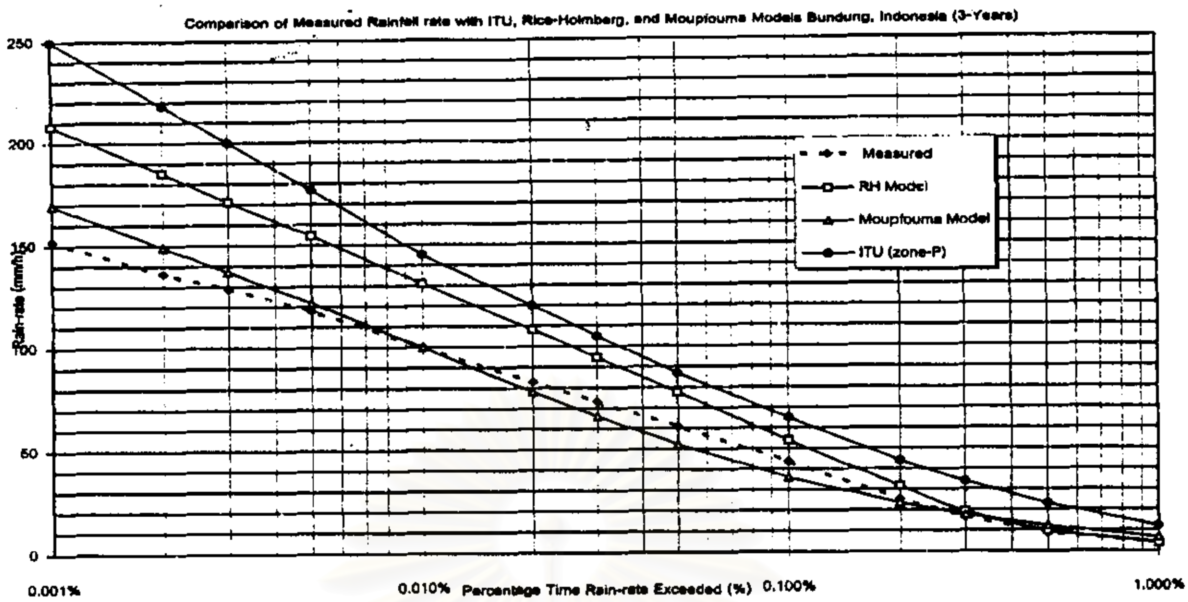

Figure 4.12 Comparison of measured rain intensity distribution in Bundung with three models.

The mathematical fitted curve using the maximum-likelihood estimation (MLE) of Bangkok and Singapore curves are considered to be a natural logarithm having correlation coefficient (R) = 0.9987 and 0.9953, and can be expressed by:

Singapore: $R(mm/h) = -103.85 - 22.926\ln(P/100)$ ------------------(4.5)

Bangkok: $R(mm/h) = -111.53 - 22.14\ln(P/100)$ ------------------(4.6)

where P is the percentage time between 0.001% - 1%.

4.7. Rain Intensity Duration Statistics

The duration of rain intensity is useful information to estimate the outage time due to rainfall and rain attenuation on the radio link above 10 GHz. The rain intensity duration is considered to be the conditional probability of rain intensity (R) that exceeds the threshold (γ) and the duration time (D) exceeds the threshold (Dq). The conditional probability of rain intensity defined by Vogel et al., [1993] , J. Goldhirsh [1995] can be obtained by:

$$P(D > Dq / R > Rq) = \frac{N(D>Dq, R > Rq)}{Nt (R > Rq)}$$ --------------------(4,7)

where

R is the measured rain intensity (mm/h),

Rq is the threshold or the episode threshold,

D is the duration (minutes) of the measured rain intensity, Rq is the specified threshold duration (minutes),

N(D>Dq, R>Rq) is the joint event number of episodes for which D>Dq and R>Rq

Nt(R>Rq) is a total number of episodes for which R > Rq

Figure 4.13 - 4.16 show rain-intensity duration distributions over a 3-year period derived in Bangkok (Figure 4.13), Si-racha (Figure 4.14), Singapore (Figure 4.15), and Bundung (Figure 4.16) respectively. The vertical axis indicates the conditional probability exceeding the threshold while the abscissa shows the duration in minutes. The threshold rain intensity curves of 5 mm/h, 10 mm/h, 20 mm/h, 30 mm/h, 50 mm/h and 100 mm/h are shown in each Figure. It is clearly indicated that the higher the rain intensity, the shorter the duration period.

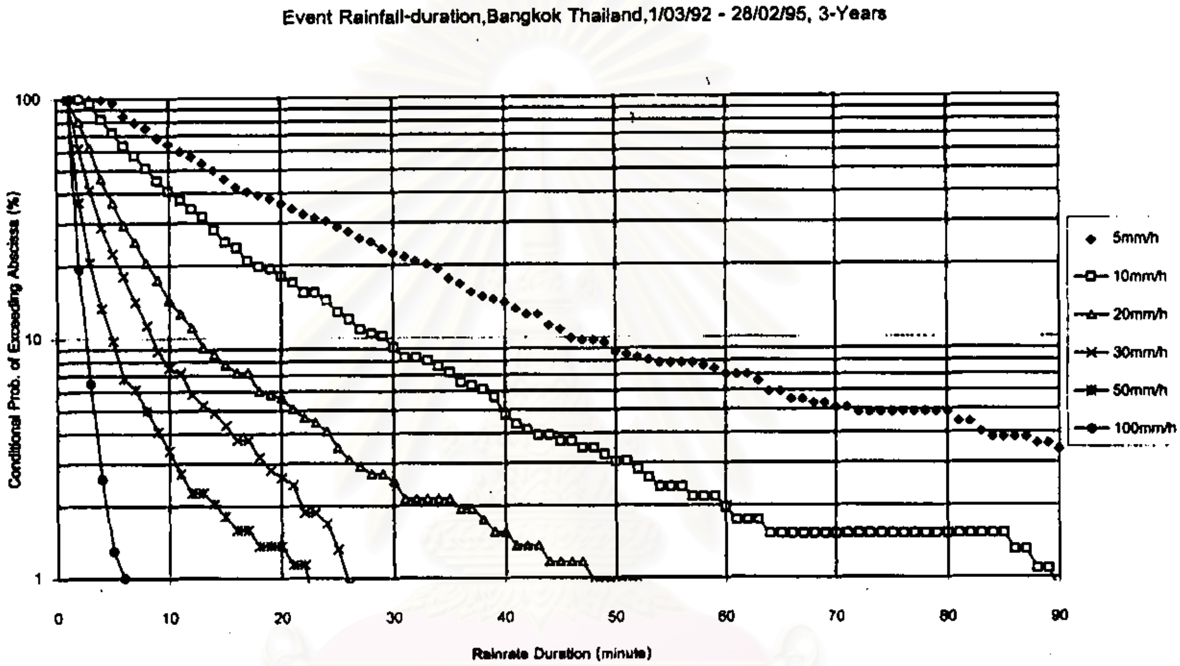

Figure 4.13 Rain intensity duration statistics in Bangkok (ITU-R zone N) over 3-years

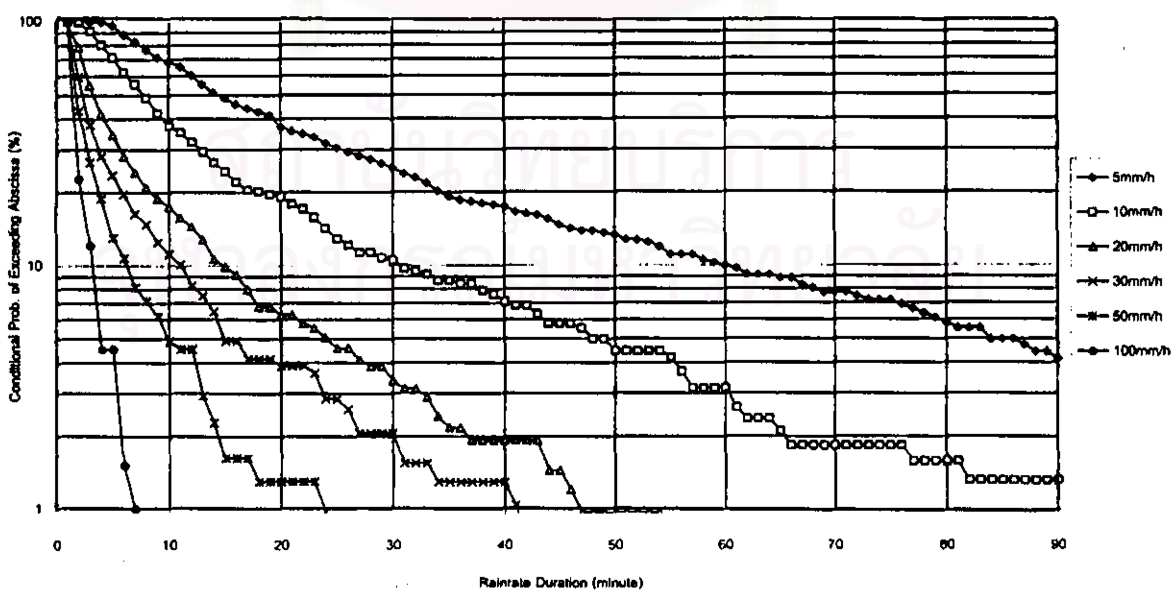

Figure 4.14 Rain intensity duration statistics in Si-racha (ITU-R zone N) over 3-years.

During an observation period, rain intensity exceeding the threshold of 10 mm/h in 1-2 minutes having the most largest event belongs to Singapore (962 events) followed by Bundung (879 events), Bangkok (459 events), and Si-racha (380 events). If 10 mm/h is considered to be rainfall event and episode , it is found that Singapore and Bundung (ITU-R zone P) have more rainfall events than Bangkok and Si-racha which is corresponding to the total rainfall accumulation shown in Table 4.1.

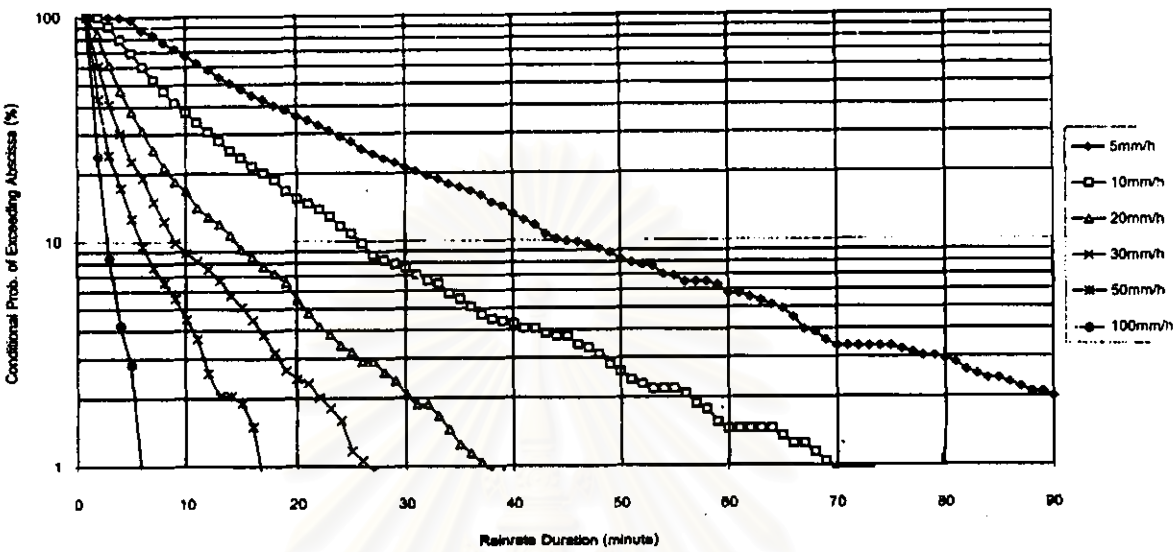

Figure 4.15 Rain-intensity duration statistics in Singapore (ITU-R zone P) over a 3-year period.

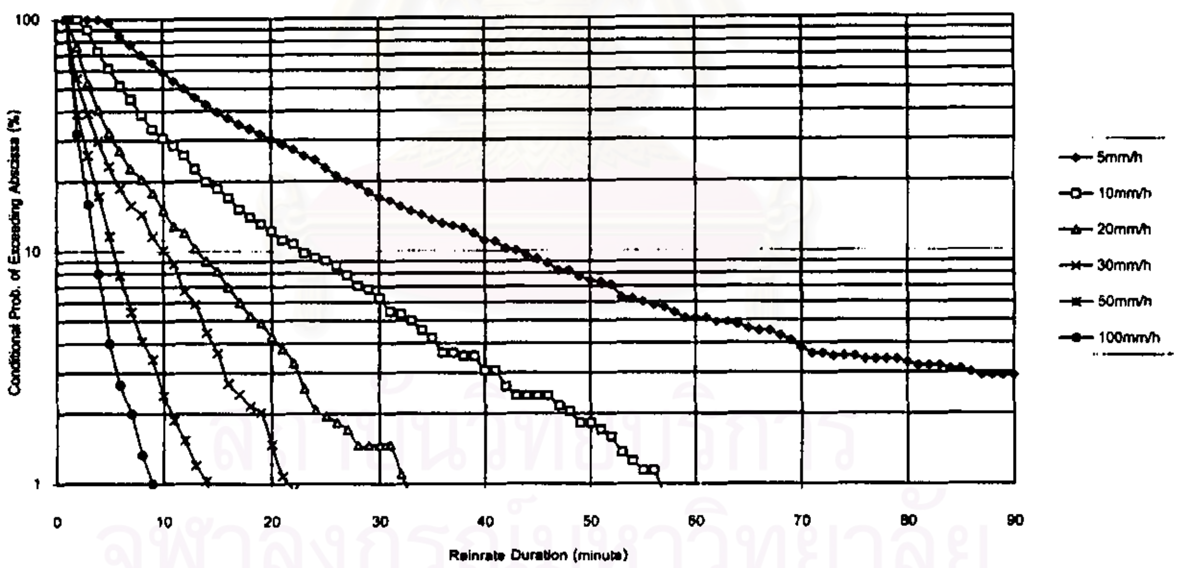

Figure 4.16 Rain-intensity duration statistics in Bundung (ITU-R zone P) over a 3-year period.

In comparison between the ITU-R Zone N and ITU-R zone P in Figures 4.17, it is remarkably indicated that the percent of rainfall durations for ITU-R zone N (Bangkok), given a specific rain intensity of 5, 20, 50 mm/h, are longer than those for the ITUR-zone P (Singapore and Bundung). It implies that rainfall in the tropical moderate climate is due to both a local convectivity and large extent of weather patterns, creating longer rainfall duration than rainfall in the tropical wet climate which is mainly due to local convectivity providing shorter rainfall durations.

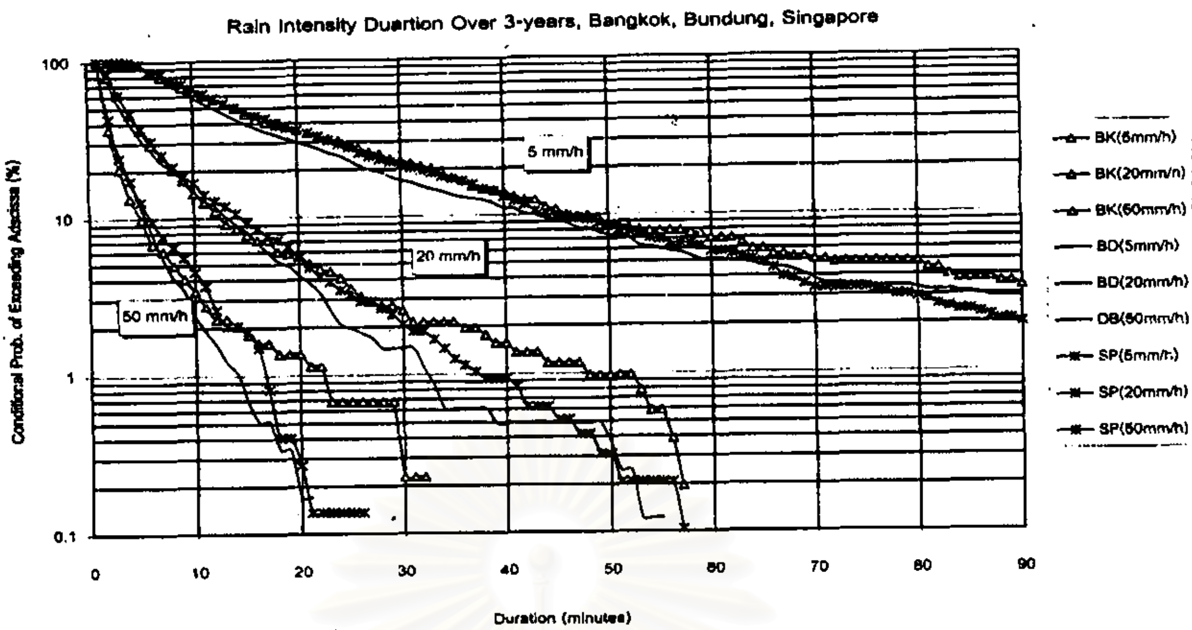

Figure 4.17 Measured rain intensity distribution in the ITU-R zone N, and the ITU-R zone P during 1992-1995.

For the rain intensity duration model, some scientists i.e., J. Goldhirst [1995], Ajayi [1982] discovered that the rain intensity duration in the tropics and in the temperate regions can be modeled by the power-law distribution. E.Vilar, A. Burgueno, and E.B. C. Ofoche [1992] compared rain intensity duration distribution in Barcelona, Spain (a temperate region) and Ile-ife Nigeria (a tropical region) and found that a log-normal distribution was well fitted with both sites.

We have tried to find the most suitable distribution i.e., an exponential distribution, a power-law distribution that will be the best fit to our measured data, but we cannot find any suitable statistical distribution that is the best fit to our three data measurements. Both power law distribution and exponential seem to fit with experimental data.

4.8. Concluding Remarks

This chapter presented various cumulative statistics of rain intensity distribution at four sites in Southeast Asia over a three-year measurement period using a variable integration time rain gauge. We found that the measured distributions of rain intensity of four locations are well fitted with a single negative exponential (Gamma) distribution for rain intensity above 5 mm/h. Year-to-year variation of the measured cumulative distribution shows a large variation in a tropical moderate climate (ITU-R zone-N), but small variation in a tropical wet climate (ITU-R Zone-P). The Diurnal variation of rainfall depends on the geographical location. There is a large seasonal variation in the distribution of rain intensity in the ITU-R zone N, but small seasonal variation in the ITU-R zone P. Moupfouma rain intensity model is found to provide a reasonable fit to the measured data. Finally statistics of rain intensity duration in the tropical moderate climate ITU-R zone N) are longer than those in the tropical wet climate (ITU-R zone-P).