# THE ESTIMATION OF PROBABLE MAXIMUM PRECIPITATION FOR SRI LANKA

By

**W.C.D.K. FERNANDO**

B. Sc. Engineering



Supervised by

Prof. S. S. Wickramasuriya



A dissertation submitted to the Department of Civil Engineering
University of Moratuwa, in partial fulfillment of the requirements
of the Master of Engineering Degree in
Environmental Water Resources Engineering and Management, 2001



Department of Civil Engineering
University of Moratuwa
Sri Lanka

2005

# DECLARATION

The author wishes to declare that the content and the outcome of this thesis are from her original work, except for commonly understood ideas and duely acknowledged references.

She also wishes to declare that the work has not been previously submitted, in part or in whole to any other university or equivalent institution for the award of any degree, diploma or any other qualification.

The work described in the thesis was carried out under the supervision of Prof. S. S. Wickramasuriya.

W. C. D. K. Fernando
May, 2005



**UOM Verified Signature**

Prof. S. S. Wickramasuriya
Supervisor

# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES

# ACKNOWLEDGEMENT


- I express my sincere thanks to the Asian Development Bank for providing funds and the Department of Civil Engineering, University of Moratuwa for providing facilities to complete this research

- It is my noble duty to present heart-felt thanks and deep gratitude to the Supervisor, Prof. S. S. Wickramasuriya, who showed me the correct path and gave his kind help

- I am indebted to the Board of Management of Kotelawala Defence Academy for their kind permission to complete this research successfully

- I would like to thank the Director, Department of Meteorology and the staff of Climatologic Branch who provided the support in copying data.

- Thanks also to my colleagues at KDA for their helpful suggestions with constructive criticisms





- A special thanks goes to all who supported me in editing this report

- I wish to thank my mother who helped me to reduce my working load in tight schedules

- Thanks are also due to my kids – Hansi, Mino and Thili – for their patience by responding quickly when I took their hours

- Finally, I owe a debt of gratitude to my loving husband, Rakitha, who has encouraged me and showed remarkable endurance with the life and living

# ABSTRACT

On 24 and 25th of December 1957 heavy rain fell in the North Central Province; 206.5mm and 219.7mm of rainfall were recorded at Anuradhapura meteorological station and were nearly twice that recorded during the previous high floods. Some of the major tanks such as Kalawewa, Nachchaduwa and Huruluwewa in Anuradhapura breached, resulting in catastrophic damage to infrastructure. The storm of 392.5 mm on 8th June 1996 over Ratnapura resulted in a disastrous flood which caused enormous damage and rendered many people homeless.

The design of a hydraulic structure often requires an estimate of the design flood which has considerable uncertainty about its magnitude. However it should be determined in relation to the project feature for which it is required. When 100% virtual security against failure is required, then the design criteria should be based on the Probable Maximum Flood, which in turn requires the estimation of Probable Maximum Precipitation (PMP).

The research compares the results of 24-hour PMP obtained by two methods. One is based on storm maximization or a hydro-meteorological method and the other uses the statistical method developed by Hershfield. In this study, the last 105 years (1896-2000) of daily rainfall data from the meteorological stations at Anuradhapura and Ratnapura have been analysed.

The 24-hour point PMP for Anuradhapura showed that the results were in the range of 600-625mm based on the statistical method while storm maximization yields a PMP of 425mm with the adjustments of moisture and wind maximization. On the other hand the statistical result for Ratnapura was in the order of 990 to 1120mm and the PMP calculated by storm maximization was 1025mm. If storm maximization was based on true rainfall, PMP values were increased up to 623mm and 1058mm for Anuradhapura and Ratnapura respectively.

Finally suggestions have been made to improve the effectiveness of the different approaches, in estimating PMP.

## CHAPTER ONE

## INTRODUCTION

### 1.1 General

Probable Maximum precipitation (PMP) is defined as "The theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year." (Wiesner, 1970) In other words, this is a finding of the physical upper limit to the precipitation using meteorology over a specified area in a specific duration.

The concept of PMP originated in the mid thirties and until 1950 it was known as Maximum Possible Precipitation (MPP). The terminology was changed from "maximum possible" to "probable maximum" due to the uncertainty, the limitation of data and the limitation of knowledge of the precipitation process. The existence of an upper limit of precipitation both mathematically and physically was concluded by Gilman (1964).



When designing a hydraulic structure such as a spillway, the engineer should analyse the hydrologic, hydraulic and structural aspects of the design. The hydrologic design is most important since the design is based on the design flood, which has considerable uncertainty. Therefore, the engineer faces a problem when selecting suitable design criteria for hydraulic structures. It is recognized that design criteria should also consider the cost factor. For example, in the case of minor structures there is no need to adopt a high design flood; it will result in unnecessarily costly structures. On the other hand, for major hydraulic structures such as spillways on large dams the risk should be very low, otherwise the damages could be catastrophic. Ideally, the designer would like to select the design flood with no-risk and the policy should be based on the Probable Maximum Flood (PMF) having virtually 100% security against failure.

The probable maximum flood is defined as "the flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the region." (Varshney, 1979) The use of PMP to determine the

PMF has become a standard in the U.S.A., Canada, China, India and Australia for design of dams where no risk of overtopping can be accepted. (Svensson and Rakhecha, 1998) In the early 1970s, the design criteria for dam safety were not based on the hydrometeorological techniques such as PMP and hence many dams failed with severe disasters around the world. Some of the notable dam failures are given in Table 1.1.

Table 1.1 - Major dam failures

| Year | Name | Location |
|---|---|---|
| 1924 | Krishnarojasagar dam | South India |
| 1932 | Devils river | Texas U.S.A |
| 1958 | Kariba Dam | Zambezi |
| 1972 | Buffalo Creek Dam | West Virginia |
| 1972 | Canyon Lake Dam | South Dakota |
| 1975 | Banqiao and Shimantan dams | China |

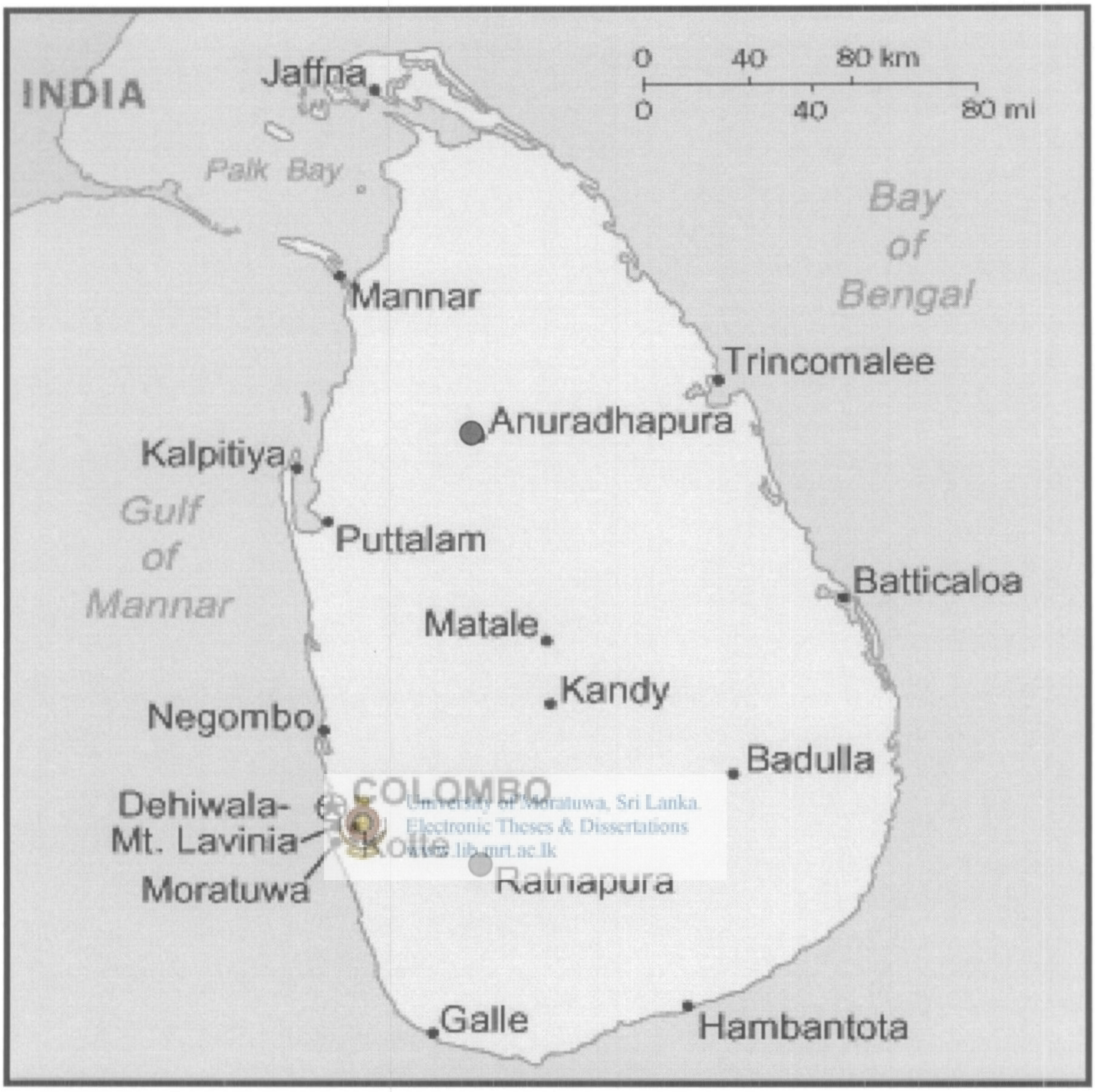
*Source: Varshney,1979; others*



Therefore, it is obvious that the estimation of PMP is useful in an investigation of spillway design floods.

## 1.2 Study Areas

In this study, two case-study areas (Anuradhapura and Ratnapura) were selected to analyse meteorological data covering both wet zone and dry zone in Sri Lanka. (Figure 1.1)





*Source: Department of Meteorology*

Figure 1.1 – Location of Anuradhapura and Ratnapura in Sri Lanka

Anuradhapura district, which has an area of 7034 $km^2$ and which was the first capital city of ancient Sri Lanka is situated at $8^0$ 21' N and $80^0$ 23'E in the North Central province having an average altitude of 90m. Since our traditional culture is agrarian, people and their rulers payed much attention to the conservation of water during north-east monsoon, from November to February for distribution during the rest of the year.

Anuradhapura, which is located in the dry zone of Sri Lanka receives an average annual rainfall of 1250 mm and the average annual temperature is greater than 27.5 $^{0}C$. The variation of average seasonal rainfall in Anuradhapura is presented in Table 1.2.

Table 1.2 - The variation of average seasonal rainfall

| Season | Rainfall (mm) |
|---|---|
| First intermonsoon | < 250 |
| Southwest monsoon | < 250 |
| Second intermonsoon | 250 – 500 |
| Northeast monsoon | 250 - 500 |

*Source : Somasekaram T. et.al.(1997)*

The majority of the major irrigation schemes 73 in number were found in the Anuradhapura district, which served an extent of approximately 32,000 hectares. Besides the above, there were several working village tanks, 6223 in number, which supplied domestic water. (Somasekaram T. et.al. 1997)



History reveals that in 1947/1948, there was a severe drought. But the heavy spell of rain at the end of December 1948 due to a depression ended the drought. At that time, one of the major tanks in Anuradhapura, Sangilikandarawa was about to breach; hence people living near the tank were evacuated to a safer place. (Arumugam, 2003)

After that, a long period of drought started in the dry season of 1955 and continued up to October 1957 having twenty dry months. In October and November 1957, rainfall was above normal and consequently most of the irrigation tanks started filling. (Arumugam, 2003)

On 24$^{th}$ December 1957, a low depression started off the east coast of Sri Lanka and moved westwards and then north. As a result, heavy rainfall occurred over Anuradhapura and some other districts. On 25$^{th}$, some of the major tanks started to spill and some of them breached resulting in a catastrophic damage. Table 1.3 presents the details of some of the major breached tanks due to this catastrophic flood.

Table 1:3 - Details of the breached tanks in Anuradhapura due to 1957 flood.

| Tank | Catchment area (Sq.miles) | FSL (ft) | Flood peak discharge (cusecs) |
|---|---|---|---|
| Kalawewa | 323 | 420 | 262,000 |
| Nachchaduwa | 236 | 333.6 | 120,000 |
| Huruluwewa | 78 | 434 | 56,500 |
| Kattiyawa | 33.5 | 175 | 19,000 |
| Sangilikandarawa | 63.5 | 277 | 91,000 |
| Medawachchiya tank | 16 | 13.5 | 19,000 |

*Source: Arumugam, 2003.*



Thus, the devastating flood of 1957 caused extensive damages to reservoirs, houses, bridges and roads etc. As shown above, major floods would occur due to unexpected meteorological conditions. Therefore, to prevent any recurrence of such damages in future, the estimation of PMP, which is based on the extreme value of precipitation, is useful to calculate PMF.

Ratnapura, which is located in the Wet Zone and situated at 06 $^{0}$ 41'N and 80 $^{0}$ 24'E in the Sabaragamuwa province has an average altitude of 34m. The mean annual precipitation is 3500 mm. Due to the monsoon circulation, almost 70% of the annual precipitation falls between May to September. The variation of mean monthly precipitation is presented in Table 1.4.

Table 1.4 - The variation of mean monthly seasonal precipitation in Ratnapura.

| Season | Rainfall (mm) |
|---|---|
| First intermonsoon | > 140 |
| Southwest monsoon | 386 |
| Second intermonsoon | 416 |
| Northeast monsoon | 164 |

*Source: Malmgren et.al., 2003*

The mean annual temperature varies between 25.0 and 27.5 $^{0}$C in Ratnapura. The highest mean monthly temperature is always greater than 30$^{0}$C and the lowest mean monthly temperature is in between 22 to 25$^{0}$C.

The eastern part of the area is mountainous with peaks reaching almost 1000m. The topography of the Southern part is also mountainous with a highest peak of 1358 m. But there are no major barriers in the rest of the area. Therefore, southwesterly air flows into the basin without any mountain barriers. The only major reservoir – Samanalaweva is situated in southeastern part of the basin.



The occurrence of unusual daily rainfall in Ratnapura had important implications for floods and land slides. Some figures on the highest daily rainfalls, which produced floods, are given below.

1. 21.06.1995
2. 08.06.1996
3. 17.05.2003

Therefore, it is important to analyse the occurrence of these extreme rainfalls in designs. The number of inundations of Ratnapura is higher than that of other areas in Wet Zone and that is one of the reasons to consider the area for the case study. The values of PMP can also be used for comparison with dry zone values.

## 1.3 Objectives of the study

The general objective is,

To estimate 24 hour, point probable maximum precipitation (PMP) in two study areas, which are situated in dry zone and wet zone of Sri Lanka.

The specific objectives of this study are as follows:

a. To determine the highest 24-hour persisting dew point temperatures in dry zone and wet zone.

b. To study whether the moisture maximization factor alone is sufficient to agree with the values of PMP estimated from the statistical method

c. To study how to use the wind maximization factor to maximize a storm in non-orographic regions.

d. To study whether the true to fixed ratio is needed in storm maximization, and, if so, how to determine a value for the above.

e. To determine the frequency factor for the statistical analysis method suited for the dry zone and the wet zone.

f. To compare the values of PMP estimated from the two methods selected which are the storm maximization method and Hershfield's statistical method.

g. To assess the usefulness of the above two methods.

# CHAPTER TWO

## BACKGROUND INFORMATION ON PMP

### 2.1 Introduction

This chapter presents the various methods of estimating PMP with their advantages and disadvantages but excludes the detailed description of the selected methods which are described in chapter 5.0

### 2.2 Methods of Estimating PMP

The following methods are used to estimate PMP (Wiesner, 1970).

1. Storm model approach.
2. Maximization and transposition of actual storms.
3. Use of generalized data or maximized depth, duration, area data from storms.
4. Use of empirical formulae determined from maximum depth, duration, and area data.
5. Use of empirical relationships between the variables in particular valleys.
6. Statistical analysis of extreme rainfalls.



#### 2.2.1 Storm Model Approach

The storm models have been developed on the basis of the following three meteorological components.

a. The convergence of air masses towards the storm area quasi-horizontally
b. The subsequent vertical motion
c. The condensation of the water vapour by adiabatic expansion from gaseous state to liquid/solid state.

Out of these three components, a high degree of precision of the data is given only for the condensation of humid air. There is no theoretical basis to assign values for either convergence or vertical motion. In addition, it is very difficult to find direct measurements for maximum values of the above. Therefore, the observed extreme rainfall values are used as indicators for convergence and vertical motion.

One of the best models used in mountainous areas is the orographic model. It is assumed that the flow of air is laminar and it occurs in a vertical plane at right angles to a mountain ridge. In this model, there are some important simplifying assumptions, such as generalization of mountain slopes, laminar flow, a continuous barrier around which the air cannot flow and uniform air saturation through a particular layer. Therefore, it is desirable to be tested, before application. Due to the above limitations and generalizations, this gives unrealistic values of PMP.

In the case of thunderstorms, another storm model which is known as convective cell model can be used. In addition, when orographic and convective effects occur simultaneously, the two types of models can be superimposed. The principle of continuity can be easily applied for extended time and space; hence, these storm models are more successful in determining PMP, over a large area in long storm durations. The absence of other meteorological data or non-representation of storm data enhances the usage of storm models.

Before using the storm models in design, it must be remembered to calibrate the above carefully with data from observed rainfall in the region of interest.



### 2.2.2 Maximization and Transposition of Actual Storms.

The deficiencies of the storm models due to their oversimplification could be overcome by the storm maximization method. The goal of this method is to increase the available rainfall data to get maximum possible moisture. The first step of this procedure is to find out the greatest observed rainfall data that have occurred over the area. These values are then adjusted by a ratio of the maximum moisture inflow at the site to the actual moisture inflow of the particular storm. This moisture inflow is usually called as precipitable water, which can be estimated from surface dew points.

Other than moisture adjustment, there are various other factors, which are collectively termed as storm efficiency or storm mechanism, including convergence, inflow winds, vertical velocities, condensation of the cloud particles etc. (Miller, 1973) It is difficult to evaluate the above factors and to maximize them, but wind maximization is sometimes used in non-orgraphic regions, when moisture maximization gives inadequate or unrealistic results. (WMO, 1986)

If sufficient major storms have not occurred over the project area, then it is possible to transpose storms from meteorologically homogeneous zones. This is based on the assumption that the selected storm in the meteorologically homogeneous zone exists over the project area, which is equally likely to occur.

In this method, a catalog of extreme storms, which contains storm date, location, and rainfall accumulation is essential. Furthermore, a record of surface dew point temperature over a period of 50 or more years is essential to calculate the maximum moisture content. Therefore, if there is a deficiency of basic data, the PMP results may be unrealistic. The greater the number of extreme storms, the greater is the reliability of the PMP results.

In addition, there is a limitation in transposing the storms. To identify the transposition limits, a meteorological analysis is needed from a long series of daily weather charts. Although this procedure is not applied for determining orographic adjustments, rarely is used in locations where the differences in elevation are greater than 500m. Therefore, this procedure is mostly applicable to non-orograhic areas. Another disadvantage is that storm transposition in time is limited to 15 days, if there is a seasonal variation of PMP.



### 2.2.3 Use of Generalized Data

The generalized chart is an isohyetal map, which shows the developed maximum precipitation values for some specified duration, basin size, and annual or seasonal variation. The basic procedure of developing this chart is the same as for determining PMP for an individual basin i.e moisture maximization, transposition and envelopment of all extreme storms. The rainfall data from each extreme storm should be transposed to a network of points in a grid.

The advantages of using generalized charts are, (WMO, 1969)

- Consistency - When compared with PMP estimates for individual basins within a region.

- Thoroughness - A complete combination of all possible approaches in a basin to estimate PMP.
- Availability - A readily available source of PMP estimates to save time.

The major limitation in these charts is the way of including the topographical effects on these. Therefore, generalized charts are best suited for large basins since there are similar topographic features between basins and charts. On the other hand, topographic features in smaller basins may not be represented in charts and hence yield less reliable results.

2.2.4 Use of Empirical Formulae

After analyzing extreme storms, a set of curves have been published, each representing a rainfall depth plotted on a graph of storm duration in hours versus storm area in square miles for various places. The values of the worlds highest recorded gauge rainfalls lie on or just under a straight line whose equation is

$$P = 422\ (T_d)^{0.475} \quad \text{(Chow, 1988)}$$



where P is the precipitation depth in millimeters and $T_d$ is the duration in hours. This equation can be used as a guideline to estimate PMP. Studies have revealed that in some areas P varies with $\sqrt{T_d}$.

In New Zealand an equation was developed (Riddell, 1980) as $P = 121.1\ (T_d)^{0.553}$ for altitudes below 900m which give higher results than storm maximization. These empirical formulae are applicable for obtaining approximate estimates of PMP. Hence, this method gives unreliable values. Specific formulae can be derived in meteorologically homogeneous zones but there is no point in using formulae if original data is available. When deriving these formulae, it is useful to consider duration and various project areas.

2.2.5 Use of Empirical Relationships

According to Wiesner (1970) this method described a relationship between the rainfall intensity and the other variables such as inflow velocity and the moisture content. For that, the suitable consistent observations are wind velocity, surface dew point and rainfall in a particular valley. After deriving the relationship, the constants in the equation can be found from past severe storms. The maximum rainfall can be computed by estimating the maximum values of dew point and wind velocities. The constants should be changed according to the situation, and the concurrent occurrence of the maximum dew point and wind in the valley.

This method is easy to apply in mountainous areas where there is limited data and manpower when compared with some storm model studies. In spite, similar relationships can also be derived using local data.

There are limitations in this method also. For instance, in the concurrent occurrence of the maximum dew point and wind velocity which is not the usual case, again the relationship may be adjusted to determine the constants. Otherwise, this may provide unrealistic results.

### 2.2.6 Statistical Analysis of Extreme Rainfalls



The method developed by Hershfield (1961, 1965) is widely used for statistical analysis. The basis of this method is the statistical variable method as in the analysis of extreme value distributions. At a particular station, the past severe rainfall is selected from a sample of the annual maximum rainfall for a particular duration usually taken as 24 hours. It must be remembered that the sample size should be large enough because each value in the series represents again a maximum of a large number of observations.

When calculating the mean and the standard deviation, the introduction of outliers should be recognized because it affects the skewness of the graph. Hence, to overcome this deficiency, adjustments to the mean and standard deviation for outliers and sample size should be applied. The mean and the standard deviation, excluding the maximum observed event to including the same is computed and adjustment is applied.

After comparing various sample sizes, Herhfield suggested a 50 year record is suitable as a standard to adjust other shorter records while 60 and 70 year records showed only a small difference.

Most of the rainfall gauges are not automatic gauges. Hence, observations are taken at a set time, for example from 0830 hrs. to 1730 hrs. Sometimes large rainfalls lie between set values and therefore the observations do not express the actual consecutive 1440 minute reading.

But it is necessary to compute the value of a 1440- minute continuous period. Weiss (1964) suggested a probability model, which gives conversion factors to estimate the maximum true values from observational values.

Hershfield's method is primarily based on point rainfall values. When designing hydraulic structures, the aerial distribution is necessary. Therefore, point rainfall values can be adjusted by using depth- area relationships. Advantages of this method are that it is easy to use and can be applied in locations where other meteorological data are not available.

## 2.3 Summary



The following facts are considered in the selection of suitable methods to estimate 24-hour point PMP.

- Storm models are applicable over large areas in long storm durations and therefore are not considered in this research.
- The use of generalized charts is best suitable for large basins and it is also difficult to develop a chart within the limited time frame in this research.
- To develop an empirical formula, it is necessary to analyse a large number of extreme storms, which also give a rough estimate and hence, produce unreliable answers. Therefore, that method is also not selected.
- According to the researcher's knowledge, not a single empirical relationship for PMP has been derived in Sri Lanka.
- Assuming that all meteorological data are available, the storm maximization is selected having considered the seasonal variation of rainfall and non-orographic areas.

- To compare the values estimated from the above method, the Hershfield method is selected. The ease of calculation with limited data is also taken into account.

Having compared the above facts the methods of maximization of actual storms and the statistical analysis of extreme rainfalls are selected to estimate 24 hour point PMP at Anuradhapura and Ratnapura in this research.

# CHAPTER THREE

# LITERATURE SURVEY

## 3.1 Survey of Recently Published Work on PMP

Most research studies on PMP calculation have been done by using one or two methods. The research studies that are used by using storm maximization – (in-situ) and the statistical method – Hershfield are summarized below.

The only local publication on PMP (Piper, 1994) uses the storm maximization to derive PMP in order to design the spillway for Victoria Dam. It reports that the most reliable approach was the storm maximization due to the availability of a dense network of rainfall data. Because of very few wind run data, the approach to maximize the storm was limited to moisture content only. The publication shows that the moisture adjustment factor is 1.25 for Victoria project. Further, it has been reported that the value of the PMP estimated from the storm of August 1947 lies between two bounds; the upper bound estimate calculated using a statistical method and the lower bound from the previous statistical analysis of the rainfall data with the storms of 1000 year return period. It has been argued here that the maximum rainfall in any year could occur in any month of the wet season, which follows that the PMP during the dry season would be lower than during the rest of the year. Thus, it has been revealed that there is a seasonal distribution of PMP.



Riddell (1980) presented the estimation of PMP by using both the storm maximization and the statistical analysis. To calculate maximum persisting dew point temperatures, data were selected from maximum dew point temperatures for each month of the year and from mean monthly sea surface temperatures. It was shown that the Moisture Adjustment Factor (MAF) was 1.42 after the transposition of the storm. However, wind maximization was not taken for the estimation. In the statistical estimate, PMP was based on the general frequency equation and it was suggested that the upper limit of PMP is given by substituting 15 for frequency factor. Further, it was shown that the statistical method gives considerably higher results (nearly 60%) than that obtained by storm maximization. K depends on the rainfall duration and the mean of the annual series, but there may be other relationships. Hence, it has stated that the value of K is doubtful.

Svensson and Rakhecha (1998) have used the hydrometeorological method involving depth-area-duration analysis, moisture maximization, and altitude adjustment to estimate PMP in China. It was shown that the selected maximum 24 hour persisting dew point temperature occurred during the time of the year that the selected storm occurred. In this study, two different methods were used to estimate the maximum 24-hour persisting dew point. One was by examining the weather charts and the other was by referring to sea surface temperatures. (SST) It was argued that the inland dew points might not represent the atmospheric moisture due to the effect of local conditions. The resulting moisture maximization factor was 1.19. The altitude adjustment factor was used due to the rugged topography in the study area. It was reported that the difficulties in estimating adjustment factors and the effect of storm transposition were the sources for uncertainties in PMP estimation. However, the results from this study agreed well with past results and hence in support of the moisture maximization factor.



Solak et.al. (2000) has reported that the South Platte Reservoir is a class I hazard structure because if the dam breaks, there would be loss of human life. Therefore, PMP would be appropriate for the spillway design. The methodology used in this study was storm maximization. In the study, it was shown that there were two storms considered, namely general and local storm. General storms were transposed to the project area and maximized under the worst scenario. The local storm PMP was found by using the largest non-orographic local storm because the project area is in the non-orographic location. The maximization factor was 1.5. The PMP obtained from general storm was 28% higher than that of the local storm at 1- hour duration. It was reported that the results will vary among individual basins, depending on basin size and elevation plus their locations relative to orographic barriers and the transposition limits of the largest storms, which comprise the historical extreme storm record.

Tingsanchali and Taesombut (2001) have done a study to determine the PMP and hence PMF for Pantabangan dam in Philippines, which had already been constructed in 1974. It was reported that the normal procedure for estimating the design storm in Southeast Asia is to maximize depth-area-duration data obtained by typhoon rainfalls. For Pantabangan dam, a hurricane model was used arguing that the above procedure could not be used for the following reasons.

- Lack of data in the area
- Difficulty in transposing storms either from a coastal area or a mountainous area

In this model, the typhoon rainfall is divided into convergent and orographic components. The convergence adjustment factors, which were South–West monsoon barrier and point rainfall reduction, and the orographic adjustment factors which were ground slope differential, wind velocity and point rainfall reduction were applied. When applying barrier adjustment factor it was assumed that the persisting 12-hour dew point temperature was 27.4°C. When calculating precipitable water, it is assumed that the top of the column of saturated air is at an elevation of 15000 m or 200 mb.

Rezacova D. et.al. (1999) have estimated PMP for Czech catchment basins. Statistical method by Hershfield was applied for 834 stations with records longer than 10 years. PMP results were presented in a different manner known as maximum frequency of point PMP (24h). It was shown that maximum frequency (about 33%) of point PMP result was at about 300 mm/24h with a large variability of 200mm to 550mm. Similarly, the maximum frequency (about 80%) of maximum precipitation of annual series (24h) was about 100 mm.



Further, it was argued, the correlation between the point PMP and the altitude is not significant but the correlation between the mean annual precipitation and the point PMP was good.

Jowett (1979) has analyzed the Clutha flood of October 1978. Storm maximization method was used to estimate PMP (48hr) and the only considered adjustment factor was moisture maximization. This PMP value was compared with the earlier calculated value. It was shown that the values were equal but the intensities had changed. Therefore, it was argued that the PMP might underestimate the maximum intensities.

Benson (1973) has shown the contrary of the concept of the PMP. He traced the evolution of the concept from "maximum possible" to "probable maximum" and concluded with the thought that it was neither "maximum" nor "probable". Further, it was considered that upper limits exist for all the elements in the meteorological processes and these limits may be derived by this procedure. But the natural meteorological processes are not physically limited by barriers; however the recorded meteorological events are short. Benson also pointed out that maximum probable precipitation values were exceeded soon after (or before) publication whereas in some instances, values have been considered by competent scientists to be absurdly high.

Benson also stated that the derived values were very large hence PMP implies complete protection by approaching a zero probability. He also agreed to assign a return period of 10,000 years as the committee (The Hydrometeorology Committee of the Hydraulics Division, ASCE) suggested for the purpose of making an economic assessment of risk in terms of spillway adequacy.

In addition to the ideas of anti PMP, he advocated a multi-station flood frequency approach to solve the problems related to the outliers. A technique of double ranking of multiple sets of data can be used to avoid exceptionally large events.

Koutsoyiannis (1999) proposed a simple alternative formulation of Hershfields's statistical method for estimating PMP. The publication accepted that the Hershfield's method is a very useful and reliable tool for hydrologic design, but anyhow it says the result may not yield PMP. It has been shown that Hershfield's data did not provide any evidence that there exists an upper bound of precipitation amount.

Further, it has been shown that Hershfield's estimate of PMP may be obtained by using the Generalized Extreme Value (GEV) distribution with shape parameter of 0.13 and corresponds to a return period of 60,000 years. According to the literature, the return period of 60,000 years is small for no-risk PMP. The proposed alternative formulation of the method was verified with 136-year annual maximum daily rainfall in Greece and fitted well with GEV distribution with three parameter sets.

In cases where rain durations are less than 24-hours, Hershfield's nomograph provides additional curves to estimate K. But in this study, it has been assumed that the rainfall depth is proportional to the square root of duration. Further more, the curves for lower durations can be directly derived from local intensity-duration-frequency curves.

The suitability of applying the statistical method for estimating PMP is strongly recommended in the publication of Fernando, 2004. (Annex 4)

### 3.2 Summary



The main findings of this literature survey are summarized below.

a. As PMP cannot theoretically be exceeded, its return period is infinite. In Hershfields statistical method, the return period and also the frequency distribution were avoided. Therefore, the upper bound estimate of PMP can be taken as the value calculated using the above statistical method.

b. A lower bound of PMP can be estimated by doing a statistical analysis of the rainfall data with the storms of 1000 year return period. Hence, PMP estimated from storm maximization lies between these two bounds.

c. Depending on the location of the catchment, the PMP would be higher during the dry season or the wet season. Therefore, there is a seasonal variation of PMP.

d. When calculating the maximum 24–hour persisting dew point temperature, the sea surface temperature (SST) should also be considered because it would be more representative of the atmospheric moisture than the inland dew points.



e. The relationship between the highest likely SST and the observed average SST during the month considered should exist between the highest persisting dew point and observed dew point temperature.

f. It can be conservatively estimated that the surface dew point temperature is about one degree less than the monthly mean SST.

g. If the catchment is in the non-orographic location, PMP can be estimated by considering general and local storms. General storms represent the transposition and the maximization of historical extreme storms under the worst scenario.

h. The depth of precipitable water is measured from 1000 mb surface to various altitudes or pressure levels. The selected top of the column of saturated air is at an elevation of 15,000 m or 200mb.

i. When calculating PMP for large number of stations, it is suitable to calculate the maximum frequency of point PMP and the maximum precipitation of annual series.

j. In some instances, PMP values calculated from two different storms may be equal but the intensities may differ. Therefore, the temporal patterns of the storms should also be considered.

k. Though the return period was not mentioned in Hershfield's paper, Koutsoyiannis found the return period was 60,000 years and the distribution was Generalized Extreme Value (GEV).

l. When compared with Benson's paper, there was a controversy about the return periods (10,000 and 60,000 years) for a design of virtually free from risk.

m. To solve the problems related to the outliers, the multi-station flood frequency approach can be introduced.

# CHAPTER FOUR

## CLIMATE OF SRI LANKA

### 4.1 Introduction

This chapter describes the relevant meteorological factors helpful to explain the climate of Sri Lanka. The climate of Sri Lanka is mainly dependent on the Asian monsoon system, and therefore, the details of classification and its effects are also described in this chapter. The storm maximization method mainly depends on rainfall, wind system and the dew-point temperature; hence, more attention is paid to those meteorological factors.

### 4.2 The Asian Monsoon

The term monsoon, which is derived from the Arabic word *mansim,* explains a season and this is applied to winds whose direction is reversed from one season to another. This wind reversal occurs throughout southern and eastern Asia on a large scale due to the size of the Asian continent, which is the largest continent, and due to the surrounding oceans. The high and elongated mountain, which is in the east-west direction of the continent, is another factor for wind reversal because it forms a barrier to the wind system.



The general tendency of the tropical air mass at the equator is to move upward due to the high temperature there. When this air mass reaches higher altitudes and transports itself to higher latitudes it creates a high pressure zone. To complete the cycle, a massive surface air mass, which is known as Trade Winds, flows towards the low-pressure equatorial region, which is called Inter Tropical Convergence Zone. (ITCZ)

As a result of the above, the tropical continents at latitudes of about 15 to 30 degrees receive a large amount of heat such that the temperature reaches a high level in those regions resulting in a new area of ITCZ being established. (Fernando, 2002) Nevertheless, when considering the seasonal changes over the ocean, there is only a small variation compared to those over the continents.

The ITCZ is located at about $10^0$ south in the northern winter due to the presence of low temperature and this results in a high pressure in the northern part of the Asian continent. Therefore, during this period, Northeast monsoon prevails over Sri Lanka.

In the northern summer, the ITCZ moves to about $25^0$ North due to the presence of high temperature causing low pressure. Hence, trade winds flow southeasterly in the direction of the Southern hemisphere and after crossing the equator they change their direction towards the southwest. During the period from May to September, Sri Lanka experiences this wind, which is known as the Southwest monsoon.

It is customary to divide the rainfall year in Sri Lanka (March – February) into four main seasons based on the relative dominance of the causative factors: (Sirinanda, 1983)

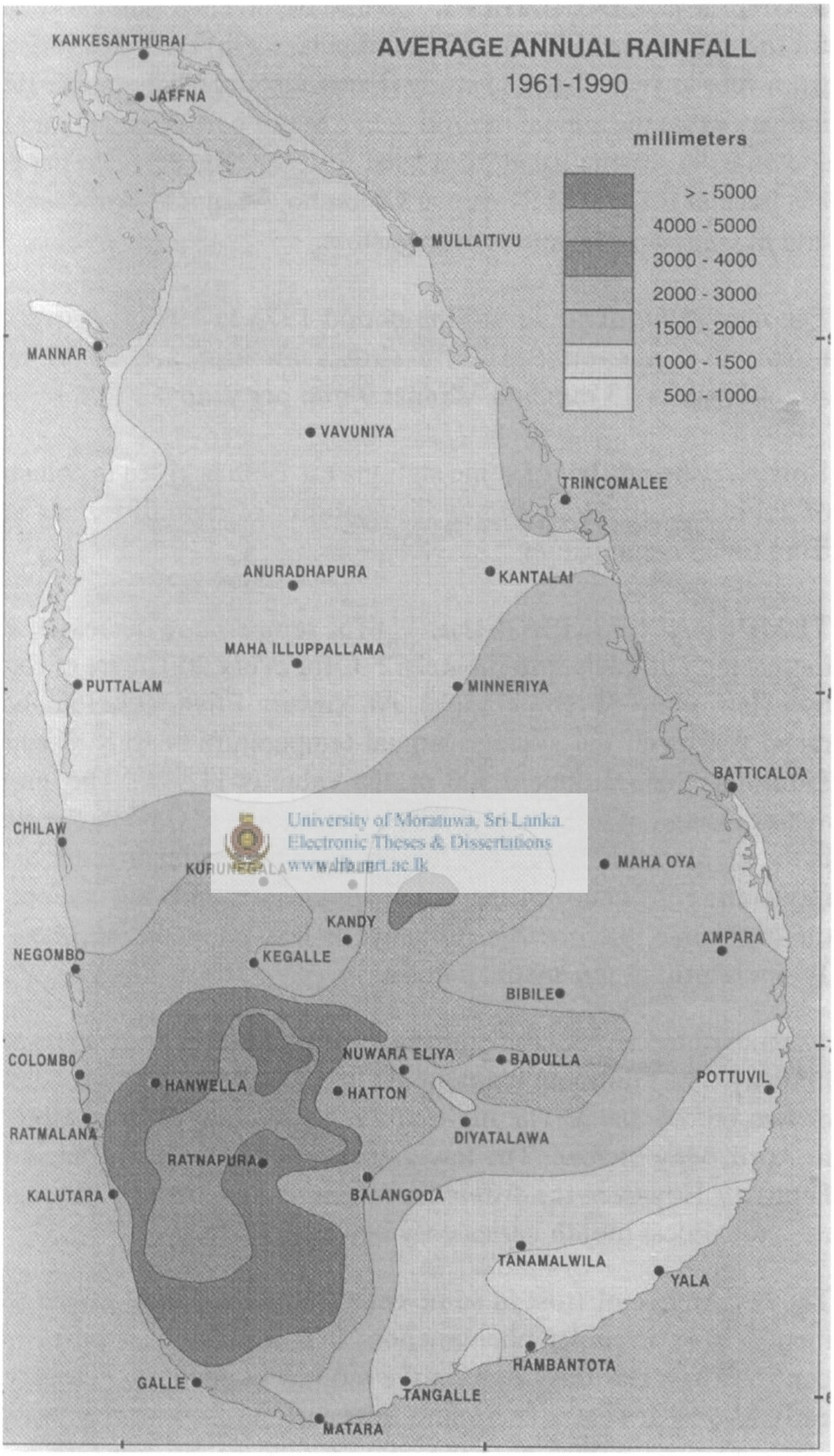
- **December to February** : Northeast monsoonal – depressional, which brings a significant amount of rainfall to the northern and eastern parts of the country.
- **March to April** : The first inter monsoon (vernal inter monsoonal ) - convectional, which gives a constant daily weather that induces convectional activity under the influence of ITCZ between $5^0$ north and $5^0$ south.
- **May to September** : The southwest monsoon, which brings the largest amount of rainfall to southeastern part of the country and central highland.
- **October to November** : The second inter monsoon (autumnal intermonsoonal) – Convectional-Cyclonic-Depressional, which produces rainfall from the cyclones other than the convectional weather.



### 4.3 Rainfall

The average annual rainfall of Sri Lanka is about 2000mm. It has a spatial variation from below 1000mm in some parts of the northern, northeastern, and southeastern areas to over 5500mm in a few places of southwestern slopes of the central hill country and Knuckles Range in the northeastern sector of the hill country. (Figure 4.1)

There are various factors that affect the distribution of rainfall such as the monsoon system, ITCZ, convection, orography, and cyclonic wind circulations. (Somasekaram, 1997) From all these factors, the Asian monsoon system characterizes the rainfall greatly.





*Source: Somasekaram, 1997*

Figure 4.1 – Average Annual Rainfall (1961-1990)

The total average rainfall in each season and the regional contribution to the total value is tabulated in Table 4.1

Table 4.1 – Average Seasonal Rainfall (1961-1990) mm

| Season | Total average value (mm) | The highest contribution to the annual total | | The lowest contribution of the annual total | |
|---|---|---|---|---|---|
| | | % | Area | % | Area |
| Northeast | <1300 | 50 | Eastern | 7 | Watawala and Ginigathena |
| First Intermonsoon | <850 | 29 | S-E lowland | 5 | North |
| Southwest | <3500 | 65 | Central highland | 10 | Northwest & Southeastern lowlands |
| Second Intermonsoon | <1500 | 30 | North & Northwestern | 19 | Watawala & Ginigathena |

*Source: Somasekaram, 1997*



The relative concentration of rainfall in each of the seasons at selected stations is set out in Table 4.2.

Table 4.2 – Mean seasonal distribution of rainfall at selected stations (in percentages)

| Station | First inter monsoon | Southwest | Second inter monsoon | Northeast |
|---|---|---|---|---|
| Anuradhapura | 19.74 | 18.05 | 33.25 | 28.98 |
| Ratnapura | 15.03 | 49.03 | 21.92 | 14.03 |

*Source: Sirinanda, 1983*

According to the rainfall rhythm, Sri Lanka can be divided into two climatic regions- the wet and dry zones. The wet zone receives the mean annual rainfall of about 2500mm throughout the year. In the dry zone, the mean annual rainfall is about 1450mm and it occurs during the northeast monsoon.

When analyzing rainfall data, in Sri Lanka one can observe instances of extremely high values of rainfall in comparison to the values in the rest of the data set. The extreme rainfalls that occurred within 24 hours in different meteorological stations are compiled in Table 4.3.

Table 4.3 – Maximum daily point rainfall recorded at selected meteorological stations

| Station | Rainfall (mm) | Date |
|---|---|---|
| Vavuniya | 805.6 | 16.12.1877 |
| Mullativu | 792.0 | 19.12.1911 |
| Balangoda | 755.9 | 17.05.1940 |
| Watawala | 524.5 | 05.10.1913 |
| Jaffna | 520.2 | 17.11.1918 |
| Amparai | 487.7 | 07.12.1881 |
| Kandy | 441.4 | 14.08.1947 |
| Ambanpitiya | 422.9 | 07.081886 |
| Ratnapura | 394.5 | 15.07.1942 |
| Batticaloa | 330.7 | 05.12.1967 |
| Trincomalee | 322.8 | 17.12.1949 |
| Anuradhapura | 319.5 | 31.12.1948 |
| Puttalam | 306.3 | 08.05.1883 |
| Colombo | 493.7 | 05.06.1992 |
| Hambantota | 296.9 | 06.05.1975 |
| Kalutara | 511.8 | 09.08.1939 |

*Source: Department of Meteorology*



This table gives a useful indication of the magnitude of extreme storms likely to occur over a catchment. The occurrence of this type of extreme rainfalls may result in floods, land slides and dam failures. Therefore, it is necessary to be aware of these high values in estimating PMP and hence PMF in hydrologic design.

## 4.4 Wind

Wind has both speed and direction. Wind speed is measured by using an anemometer where it is installed about 10m high in an environment free from trees, buildings and other obstacles. But no standard anemometer level has been adopted. The wind direction is measured by a separate wind wane. The wind direction is the direction from which it is blowing and it can be identified from the arrow of the wane. Direction is usually expressed in terms of 16 compass points (N, NNE, NE, ENE etc.) but usually it is summarized in terms of eight points only.

Wind climate is also characterized by the monsoon system. Southwest monsoon is the strongest out of the two monsoon wind systems. SW winds strongly occur on the coastal areas in the southeast, northwest, north and the northeast as well as the central and Sabaragamuwa mountain ranges with varying intensity. In summer monsoon, direction is mainly southwesterly and a reasonably high amount is from easterly direction. (Fernando, 2002)



Northeast winds occur in the coastal areas but not in the mountain regions due to the lack of strength. Wind direction is mainly north-northeasterly. Generally, the northeasterly winds are weaker than the southwesterly winds on the island. (Yoshino, 1983) In addition to monsoon winds, cyclonic storms and depressions could occur. The cyclonic storm season is from November to December. Depressions frequently occur in late May and early June and again in late September and October. During March to April, the wind direction is a variable. Local winds also occur during day and night.

Table 4.4 shows the yearly means of daily wind mileage from 1931-1960 averages at selected meteorological stations.

Table 4.4 – Yearly means of daily wind mileage

| Station | Wind Mileage | Station | Wind Mileage |
|---|---|---|---|
| Colombo | 131 | Hambantota | 298 |
| Puttalam | 180 | Trincomalee | 239 |
| Jaffna | 236 | Galle | 206 |
| Anuradhapura | 146 | Mannar | 210 |

*Source: Department of Meteorology , Report for 1974*

Table 4.5 shows the percentage of wind directions in 1974 in Anuradhapura at 0830 hours.

Table 4.5 – The percentage of wind directions in 1974 in Anuradhapura at 0830 hours

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N | 11 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 3 |
| NE | 65 | 71 | 26 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 13 | 84 |
| E | 11 | 18 | 56 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 |
| SE | 0 | 0 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 |
| S | 0 | 0 | 3 | 23 | 10 | 2 | 0 | 2 | 0 | 0 | 3 | 0 |
| SW | 0 | 0 | 0 | 37 | 79 | 85 | 100 | 92 | 95 | 81 | 13 | 0 |
| W | 0 | 0 | 0 | 0 | 5 | 13 | 0 | 6 | 5 | 19 | 8 | 0 |
| NW | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 0 |
| Calm | 13 | 11 | 6 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 33 | 13 |

*Source: Department of Meteorology, Report for 1974*



From December to February (i.e. during NE monsoon), the highest percentage of wind direction was from NE direction. Within these three months, the direction varied from north to east quadrant. In March, the direction was mainly from east. In April, wind direction was a variable but in most cases, it was from SW direction. During March to April, the wind is characterized by the first Intermonsoon. From May to September, (i.e. during SW monsoon) the highest percentage of wind direction was from SW direction. Mainly the direction varied between south and west. In October, a high percentage goes to SW direction but a reasonable amount comes from the west direction also. In November, there is no clearly identified wind direction, which gives a high percentage.

No record could be traced for wind mileage and direction in Ratnapura.

### 4.5 Dew-point Temperature

Dew-point temperature is the temperature at which the air becomes saturated when cooled under constant pressure and with constant water vapour content. Changes in temperature do not alter an air parcel's dew point temperature but if the moisture is extracted from or added to an air parcel, the dew-point temperature will decrease or increase respectively.

Dew-point temperature is calculated from the dry-bulb temperature and the wet-bulb depression by using psychrometric tables. The wet-bulb depression is the difference between the dry-bulb temperature and the wet-bulb temperature. From the psychrometric tables it can be seen if the air temperature is $70^0$F or above and the wet-bulb depression is $1^0$F then the dew-point temperature equals to wet-bulb temperature. In all other cases except when the wet-bulb depression is greater than $5^0$F, the dew-point temperature is close to wet-bulb temperature.
Table 4.6 shows the monthly averages of dew-point data in 1974.



Table 4.6 – Monthly averages of Radiosonde data – 1974

| Month | Surface dew-point temperature ($^0$C) | 1000mb dew-point temperature ($^0$C) |
|---|---|---|
| January | 20.8 | 19.7 |
| February | 22.9 | 22.0 |
| March | 23.6 | 22.8 |
| April | 24.9 | 24.2 |
| May | 25.3 | 24.4 |
| June | 25.3 | 24.7 |
| July | 24.5 | 23.7 |
| August | 24.3 | 23.5 |
| September | 24.4 | 24.0 |
| October | 24.1 | 23.6 |
| November | 22.8 | 22.5 |
| December | 24.0 | 23.3 |

*Source: Department of Meteorology, Report for 1974*

Dew-point temperature is measured at 3-hourly intervals but no daily dew-point value is recorded in the manuscripts. However, records show the monthly dew-point temperature values. In addition to that, Radiosonde data give dew-point temperature values at the surface and at various pressure levels in Colombo.

### 4.6 Wet-Bulb Temperature

The wet-bulb temperature is the temperature to which a parcel of air is cooled by evaporating water into it at a constant pressure until the air is saturated.

Table 4.7 shows the highest and the lowest wet bulb temperature in 1974 by considering the extreme wet bulb temperatures in each month.

Table 4.7 – Extreme wet-bulb temperatures in 1974

| Station | Highest Temperature ($^{0}$C) | Lowest Temperature ($^{0}$C) |
|---|---|---|
| Anuradhapura | 28.3 | 16.2 |
| Ratnapura | 28.7 | 15.3 |
| Ratmalana | 28.6 | 15.3 |
| Galle | 27.8 | 17.2 |
| Mannar | 30.0 | 18.3 |
| Hambantota | 28.3 | 17.8 |



*Source: Department of Meteorology , Report for 1974*

Generally, the maximum and minimum wet-bulb temperature through out the country is about 29$^{0}$C and 16$^{0}$C respectively but in the Central region, the values are lower. In most cases, maximum wet-bulb temperature occurred in April and the minimum in January/February.

Table 4.8 shows the monthly averages of maximum wet bulb temperatures during the period 1931-1960.

Table 4.8 – Monthly mean maximum wet-bulb temperature ($^0$C) during 1931-1960

| Station | Wet-bulb temperature ($^0$C) |
|---|---|
| Anuradhapura | 25.4 |
| Ratnapura | 26.2 |
| Ratmalana | 26.0 |
| Galle | 25.6 |
| Mannar | 26.1 |
| Hambantota | 26.0 |

*Source: Department of Meteorology , Report for 1974*

**4.7 Air Temperature**

The highest air temperature can be seen in the months of April, May or June. The low values are in December, January or February. However, the difference between the highest and the lowest is in a range of 1.5 – 4.0 $^0$C.

Table 4.9 shows the annual average of monthly averages of air temperatures ($^0$C)



| Station | 1931-1960 | 1961-1990 |
|---|---|---|
| Anuuradhapura | 27.3 | 27.7 |
| Ratnapura | 27.2 | 27.4 |
| Galle | 26.2 | 26.9 |
| Mannar | 27.8 | 28.0 |
| Hambantota | 27.1 | 27.2 |

*Source: Department of Meteorology , Report for 1974*

**4.8 Sea Surface Temperature (SST)**

Sea surface temperature reflects the temperature of the upper few inches of the sea surface. The data collected during 1901-1988 have been used in this study. Table 4.9 shows the monthly mean sea surface temperatures at four locations from 1901 to 1988.

Table 4.10 – Monthly mean sea surface temperature during 1901-1988

| Location | East off 80-85$^0$E 5-10$^0$N | West off 75-80$^0$E 5-10$^0$N | Southeast off 80-85$^0$E 0- 5$^0$N | Southwest off 75-80$^0$E 0- 5$^0$N |
|---|---|---|---|---|
| Maximum SST ($^0$C) | 30.65 | 30.54 | 30.51 | 30.75 |
| Mean SST ($^0$C) | 28.05 | 27.86 | 28.20 | 28.23 |

*Source: Nakagawa, 1989*

The analysis revealed that the mean sea surface temperature was above 28$^0$C, which is called as warm pool in tropical seas. It is known that where the SST is above 28$^0$C such areas are subjected to cyclones.

# CHAPTER FIVE

# METHODOLOGY

## 5.1 Introduction

This chapter describes in detail the two methods, storm maximization and the statistical method, which have been selected to calculate point PMP as, discussed in Chapter Two.

## 5.2 Method used in Storm Maximization

Storm maximization can be done in either of the two ways, namely, by "in-situ" or by "transposition". In this research, only the method of insitu maximization was considered because a sufficient number of storms occurred over the basins concerned.



The general procedure is summarized in these steps.

Step 1. Inventory of historical storms

Step 2. Depth-Area-Duration analysis of historical storms

Step 3. Maximum moisture adjustment

- a) Dew point – Moisture maximization
- b) Wind velocity – Wind maximization

Step 4. Enveloping the maximum adjusted values

### 5.2.1 Inventory of Historical Storms

In general, the past rainfall records were examined to select the date of occurrence of major storms that occurred over the basins. The research concentrates on estimating point PMP for two different locations; hence, the selection of the highest observed rainfall over the area was sufficient.

### 5.2.2 Depth-Area-Duration Analysis of Historical Storms

The aim of this depth-duration analysis is to determine the largest average depth of rainfall which occurred over various sizes of areas during various time periods. This research was limited to estimate 24-hour point PMP and hence the above DAD analysis was not needed.

### 5.2.3 Maximum Moisture Adjustment

One of the main assumptions in the storm maximization is that PMP is a result of the combination of

a) the storm efficiency of the storm – i.e. changing water vapour and droplets into rain, (Mutreja, 1986) and
b) the moisture content

Since there is no standard procedure to evaluate the storm efficiency, only the moisture content is considered for maximization. Maximization of the selected storm can be done in two ways.

a) Using moisture maximization factor (MMF) / moisture adjustment factor (MAF)
b) Using wind maximization factor (WMF)



a) Moisture Maximization Factor (MMF)

This can be defined as the ratio of the maximum precipitable water ($W_m$) estimated for the area to the amount of precipitable water recorded during the storm ($W_S$)

i.e. $MAF = W_m/W_s$

The precipitable water is the mass of water vapour in a saturated vertical column of the atmosphere extending up from the earth's surface. This can be defined as the depth of water which would result from the condensation of all the water vapour in the column of air. But, it is of course, impractical to occur in nature, and all air masses contain some precipitable water. (Wiesner, 1970) This can be calculated as,

$W = \int \rho_w \, dz = -\int (\rho_w/\rho_a g)dp = \int (q/g)dp$

Where, z-altitude

$\rho_a, \rho_w$ – densities of air and water respectively

q- specific humidity

g- acceleration due to gravity

To calculate precipitable water, it is necessary to find the sea-level dew point temperature. To compare dew points at different elevations and at various stations, they should be adjusted to a common pressure; which is 1000mb (approximately sea level pressure) Hence, observed storm dew point and maximum dew point should be adjusted pseudo-adiabatically. In this research, the elevations at Anuradhapura and Ratnapura are 89.9 and 86.3m respectively. The pressure is almost equal to sea-level pressure (1000mb) and, therefore it is not necessary to convert the observed dew points pseudo-adiabatically.

According to Wiesner (1970), for a storm of D hour duration, it is possible to select the highest D hour persisting dew point or the highest dew point that can persist for D consecutive hours. In general, the maximum persisting dew point in 12 hours is considered because a great proportion of rain falls in the most intense 12 hours. In this study, the selected storm duration is 24 hours and hence the highest 24-hour persisting dew point is considered. The surface dew-point which represents the storm should not be higher than the minimum temperature within that period. (Wiesner, 1970)

The dew point in an air column changes with the altitude having a pseudo-adiabatic lapse rate. According to the above assumption, the WMO manual (1986) has presented two tables (Table A.1.1 and A.1.2 - attached in Annex1) to calculate precipitable water. The summation of precipitable water is carried from sea level to an elevation of 12200m (200mb pressure). There is little moisture available above the elevation 12200m.



If there is an inflow barrier for the airflow, it causes a reduction of precipitable water. The amount of precipitable water calculated from sea level to the height of the inflow barrier is subtracted from the total precipitable water, which is calculated from sea level to 200mb pressure. In the catchments considered, there are no massive mountain barriers obstructing the flow of moist air from the eastern Indian Ocean.

When determining maximum precipitable water ($W_m$), the maximum 24-hour persisting dew point is considered. To find that dew point, it is necessary to survey a long record (50-years) of dew points at a station. Considering all high values, a seasonal envelope can be drawn to identify the maximum dew point. As there is a seasonal variation in precipitation, two envelopes have been drawn for two basins considering only the respective monthly maps.

Sea surface temperature represents atmospheric moisture than the inland dew points, which, may be affected by local conditions. But it has to be considered that the moist air is modified as it passes over land. (WMO, 1986) The highest dew points were selected by considering sea level dew points and inland dew points. After determining $W_m$ and $W_s$, the moisture adjustment factor can be calculated.

b) Wind Adjustment Factor (WAF)

Wind maximization is commonly used in orographic regions but is sometimes used in non-orographic regions where moisture adjustments alone appear to yield inadequate results. (WMO, 1986) Storms with high wind speeds tend to produce heavy rainfall bringing high moisture content. This can be used to compensate for results obtained from limited hydrometeorological data.

Wind maximization ratio is the ratio of the maximum daily wind run for the critical direction to the observed daily wind run for the same direction in the storm being maximized.



Usually moisture enters the storm system in the troposphere i.e. in the lowest 1500m, therefore, surface data is used as an index of wind movement. When deriving the wind maximization ratio, winds coming from critical directions must be considered. Wind direction is expressed in terms of 16 compass points (N,NNE,NE etc.) for surface wind. In Sri Lanka, wind climate i.e. both wind direction and wind speed is largely characterized by the monsoon system, hence the critical direction is selected considering the monsoon effects. When calculating wind speed, the total wind movement for a 24-hour period is taken, but the actual wind speed during the storm was not available. A long record of (50 years) wind speed observations is necessary to get the maximum wind speed.

In this research, wind maximization is introduced due to the limited dew point temperature data. This may yield higher PMP results than those obtained from moisture adjustment alone. Critical direction is taken as the direction of the highest storm selected.

### 5.2.4 Enveloping the Maximum Adjusted Values

In this last step, the storm is adjusted for maximum moisture by multiplying it by moisture adjustment factor, wind adjustment factor and the ratio of true to fixed interval maximum rainfall. If this analysis is done for a basin, the adjusted data are plotted on a graph and a smooth envelope curve is drawn through the highest values. This envelope gives the values of probable maximum precipitation for the basin.

This study is limited to calculate point PMP and hence, an envelope curve has not been drawn. Then the PMP is calculated by adjusting the maximum storm by respective adjustment factors.

## 5.3 Method used in Statistical Analysis

Hershfield's method, which is one of the statistical methods to estimate PMP is selected due to the widest acceptance it has received. The purpose is to reduce the range of uncertainty in the rainfall series in PMP estimates.



### 5.3.1 Basis (Hershfield, 1961)

Hershfield's statistical method is based on the general frequency equation

$$X_t = X_n + KS_n$$

Where,

$X_t$ - rainfall for return period t in years

$X_n$ , $S_n$ – mean and the standard deviation of a series of n annual maxima respectively

K – Statistical variable that varies with the different frequency distributions

If the probable maximum precipitation, PMP is substituted for $X_t$ and $K_m$ for K where $K_m$ is the highest value of K to yield PMP, then the equation becomes,

$$PMP = X_n + K_m S_n$$

$K_m$ values were computed by assuming that $X_t$ was the maximum observed rainfall of a series of annual maximum rainfalls. This maximum observed rainfall was not included in the computation of the mean and the standard deviation. From those $K_m$ values, Hershfield developed a working diagram (Hershfield, 1965)) to estimate $K_m$ in PMP estimates with the combination of the mean, the standard deviation, and the duration.

### 5.3.2. Adjustments of $X_n$ and $S_n$ for Maximum Observed Event

An unexpected extreme rainfall event, called outlier may cause a significant change on the mean and the standard deviation of the annual series, but the effect of the outlier is much higher on the standard deviation than the mean. Hershfield (1961) used a hypothetical series to create a test statistic, which contained a ratio of mean ($X_{n-m}$ / $X_n$) and a ratio of standard deviation ($S_{n-m}/S_n$) to compensate the effect of outlier. These ratios were calculated by varying record lengths where the numerator does not include the maximum observed event and the denominator includes all values. Figures A.2.1 and A.2.2 show the adjustments of mean and standard deviation of annual series for outliers are attached in Annex 2.

### 5.3.3. Adjustment of $X_n$ and $S_n$ for Sample Size

As sample size increases, there is a tendency to increase the mean and the standard deviation due to the right skewness in the frequency distribution. Hershfield (1961) found that a 50-year record could be used as a reference standard to adjust other short records. (Annex 2 – Figure A.2.3) In addition, the large sample sizes such as 60,70-years showed negligible difference with a 50-year mean.

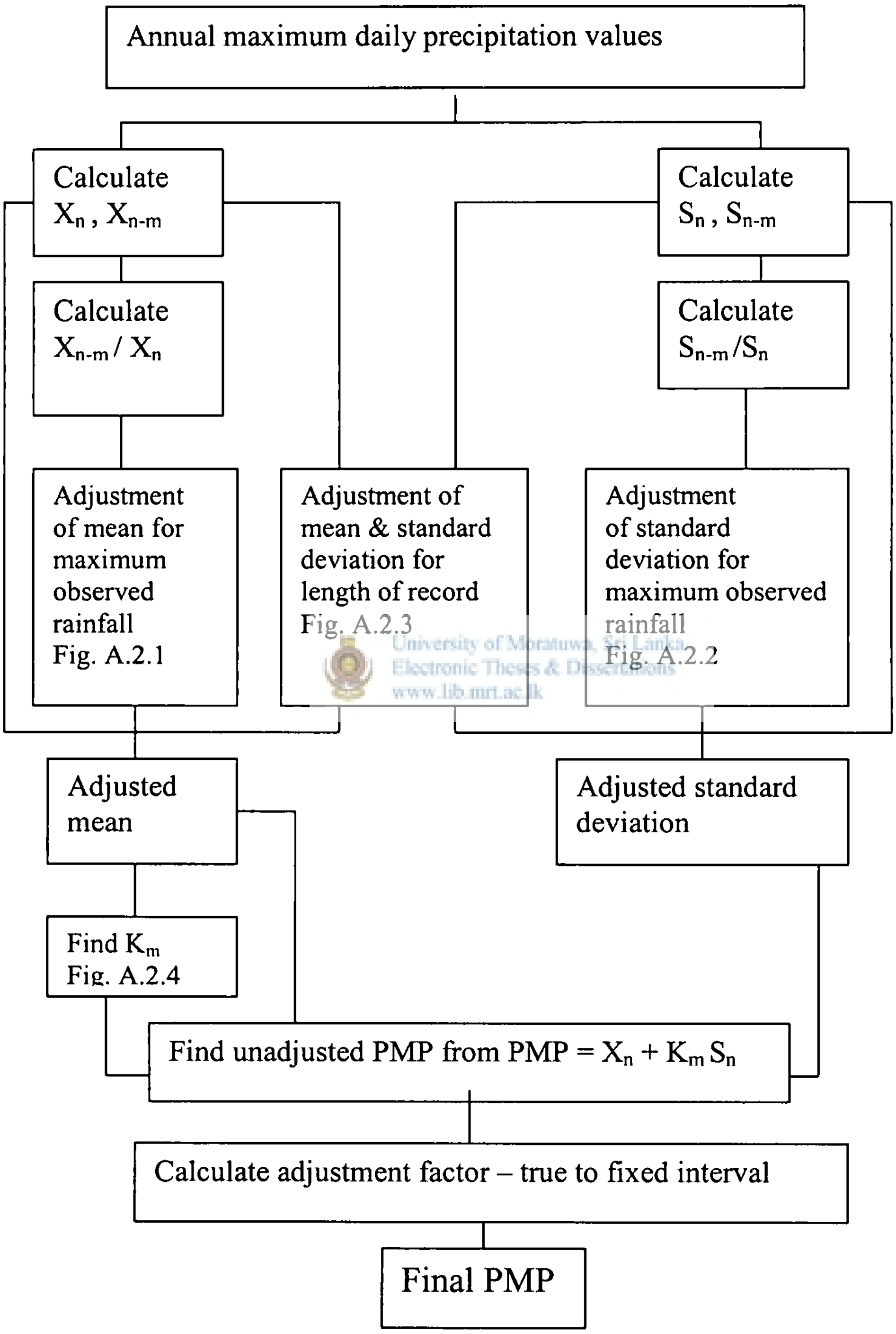


### 5.3.4. Adjustment for Fixed Observational Time Intervals

In Sri Lanka, usually the daily rainfall data are recorded at fixed time interval (8.30 am to 8.30am). When the period of rainfall lies between both sides of the time of observation, this does not show the true maximum daily rainfall. Then the result shows the part of the rainfall for one day and the remainder for the next day. Finally, the maximum fixed observational values are less than the true values recorded from1440 consecutive minutes. Weiss (1964) used a probability model to find conversion factors to estimate maximum true interval value from observational time intervals. The values complied with those are calculated empirically. The conversion factor of true amount to observational amount for any time interval of same length is 1.143. Lesser conversion factors can be used for two or more observational units.

5.3.5. The Procedure

The flowchart of the procedure for the estimation of PMP is as follows.



## 5.4 Summary

In this research, the methods of storm maximization and the statistical analysis were used to estimate 24-hour point PMP for the purpose of comparison from the methods discussed in Chapter Two. In storm maximization, the transposition of storms has not been considered assuming sufficiently great storms occurred over the basins. The PMP estimated from the hydrometeorological method involved moisture maximization and wind maximization. Depth-area-duration analysis was not needed due to the calculation of 24-hour point PMP. The daily rainfall data recorded at fixed time were used to calculate the maximum rainfall depth and were adjusted. (Varshney, 1979) This is satisfactorily done by using the ratio of true to fixed time interval.

The statistical method by Hershfield is based on the general frequency equation. Adjustments for the maximum observed event, sample size and true-fixed interval ratio is necessary to calculate the final PMP.

# CHAPTER SIX

## DATA PRESENTATION

### 6.1 Introduction

This chapter presents the geographical data and the meteorological data, which help to do the storm maximization and the statistical analysis. Rainfall, dew point temperature and wind data are mainly discussed under meteorological data.

In this research, the selected locations are Anuradhapura and Ratnapura. (Figure 1.1)

### 6.2 Geographical Data

Table 6.1 describes the geographical coordinates and the elevations of selected stations.



Table 6.1 – Geographical Data

| Description | Anuradhapura | Ratnapura |
|---|---|---|
| Geographical Coordinates | | |
| Latitude | $8^0$ 21' N | $6^0$ 41' N ( $6^0$ 43' N)* |
| Longitude | $80^0$ 23' E | $80^0$ 24' E ($80^0$ 24' E)* |
| Elevation (m) | 89.9 | 34.45 (86.294)* |

*Source: Department of Meteorology*

- The meteorological station at Ratnapura was moved to a new site in August 1993. The data presented in parenthesis is after moving the station.

## 6.3 Meteorological Data

### 6.3.1 Rainfall Data

A long period of daily rainfall data is required for estimating the probable maximum precipitation. Rainfall data are available from 1889 to 2000 for Anuradhapura and from 1895 to 2000 for Ratnapura, but the data is missing for the period 1941-1950 for Anuradhapura.

In the method of storm maximization, the selected period is 1951-2000. The longest of the series is 50 years. By selecting the above period, a complete data set could be obtained. During that period, graphs (Figure 6.1 and 6.2) were prepared considering annual maximum daily precipitation (Annual series).

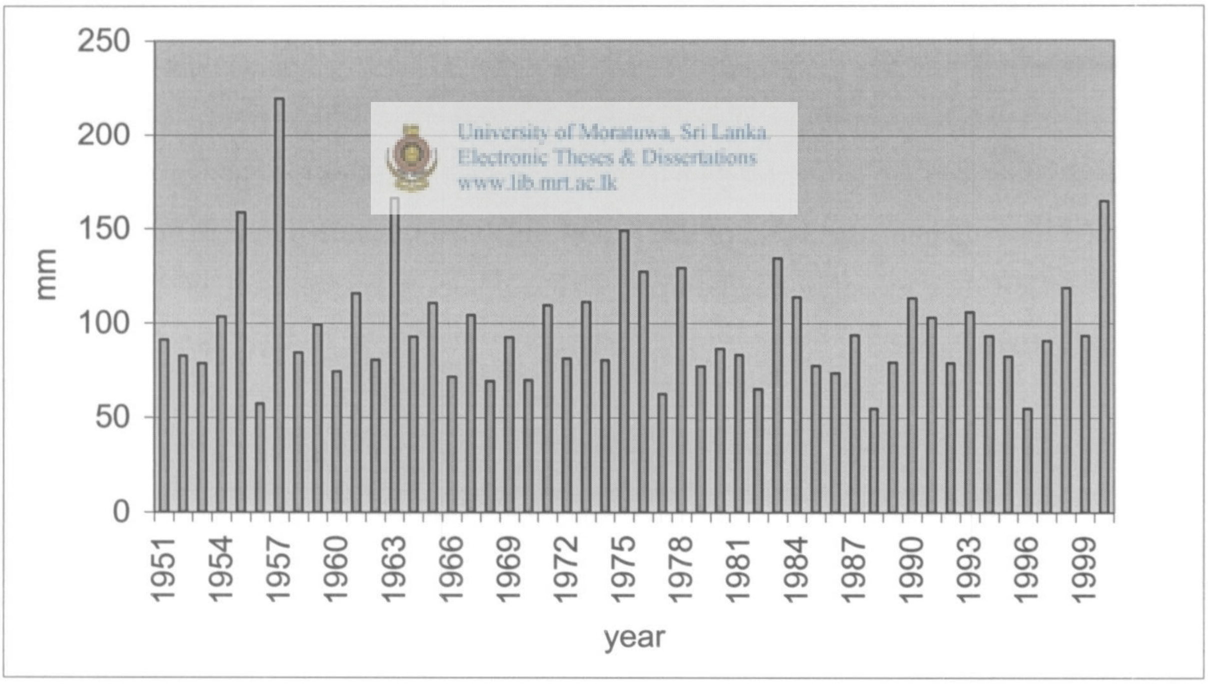




Figure 6.1 – Annual Maximum Daily Precipitation in Anuradhapura

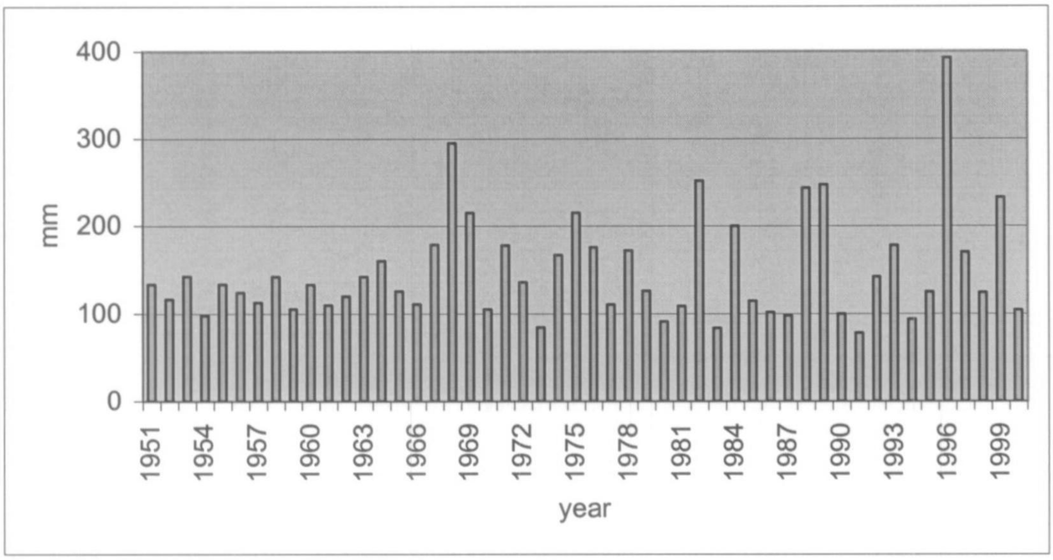



Figure 6.2 – Annual Maximum Daily Precipitation in Ratnapura

From these two figures, five major storms are selected for each station, and the values are presented in Tables 6.2 and 6.3

Table 6.2 – Major Storms occurred during 1951-2000 at Anuradhapura

| Date | Rainfall (mm) |
|---|---|
| 25.12.1957 | 219.7 |
| 24.12.1957 | 206.5 |
| 06.01.1963 | 166.3 |
| 26.12.2000 | 164.7 |
| 18.04.1955 | 158.7 |
| 24.05.1975 | 149.1 |

*Source: Department of Meteorology*



Table 6.3 – Major Storms occurred during 1951-2000 at Ratnapura

| Date | Rainfall (mm) |
|---|---|
| 08.06.1996 | 392.5 |
| 04.06.1968 | 294.9 |
| 08.06.1982 | 251.7 |
| 11.07.1989 | 246.9 |
| 01.06.1988 | 243.6 |

*Source: Department of Meteorology*

The most significant storms that occurred in Anuradhapura and Ratnapura were on 25th December, 1957 and 08th June 1996 respectively.

The variation of the rainfall of the selected storm for Anuradhapura and Ratnapura can be tabulated as below. (Table 6.4 and 6.5)

Table 6.4 – The Variation of the most significant storm in Anuradhapura

| Date | Time (hrs.) | Rainfall (mm) | Total Rainfall/daily (mm) |
|---|---|---|---|
| 24.12.1957 | 0830-1730 | 45.2 | |
| | 1730-0830 | 161.3 | 206.5 |
| **25.12.1957** | 0830-1730 | 158.2 | 319.5 |
| | 1730-0830 | 61.5 | **219.7** |

Table 6.5 – The Variation of the most significant storm in Ratnapura

| Date | Time (hrs.) | Rainfall (mm) | Total Rainfall / daily (mm) |
|---|---|---|---|
| 08.06.1996 | 0300 | 0 | |
| | 0600 | 0 | |
| | 0900 | 1.8 | |
| | 1200 | 1.3 | |
| | 1500 | 2.5 | |
| | 1800 | 45.5 | |
| | 2100 | 49.0 | |
| | 2400 | 109.8 | 209.9 |
| 09.06.1996 | 0300 | 150.5 | 360.4 |
| | 0600 | 34.9 | 393.5 |
| | 0900 | 0.3 | **392.5** |
| | 1200 | $0^+$ | 390.0 |
| | 1500 | 0.2 | 344.7 |
| | 1800 | 6.0 | 301.7 |
| | 2100 | 1.4 | 193.3 |
| | 2400 | 0.3 | 193.6 |

In storm maximization, the length of record considered is 50 years, starting from 1951 – 2000. Dew point temperature and wind data are also needed for this study but those data were not available before 1951. In statistical analysis, the total record of data was considered by varying the sample size.

6.3.2 Dew Point Temperature Data

In order to find the maximum 24-hour persisting dew point values, the surface dew point temperature values are needed during the period of 1951 – 2000. There is a seasonal variation in precipitation, hence dew point values from the records of respective monthly values, in which, the month that the major storm occurred, were considered for the two locations. Therefore, for Anuradhapura all December values and for Ratnapura all June values were extracted during 1951 – 2000.

The Department of Meteorology published only the monthly averages of dew point temperature data, although they have measured three hourly data. Therefore, wet bulb temperature values were extracted in order to calculate precipitable water instead of dew point temperature data. The dew point temperature is always below the wet bulb temperature and the value is very close to wet bulb temperature, when the wet bulb depression is low. Hence, the substitution of wet bulb temperature to dew point data does not greatly affect the final result.



The wet bulb temperature data measured during the selected storm:

a) 21.6 $^0$C on 25.12.1957 at Anuradhapura
b) 26.0 $^0$C on 08.06.1996 at Ratnapura

However, the surface dew point temperature for June 1996 storm was found to be 25.1 $^0$C at 0900 hours. The average dew point temperature in the storm was 24.4 $^0$C.

24-hour persisting surface dew point values were taken by drawing the graphs considering all daily wet bulb temperature values in December and June for each year during 1951-2000 for Anuradhapura and Ratnapura respectively. These 50 graphs for each basin are attached in Annex 3.

Figures 6.3 and 6.4 shows the monthly averages of dew point temperature in December and June for Anuradhapura and Ratnapura respectively.

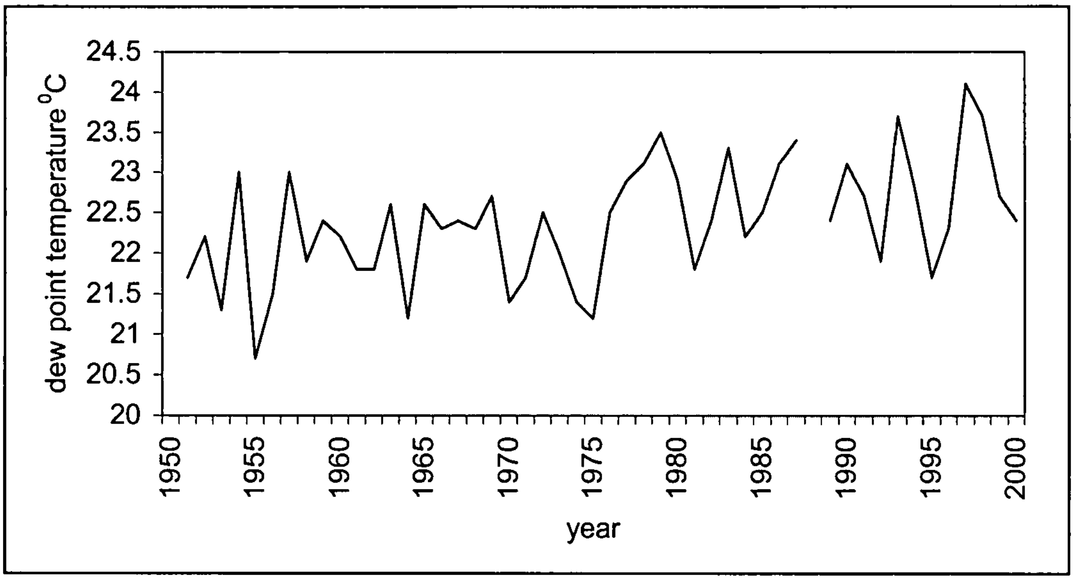



Figure 6.3 – Monthly (December) averages of dew point temperature in Anuradhapura

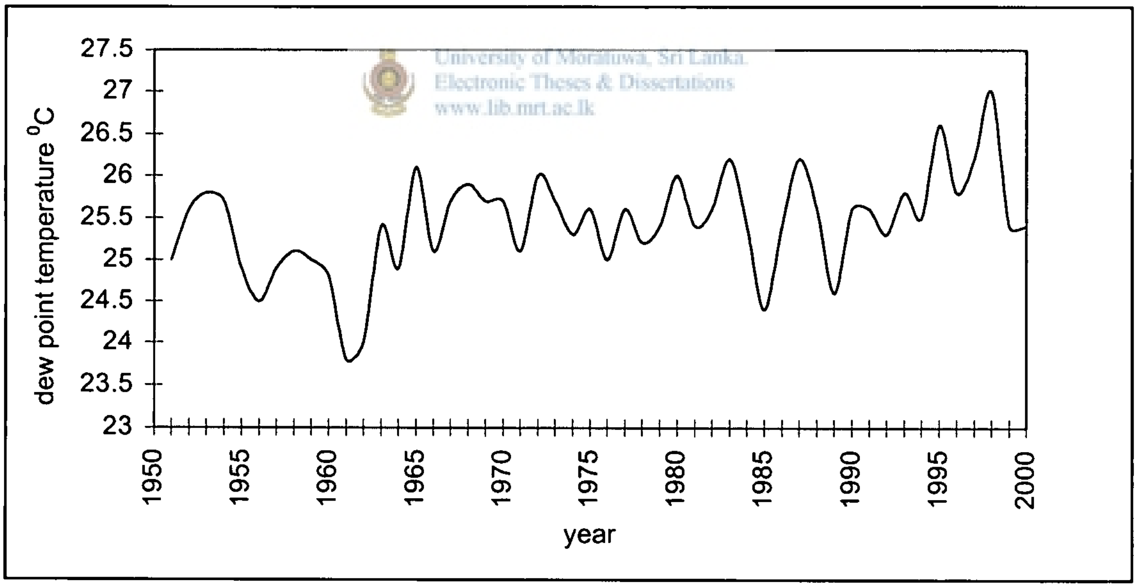





Figure 6.4 – Monthly (June) averages of dew point temperature in Ratnapura

### 6.3.3. Wind Data

I. Wind data measured during the storm are as follows.

| Station | Anuradhapura | Ratnapura |
|---|---|---|
| Daily wind run (km) | 338 | 173 |
| Wind direction | NW | N |

*Source: Department of Meteorology*

Very few wind run data were available for analysis in Ratnapura. Wind data was taken only after moving the site, i.e. after August 1993. Hence, there is no long record (only 7 years) to get the maximum wind speed.

II. Wind data measured during 1951 – 2000 at Anuradhapura

First, critical direction should be selected to find maximum wind run. Wind direction is largely characterized by the monsoon in December. Therefore, the wind direction is NE. Nevertheless, during the selected storm, direction was NW. Hence, to find the maximum wind run NE-NW quadrant was considered.

Wind run data greater than 300 km were tabulated in Table 6.6



Table 6.6 – Daily wind run in Anuradhapura

(Values greater than 300 km were listed)

| Date | Direction | Wind run (km) |
|---|---|---|
| 14.07.1965 | NW | 440 |
| 26.12.1957 | NE | 391 |
| 16.07.1965 | NW | 362 |
| 22.12.1964 | NE | 322 |

*Source: Department of Meteorology*

III. Wind Data measured during 1994 – 2000 in Ratnapura.

Having referred the past records, it can be seen that the wind direction in June is mainly NW. But during the storm selected, the direction is N. Hence, as critical direction both NW and N directions were selected.

Considering seven years wind run data in Ratnapura, the following high values were selected and tabulated in Table 6.7

Table 6.7 - Daily wind run in Ratnapura in N and NW directions

| Date | Wind Direction | Wind run (km) |
|---|---|---|
| 13.06.1996 | N | 415 |
| 14.06.1996 | NW | 366 |
| 30.06.1994 | NW | 357 |
| 15.06.1996 | N | 342 |
| 29.06.1994 | NW | 310 |

*Source: Department of Meteorology*

### 6.3.4. Air Temperature

Minimum air temperature during the December, 1957 storm in Anuradhapura was $21.9^0C$
Minimum air temperature during the June, 1996 storm in Ratnapura was $21.9^0C$

### 6.3.5. Sea Surface Temperature (SST)

The sea surface temperature for the Indian Ocean was examined at four different locations as follows.



| | Longitude E | Latitude N |
|---|---|---|
| East off | 80-85 | 5-10 |
| West off | 75-80 | 5-10 |
| Southeast off | 80-85 | 0-5 |
| Southwest off | 75-80 | 0-5 |

Out of these four, only two locations – east off and west off – were considered by examining the wind directions of two stations. For the period 1939 to 1988 (50-year period), sea surface temperatures for the months of June and December were given in Table 6.8

Table 6.8 – Sea Surface Temperatures for June and December

| | East off | West off |
|---|---|---|
| Sea surface temperature – June 1996 | N/A | N/A |
| Highest mean monthly SST in June | 29.79 | 29.49 |
| Mean monthly SST in June | 28.67 | 28.10 |
| SST – December 1957 | 27.88 | 28.17 |
| Highest mean monthly SST in December | 28.5 | 28.80 |
| Mean monthly SST in December | 27.56 | 27.90 |

### 6.4 Difficulties in conducting research on PMP

When conducting the research on PMP the researcher got into some difficulties with the methodology and data collection. These difficulties are discussed as follows.

a) A long length of record is needed when calculating maximum persisting dew point temperature, maximum daily wind run and as well as in statistical analysis to limit adjustment factors. Otherwise, the analysis does not yield maximum values representing maximum moisture. Hence, 50-year sample size was selected but finding the past data (before 1950) on dew point and wind speeds was difficult. Therefore, the maximum length of record chosen was 1951 – 2000.

b) Most of the meteorological data were available only from the original manuscript records; therefore, a considerable amount of time was spent examining the basic records. So, finding the maximum wind run values and making copies of these data took much time within the limited time frame.

c) Dew point temperature values were not published on a daily basis by the Department of Meteorology but on a monthly basis. Then to calculate maximum persisting dew point value, wet bulb temperature was selected. However, monthly mean dew point temperatures have been taken into consideration.

d) Since, the research will estimate point PMP, the maximum dew point values for each month of the year were not prepared. It is assumed that the values of the respective month may be adequate to define the seasonal variation of maximum moisture.

e) Sea surface temperatures were used to examine 24-hour persisting dew point temperature as a check, due to the non-availability of daily dew point records.

f) WMO manual (1986) pointed out that only winds from critical directions are considered in deriving wind – adjustments ratios. Finding the critical wind direction is somewhat difficult because more than one direction is available to provide moist air. However, the pattern of the Asian monsoon and the wind direction of the particular storm were considered when determining the critical direction.

g) In Ratnapura, wind records were available only for seven years. This type of short records is unlikely to yield maximum wind speeds.

h) When calculating wind maximization ratio, the maximum 24-hour average speed of the wind from the moisture inflow direction is needed. But in the published data, the given wind speed is instantaneous. Therefore, daily wind run is taken after considering the critical direction.

i) In statistical analysis, it is recommended to compare mean and standard deviation with nearby stations. This couldn't be done with the limited time frame.

# CHAPTER SEVEN

## DATA ANALYSIS

### 7.1 Introduction

This chapter analyses the data presented in Chapter Six. This will start with the analysis of storm maximization by calculating maximization factors, and it will be followed by the statistical analysis done by using the Hershfield method for both stations, also varying the sample sizes.

### 7.2 Analysis in Storm Maximization

#### 7.2.1 Selection of Event to Maximize



During the observation period 1951 to 2000, 25th December 1957 produced the largest rainfall at Anuradhapura. In an investigation of peak rainfalls in Anuradhapura from 1889 to 2000, the 1957 rainfall on 25th December was the third highest. During this 112-year study period, only four rainstorm values, which were larger than 200mm/day, were recorded and listed in Table 7.1.

Table 7.1 – Observed point rainfall greater than 200mm/day at Anuradhapura

| Date | Rainfall (mm) |
|---|---|
| 20. 05. 1891 | 236.7 |
| 31. 12. 1948 | 319.5 |
| 25. 12. 1957 | 219.7 |
| 24. 12. 1957 | 206.5 |

*Source : Department of Meteorology*

However, the first two extreme rainfalls couldn't be analyzed due to the non-availability of meteorological data.

The daily rainfall on 08th June 1996 was the highest rainfall in Ratnapura during the study period 1951-2000. In an investigation of rainstorms larger than 300mm/day showed that the June 1996 rainfall was the second highest out of the four events during 1895 – 2003 The values greater than 300mm/day rainfall are shown in Table 7.2

Table 7.2 – Observed point rainfalls greater than 300mm/24 hours at Ratnapura

| Date | Rainfall (mm) |
|---|---|
| 15.07.1942 | 394.4 |
| 08.06.1996 | 392.5 |
| 26.08.1949 | 330.4 |
| 06.05.1939 | 302.3 |

*Source: Department of Meteorology*

By considering the requirement of getting dew point temperature and wind data, the December 1957 and June 1996 rainfalls have been selected to obtain the PMP in Anuradhapura and Ratnapura respetively.



7.2.2. Depth –Area – Duration Analysis

The DAD analysis has not been done for the selected major storms because the main idea was to calculate 24-hour, point PMP.

7.2.3 Maximum Moisture Adjustment

7.2.3.1Moisture Maximization Factor

The moisture maximization factor was determined for Anuradhapura and Ratnapura on the basis of two surface dew point values.

a) Observed dew point for the storm
b) Estimated maximum persisting dew point.

a) The wet bulb temperature for the storm was found to be
   21.6 $^0$ C at Anuradhapura
   26.0 $^0$ C at Ratnapura

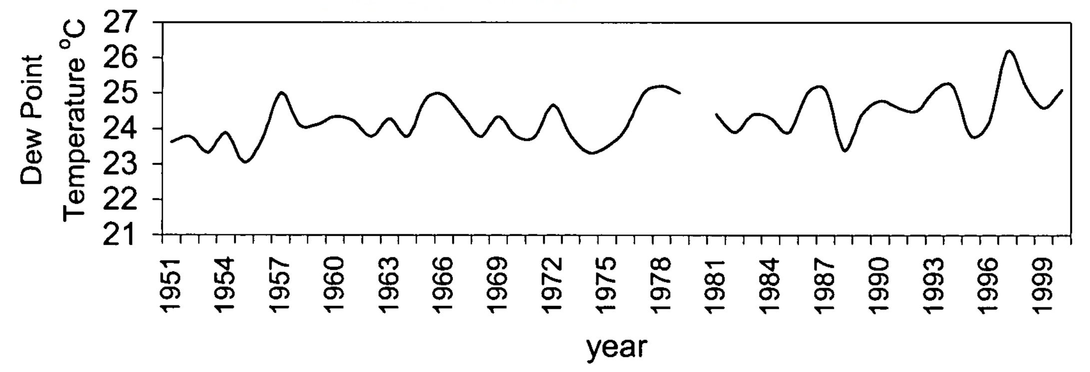
The surface dew point temperature for the June 1996 storm was found to be 25.1 $^0$C. But, Anuradhapura data was not available.

Wiesner (1970) pointed out that the surface dew point of the storm should not be higher than the minimum air temperature within the period. This can be used as a check.
In Anuradhapura, minimum air temperature on 25.12.1957 was 21.9 $^0$ C
Hence, surface dew point < minimum air temperature at Anuradhapura
In Ratnapura, minimum air temperature on 08.06.1996 was 26.8 $^0$ C
Hence, surface dew point < minimum air temperature at Ratnapura

b) In this research, the maximum 24-hour persisting dew point was estimated in two different ways. Firstly, the dew point temperature graphs attached in Annex 2 were examined. The 24-hour persisting dew point values were found for each year. With those values, Figures 7.1 and 7.2 were compiled to get the maximum persisting dew point for Anuradhapura and Ratnapura respectively.

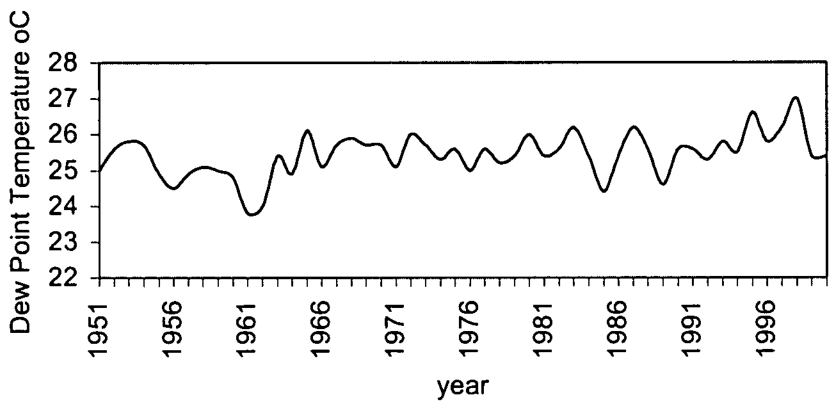
Figure 7.1 Maximum Persisting 24h Dew Point Temperature - Anuradhapura






Maximum 24-hour persisting dew point temperature = 26.2 °C

**Figure 7.2 Maximum Persisting 24-hour Dew Point Temperature - Ratnapura**




Maximum 24-hour persisting dew point temperature = 27 °C

Secondly, the sea surface temperature (SST) was examined to calculate the maximum 24-hour persisting dew point temperature according to Rezacova (1999). Generally, in Anuradhapura moist air is supplied from east off the Indian Ocean but during cyclonic storms the wind brings the moisture from west off the Indian Ocean also. However, out of these two locations, west off gives higher values. Hence, the study was based on west off values.



During 1939 to 1988 (50-years), the mean monthly SST for December was 27.9 $^0$C and the standard deviation was 0.386. Assuming 99% normal distribution, the frequency factor is 2.575. Therefore, the highest SST that is likely to occur would be (=27.9 + 0.386 x 2.575) 28.9 $^0$C. This value coincides with the highest mean monthly SST in December. This is approximately 1 $^0$C higher than that of December 1957 value (i.e. 28+1=29) The same relationship remains between the maximum of the mean monthly dew point temperature (24 $^0$C) and the value during the storm(23 $^0$C). There is no firm relationship between SST and the surface dew point temperature. However, the mean SST is 1-2 $^0$C higher than the maximum 12-hour persisting dew point temperature (WMO, 1986). When extending 12 hour to 24-hour duration, the dew point temperature reduces (Wiesner, 1970). But in this research, wet bulb temperature is used instead of dew point temperature. Therefore, as a conservative estimate, it could be assumed the persisting dew point temperature is about 2 $^0$C less than the mean SST. (27.9 ~ 28-2 = 26 ~ 26.2 $^0$C) Thus, the highest 24-hour persisting dew point temperature in the month of December in Anuradhapura was estimated to be 26.2 $^0$C.

In Ratnapura, wind direction is mostly NW, hence the source of moisture can be considered as from west off location. During 1939 to 1988, the mean monthly SST in June was 28.1 $^0$C and the standard deviation was 0.54. As in the case of Anuradhapura, the highest SST that is likely to occur would be 28.1+0.54x2.575 = 29.49 $^0$C. This value coincides with the highest mean monthly SST in June. However, the SST of 1996 was not available but assuming the same relationship, SST in June, 1996 could be 29.5-1 = 28.5 $^0$C. Considering the mean monthly dew point temperatures, the maximum value (25 $^0$C) is $1^0$ less than the value of the storm (24 $^0$C).

During the storm, the dew point temperature was 25.1 $^0$C hence maximum persisting dew point temperature would be 25.1+1 = 26.1 $^0$C. Considering mean SST, the persisting dew point temperature was 28.1-2 = 26.1 $^0$C. However, from Figure 7.2, persisting dew point (wet bulb) temperature was 27 $^0$C. Thus, the highest 24-hour persisting dew point temperature in the month of June in Ratnapura was estimated to be 26.1 $^0$C.



To compute the moisture maximization factor, the values of precipitable water were calculated using the tables attached in Annex 1. These values are varied with dew point temperature and altitude (WMO, 1986). The following steps were used to estimate precipitable water for the representative storm and the maximum during the selected period..

1. Total precipitable water for a moisture column with base at 1000mb (sea level) and top at 200mb.
2. Precipitable water for the column with base at sea level and top at the elevation of the station
3. Residual precipitable water

Then the resulting moisture maximization factors were calculated as shown in Table 7.3.

Table 7.3 – Moisture Maximization Factors for Anuradhapura and Ratnapura

| Station | Anuradhapura | Ratnapura |
|---|---|---|
| Average elevation of catchment (m) | 90 | 86.3 |
| Storm dew point at sea surface level ($^0$C) | 21.6 | 25.1 |
| Precipitable water, $W_s$ for storm dew point (mm) | | |
| a) from 1000mb to 200mb (Annex 1 – Table A.1.1) | 60.0 | 81.7 |
| b) from 1000mb to elevation (Annex 1 – Table A.1.2) | 1.8 | 2.1 |
| c) residual | 58.2 | 79.6 |
| Maximum dew point for catchment at sea surface level ($^0$C) (Figure 7.1 and Figure 7.2) | 26.2 | 26.1 |
| Precipitable water, $W_m$ for maximum dew point (mm) | | |
| a) from 1000mb to 200mb (Annex 1 – Table A.1.1) | 89.6 | 88.8 |
| b) from 1000mb to elevation (Annex 1 – Table A.1.2) | 2.2 | 2.1 |
| c) residual | 87.4 | 86.7 |
| Moisture Maximization Factor | 87.4/58.2 = 1.5 | 86.7/79.6 = 1.09 |



7.2.3.2 Wind Maximization Factor

Critical wind directions for Anuradhapura and Ratnapura were NE – NW quadrant and N direction respectively. Wind run values are tabulated in Table 7.4

Table 7.4 – Wind Maximization Factor

| Station | Anuradhapura | Ratnapura |
|---|---|---|
| Daily wind run during the storm (km) | 338 | 173 |
| Maximum daily wind run (km) | 439.5 | 415 |
| Wind Maximization Factor | 1.3 | 2.4 |

### 7.2.4 Calculation of PMP

The probable maximum precipitation for Anuradhapura and Ratnapura was obtained by multiplying the observed rainfall with the calculated moisture maximization factor and wind maximization factor from Tables 7.3 and 7.4 respectively. The resulting PMP values are shown in Table 7.5

Table 7.5 – Estimated PMP for selected stations

| Station | Observed rainfall (mm) | Moisture Max. Factor | Wind Max. Factor | PMP (mm/24-hour) |
|---|---|---|---|---|
| Anuradhapura | 219.7 | 1.5 | 1.3 | 428.42 |
| Ratnapura | 392.5 | 1.09 | 2.4 | 1026.78 |

## 7.3 Statistical Method

In this analysis, PMP estimates were obtained by the statistical method of a series of annual maximum daily precipitation amounts based on Hershfield's method. Precipitation records greater than 20 years were considered, because a long record of data yields reliable PMP values than a short record in equal quality (WMO, 1986). Hence, precipitation data were divided into 20,30 and 50 sample size groups. Maximum daily rainfall was also varied according to the considered sample.

### 7.3.1 Statistical Estimate of PMP for Anuradhapura



By taking the sample size as 20, during the1891-2000 except 10 years from 1941-1950, the data sets of annual maximum daily precipitation were prepared as shown in Table 7.6

Table 7.6 – Summary of statistical analysis in Anuradhapura Sample size –20

| Period | 1891-1910 | 1921-1940 | 1951-1970 | 1961-1980 | 1981-2000 |
|---|---|---|---|---|---|
| Max. daily rainfall (mm) | 236.7 | 160.7 | 219.7 | 166.3 | 164.7 |
| $X_n$ | 109.37 | 106.96 | 101.24 | 99.48 | 93.76 |
| $X_{n-m}$ | 102.67 | 104.13 | 95.00 | 95.97 | 90.02 |
| Adjusted mean | 109.33 | 110.19 | 101.2 | 101.47 | 95.64 |
| $S_n$ | 39.03 | 27.37 | 39.2 | 28.09 | 25.66 |
| $S_{n-m}$ | 25.69 | 24.93 | 28.32 | 23.91 | 21.35 |
| Adjusted Std. Deviation | 31.61 | 31.04 | 34.29 | 28.82 | 26.05 |
| $K_m$ | 14.5 | 14.5 | 15.25 | 15.2 | 15.3 |
| Unadjusted PMP | 567.68 | 560.27 | 624.12 | 539.53 | 494.20 |
| PMP | 648.86 | 640.39 | 713.37 | 616.68 | 564.87 |

During 1891-2000 (except 10 years, 1941-1950,) and considering sample size be 20, maximum daily rainfall varies from 160.7mm to236.7mm. After adjusting for maximum observed event and sample size, the adjusted mean varies from 95.64 to 110.19mm. Similarly, the adjusted standard deviation varies from 26.05 to 34.29. $K_m$ varies from 14.5 to 15.3. Because of less rainfall at this station, $K_m$ is close to 15. The adjusted PMP varies from 565 to 714mm. When comparing 1891-1910 and 1921-1940 periods, PMP values are almost identical although they had two different values for maximum observed event.

By taking the sample size to be 30, during the period 1891-2000 except 10 years from 1941-1950, the data sets of annual maximum daily precipitation were prepared as shown in Table 7.7

Table 7.7 – Summary of statistical analysis in Anuradhapura Sample size –30

| Period | 1891-1920 | 1911-1940 | 1951-1980 | 1961-1990 | 1971-2000 |
|---|---|---|---|---|---|
| Max. daily rainfall (mm) | 236.7 | 160.7 | 219.7 | 166.3 | 164.7 |
| $X_n$ | 108.62 | 107.01 | 101.34 | 95.96 | 96.35 |
| $X_{n-m}$ | 104.2 | 105.16 | 97.26 | 93.53 | 93.99 |
| Adjusted mean | 108.61 | 109.70 | 101.33 | 97.40 | 98.29 |
| $S_n$ | 35.25 | 27.09 | 35.36 | 27.06 | 26.88 |
| $S_{n-m}$ | 26.09 | 25.57 | 27.88 | 23.99 | 24.00 |
| Adjusted Std. Deviation | 30.06 | 29.30 | 32.73 | 28.14 | 27.96 |
| $K_m$ | 15.0 | 15.1 | 15.2 | 16.3 | 16.2 |
| Unadjusted PMP | 559.51 | 552.13 | 598.83 | 556.08 | 551.24 |
| PMP | 639.52 | 631.08 | 684.46 | 635.60 | 630.07 |



During the period 1891-2000 (except 1941-1950) and considering sample size to be 30, maximum daily rainfall varies from 160.7mm to 236.7mm. After adjusting for maximum observed event and sample size, the adjusted mean varies from 97.4 to 109.7mm. Similarly, the adjusted standard deviation varies from 27.96 to 32.73. The adjusted PMP varies from 630 to 685mm. During 1951-1980 PMP shows 9% deviation when compared with other values but 1891-1920 period gives the maximum daily rainfall.

Table 7.8 shows the statistical analysis during 1891-2000 by varying the sample size as 50.

Table 7.8 – Summary of statistical analysis in Anuradhapura Sample size –50

| Period | 1891-1940 | 1951-2000 |
|---|---|---|
| Maximum daily rainfall (mm) | 236.7 | 219.7 |
| $X_n$ | 107.95 | 98.31 |
| $X_{n-m}$ | 105.32 | 95.83 |
| Adjusted mean | 107.41 | 97.82 |
| $S_n$ | 32.04 | 32.09 |
| $S_{n-m}$ | 26.37 | 27.16 |
| Adjusted Standard Deviation | 28.20 | 29.52 |
| $K_m$ | 14.9 | 15.2 |
| Unadjusted PMP | 527.59 | 546.52 |
| PMP | 603.04 | 624.68 |

During the period 1891-2000 (except 1941-1950) and considering sample size to be 50, the maximum daily rainfall varies from 219.7mm to 236.7mm. After adjusting for the maximum observed event and sample size, the adjusted mean varies from 97.82 to 107.41mm. Similarly, the adjusted standard deviation is in a range of 28.2 to 29.52. $K_m$ value is close to 15 in both cases, producing the adjusted PMP to be in a range of 603 to 625mm. Though the maximum daily rainfall is high during 1891-1940 period, it does not mean that PMP should be high in the same period.

### 7.3.2 Statistical Estimate of PMP for Ratnapura

By taking the sample size to be 20, during 1895-2000 the data sets of annual maximum daily precipitation were prepared for Ratnapura as shown in Table 7.9

Table 7.9 – Summary of Statistical Analysis in Ratnapura. Sample size 20

| Period | 1901-1920 | 1921-1940 | 1941-1960 | 1961-1980 | 1981-2000 |
|---|---|---|---|---|---|
| Max. daily rainfall (mm) | 269.2 | 302.3 | 394.4 | 294.9 | 392.5 |
| $X_n$ | 144.22 | 159.96 | 167.28 | 150.65 | 159.28 |
| $X_{n-m}$ | 137.64 | 152.47 | 155.33 | 143.06 | 147.0 |
| Adjusted mean | 146.37 | 162.34 | 165.51 | 152.89 | 156.29 |
| $S_n$ | 44.50 | 50.37 | 85.43 | 50.98 | 80.45 |
| $S_{n-m}$ | 34.30 | 38.64 | 68.46 | 39.08 | 60.42 |
| Adjusted Std. Deviation | 42.77 | 48.42 | 84.88 | 49.0 | 73.85 |
| $K_m$ | 13.8 | 13.1 | 13.2 | 13.6 | 13.3 |
| Unadjusted PMP | 736.60 | 796.64 | 1285.93 | 819.29 | 982.21 |
| PMP | 841.93 | 910.56 | 1469.81 | 936.45 | 1122.67 |

During the period 1901-2000 (100 years) considering sample size to be 20, the maximum daily rainfall varies from 269.2 to 394.4mm. After adjusting for maximum observed event and sample size, the adjusted mean varies from 146.37 to 165.51mm. Similarly, the adjusted standard deviation varies from 42.77 to 84.88mm. But the range of the deviation is very high and when considering the upper value in this range, it is nearly double the lower value, mainly due to the maximum observed event. $K_m$ varies from 13.1 to 13.8 There is no significant difference in the range because $K_m$ depends only on the mean of the annual series and the duration of the rainfall. In this case, the duration is a constant. The adjusted PMP varies from 842 to 1470mm. The above range has a large variability mainly due to the variability of standard deviation.



Table 7.10 shows the statistical analysis in Ratnapura varying the sample size as 30

Table 7.10 – Summary of Statistical Analysis in Ratnapura. Sample size -30

| Period | 1901-1930 | 1911-1940 | 1921-1950 | 1951-1980 | 1971-2000 |
|---|---|---|---|---|---|
| Max. daily rainfall (mm) | 269.2 | 302.3 | 394.4 | 294.9 | 392.5 |
| $X_n$ | 150.65 | 162.96 | 176.85 | 141.75 | 154.61 |
| $X_{n-m}$ | 146.56 | 158.16 | 169.35 | 136.47 | 146.40 |
| Adjusted mean | 152.16 | 164.59 | 176.83 | 141.74 | 153.03 |

| | | | | | |
|---|---|---|---|---|---|
| $S_n$ | 41.08 | 48.63 | 75.27 | 44.05 | 69.61 |
| $S_{n-m}$ | 35.05 | 41.62 | 64.18 | 33.81 | 54.11 |
| Adjusted Std. Deviation | 39.73 | 48.05 | 72.80 | 39.40 | 61.54 |
| $K_m$ | 13.5 | 13.2 | 12.7 | 13.9 | 13.5 |
| Unadjusted PMP | 688.52 | 798.85 | 1101.39 | 689.4 | 938.82 |
| PMP | 786.98 | 913.08 | 1258.89 | 787.98 | 1073.07 |

During the period 1901-2000 (100 years), considering sample size to be 30, the maximum daily rainfall varies from 269.2 to 394.4mm. After adjusting for maximum observed event and sample size, the adjusted mean varies from 141.74 to176.83mm. Similarly, the adjusted standard deviation varies from 39.40 to 72.80mm. In this analysis also, the range of standard deviation is high. The ratio of upper to lower values of standard deviation is 1.85. The range of adjusted mean is also higher when compared to the previous analysis (Sample size 20). $K_m$ value varies from 12.7 to 13.9. Due to the high-adjusted mean, $K_m$ is getting reduced. Except the lowest value of the mean, the range of $K_m$ is having similar values. The adjusted PMP varies from 787mm to 1259mm. The highest PMP value of this sample shows a 57% deviation.



After taking the sample size as 50, the statistical analysis in Ratnapura is given in Table 7.11

Table 7.11 – Summary of Statistical Analysis in Ratnapura Sample size 50

| Period | 1896-1945 | 1901-1950 | 1946-1995 | 1951-2000 |
|---|---|---|---|---|
| Max. daily rainfall (mm) | 394.4 | 394.4 | 330.4 | 392.5 |
| $X_n$ | 160.54 | 163.80 | 148.23 | 148.76 |
| $X_{n-m}$ | 154.53 | 159.09 | 144.52 | 143.78 |
| Adjusted mean | 156.53 | 162.16 | 146.75 | 147.27 |
| $S_n$ | 58.66 | 66.19 | 59.21 | 61.10 |
| $S_{n-m}$ | 49.61 | 57.81 | 53.61 | 50.47 |
| Adjusted Std. Deviation | 53.38 | 62.22 | 58.02 | 54.99 |
| $K_m$ | 13.3 | 13.1 | 13.8 | 13.7 |
| Unadjusted PMP | 866.48 | 977.24 | 947.43 | 900.63 |
| PMP | 990.39 | 1116.99 | 1082.91 | 1029.42 |

During the period 1896-2000 (105 years) considering the sample size to be 50, the maximum daily rainfall varies from 330.4 to 394.4mm. After adjusting for maximum observed event and sample size, the adjusted mean varies from 146.75 to 162.16mm. Similarly, the adjusted standard deviation varies from 53.38 to 62.22mm. In this case, the range of standard deviation is small because all maximum observed events are identical. $K_m$ varies from 13.1 to 13.8. The adjusted PMP varies from 990 to 1117mm, which is closer to previous analysis. In this study, both upper and lower PMP were obtained for one particular maximum daily rainfall while showing an 11% deviation.

# CHAPTER EIGHT

## RESULTS AND DISCUSSION

### 8.1 Introduction

This chapter presents the discussion on storm maximization and Hershfield's statistical method of the study. In formulation of the discussion, outcomes of the analysis of Literature survey, Meteorological data collection and data analysis were considered. Comparison of storm maximization and statistical analysis is also presented herein. Presentation of main findings was made and next followed by conclusions drawn from this chapter.

### 8.2 Discussion on Storm Maximization



The heavy precipitation in Anuradhapura generally occurs in December – February period during the N-E monsoon, with December usually being the month with the heaviest precipitation. In Ratnapura, the maximum precipitation occurs during S-W monsoon season, which lasts from May to September and usually the months of May / June shows the maximum amount.

Inspection of the series of rainfall values revealed that there is a seasonal variation of rainfall for Anuradhapura, which is in the dry zone, and for Ratnapura, which is in the wet zone. When calculating the precipitable water, the use of dew point temperature from the months that yield heavy precipitation is effective due to the seasonal variation of precipitation.

The source of uncertainty in determining moisture maximization factor is the difficulty of getting the dew point temperatures. Due to the non-availability of published daily dew point temperature values, wet bulb temperature values were used to calculate maximum persisting dew point temperature.

Riddell (1980) considered the maximum dew point temperatures for each month of the year when selecting the maximum persisting value. However, in that study, there was no seasonal variation in rainfall. Considering the above factors, the monthly average dew point data were taken according to the month that yields heavy precipitation. During 1951-2000, the maximum monthly average dew point data for Anuradhapura (in December) and Ratnapura (in June) recorded were 24.1 $^{0}$C and 24.9 $^{o}$C respectively. However, in this study the maximum 24-hour persisting dew point temperature (wet bulb temperature) values are 26.2 and 27.0 $^{0}$C for Anuradhapura and Ratnapura respectively.

In Anuradhapura and Ratnapura, air temperature is greater than 21 $^{0}$C and wet bulb depression is nearly 1 $^{0}$C. Hence, according to psychrometric tables wet bulb temperature is close to dew point temperature. This shows that the substitution of wet bulb temperature does not affect the final result much.

The sea surface temperature (SST), which is a representation of atmospheric moisture, is also used to obtain precipitable water. No firm relationship has been developed between persisting dew point temperature in the locations and SST. However, it can be considered that the persisting dew point temperature is 2 $^{0}$C lower than the SST. Thus, the persisting dew point temperatures are 26.2 and 26.1$^{0}$C for Anuradhapura and Ratnapura in respective months.



The resulting moisture maximization factor for Anuradhapura and Ratnapura were 1.5 and 1.09 respectively. In this study, the observed dew point at Ratnapura was close to the maximum dew point, resulting in a lesser value for the moisture maximization factor. The maximum persisting dew point temperatures are almost same for both wet and dry zones and hence the MMF greatly depends on the observed dew point. Generally the dew point in dry zone is lower than the dew point in wet zone, resulting MMF is higher in Dry Zone.

Generally, wind maximization factor (WMF) is not computed in storm maximization in non-orographic regions. As WMO (1986) pointed out, WMF can be used when the results are inadequate. WMF is affected by daily wind run and maximum of that. The magnitude of the maximum daily wind run is same through out the island. Hence, daily wind run during the storm is critical. In this study, Anurdapura wind speed being higher than Ratnapura may be due to the location of Anuradhapura, which is in a cyclone prone area. Therefore, in these areas WMF is lower than the rest of the country.

The difficulties in determining the wind maximization are the lack of wind run data available and finding the critical wind direction. In Ratnapura, only 7 years of wind run data was available to find maximum daily wind run. This will affect the final result. The critical wind direction is taken by considering the monsoon system and the direction of wind on the day that the maximum storm occurred.

## 8.3 Discussion on Statistical Analysis

Statistical estimates of PMP were made by dividing the sample into groups of 20, 30 and 50 sizes. According to the sample size, the range of PMP can be list down in Table 8.1.

Table 8.1 – Summary of Statistical Analysis in Anuradhapura



| | Adjusted mean | | Adjusted std. dev. | | $K_m$ | PMP | |
|---|---|---|---|---|---|---|---|
| Sample size | Lower | Upper | Lower | Upper | | Lower | Upper |
| 20 | 96 | 110 | 26 | 34 | 15.3 | 565 | 714 |
| 30 | 97 | 110 | 28 | 33 | 16.3 | 630 | 685 |
| 50 | 98 | 107 | 28 | 30 | 15.2 | 603 | 625 |

The PMP in 20-year sample size shows a high range of values when compared with 30 and 50 sample sizes. Just because the maximum daily rainfall is high in one particular period, it does not mean that PMP should be high in the same period. This is clearly shown in 50-year sample size analysis (Table 7.8). On the other hand, the amount of the maximum daily rainfall does not directly affect the result of PMP, because of the adjustments of mean and standard deviation.

The lower values of the adjusted mean increase with increasing sample sizes but the upper values are reduced, thus reducing the range of adjusted mean. A similar theory is applied for the adjusted standard deviation also.

Hershfield (1961) found that in many worldwide precipitation analyses, the frequency factor did not exceed the value of 15. However, in Anuradhapura, most K values exceed 15. In addition, there are two K values, which exceed 16. These high K values are mainly due to low mean rainfall.

For Anuradhapura, the lowest PMP is 600mm and the upper limit is 625mm.

Table 8.2 – Summary of statistical Analysis in Ratnapura

| | Adjusted mean | | Adjusted std.dev. | | $K_m$ | PMP | |
|---|---|---|---|---|---|---|---|
| Sample size | Lower | Upper | Lower | Upper | | Lower | Upper |
| 20 | 146 | 166 | 43 | 85 | 13.8 | 842 | 1470 |
| 30 | 142 | 177 | 39 | 73 | 13.9 | 787 | 1259 |
| 50 | 147 | 162 | 53 | 62 | 13.8 | 990 | 1117 |

The lower value of the adjusted mean in 30-year sample size decreases with respect to 20-year sample size. During 1901-1920 the adjusted mean was 146 but 1901-1930 period the mean was increased 152mm. However, during 1961-1980 period the adjusted mean was 153 and 1951-1980 it was reduced up to 142. Generally, the sample size increases, the lower mean value increases too. That basic did not apply for 1951-1980 period, due to less rain during 1951-1960.



The range of standard deviation is also high when compared with other values. The frequency factor, K was 13.9 in Ratnapura that is not exceeded by 15. In 50-year sample size, both upper and lower PMP were obtained for one particular maximum daily rainfall. For the same rainfall, PMP was high as 1259 in 30-year sample size. Therefore for Ratnapura, the upper limit of PMP is taken as 1117mm while the lower limit of PMP is 990mm.

In Sri Lanka, usually rainfall data are recorded at fixed time intervals (8.30 am, 5.30pm). When considering daily rainfall data, values are taken from one day at 8.30 am to the next day at 8.30 am. But there may be some occasions where the maximum rainfall has occurred over a two day period. In that case, the observed values are lesser than the true values. To overcome the above problem, the conversion factors are found by using

Weiss(1964) Probability Model. Weiss conveys that the conversion factor of true to observational amount for any time interval of same length to be 1.143.

When considering the variation of the most significant storm in Anuradhapura as stated in Table 6.4 was 219.71 mm from 25.12.1957 at 0830 hours to 26.12.1957 at 0830 hours. However, the true 24-hour maximum value was 319.53mm. This shows a factor of 1.454 as true to fixed ratio. Similarly, (Table 6.5) in Ratnapura the observed 24-hour rainfall was 392.5mm from 08.06.1996 at 0900 hours to 09.06.1996 at 0900 hours. However, true 24-hour maximum rainfall was 393.5mm.

The introduction of true to fixed observational factor was not included in WMO manual (1986). But Varshney(1979) reveals that the adjustment of true to fixed observation affects the final result of PMP. Hence, this adjustment should be introduced in the estimation of PMP by storm maximization also.

If the conversion factor (Weiss, 1964) is included and applied in the storm maximization, then the revised estimates of PMP will be 490mm and 1174mm for Anuradhapura and Ratnapura respectively. With the application of true 24-hour maximum rainfall values, the PMP obtained by storm maximization increases up to 623mm and 1027mm respectively. Therefore, if true maximum values are considered in the analysis, the estimates of PMP obtained by both methods will agree well.



### 8.4 Comparison of Storm Maximization and Statistical Analysis

The following table compares the results of PMP in Anuradhapura and Ratnapura.

Table8.3 – Comparison of PMP in Anuradhapura and Ratnapura

| Station | Storm Maximization | | Statistical Analysis | |
|---|---|---|---|---|
| | With fixed rainfall | With true rainfall | Lower | Upper |
| Anuradhapura | 425 | 623 | 600 | 625 |
| Ratnapura | 1027 | 1027 | 990 | 1117 |

In Anuradhapura, lower and upper values in statistical analysis of PMP show a remarkable degree of consistency but PMP in storm maximization with fixed rainfall shows a deviation of 32%. Generally, storm maximization values are lower than statistical analysis values. Ridell (1980) has pointed out that the storm maximization gives 25-35% lower results than statistical estimate. Hence, this 32% reduction agrees well with the above percentage. If true maximum value of rainfall is used, the result is almost identical.

In Ratnapura, the range of lower to upper values of PMP in statistical analysis is higher than the range calculated in Anuradhapura. However, this shows a deviation of 13%. The result of storm maximization shows a remarkable degree of consistency with statistical analysis results.

### 8.5 Main Findings

- There is a seasonal variation of rainfall in both dry zone and wet zone in Sri Lanka. PMP for Anuradhapura is high in N-E monsoon but for Ratnapura high values are given in S-W monsoon. Piper (1994) conveys that PMP in Victoria project, which is in the central highlands of Sri Lanka, is seasonal. However, it can occur in any month of the wet season and in addition, those values should be higher than that during the rest of the year.
- The 24-hour persisting dew point temperature at the relevant locations is 2 $^{0}C$ lower than sea surface temperature at offshore.
- The highest 24-hour persisting dew point temperature representing the month of December in Anuradhapura and of June in Ratnapura are 26.2 $^{0}C$ and 26.1 $^{0}C$ respectively. This shows the above temperature is almost same for different locations in monsoon seasons of the island.
- The moisture maximization factor greatly depends on the observed dew point, because of the same magnitude of the maximum persisting dew point through out the island. Therefore, MMF is higher in dry zone than in wet zone.
- Wind maximization factor is low in cyclonic prone areas because the maximum wind run is in same magnitude through out the country.
- In Anuradhapura, during NE monsoon, the wind direction is mainly (about 65%) from NE. But in certain cases such as during cyclones, the moisture comes from

NW direction also. Hence, in determining the critical wind direction, NE to NW quadrant should be considered.

- Although, the ratio of true to fixed observational unit is not included in WMO manual, the adjustment should be introduced in storm maximization.
- Though the factor given by Weiss (1964) is 1.143 for any time interval of same length, this factor has increased up to 1.454 in Anuradhapura. However, in Ratnapura, the factor is 1.0. Therefore, it is better to consider this aspect when calculating PMP.
- For dry zone area, the value of frequency factor can be taken as greater than 15. The same for wet zone is less than 15. The substitution of 15 as the frequency factor may yield higher results for wet zone. Therefore, more work is needed in this area.
- When considering storm maximization, the point PMP is 425 mm and 1025 mm for Anuradhapura and Ratnapura respectively.
- In Hershfield's statistical analysis, the PMP in Anuradhapura is 625 mm while in Ratnapura it is 1100 mm.
- The storm maximization method gives estimate, which is 32% lower than that obtained by calculation of PMP using statistical method for Anuradhapura. However, for Ratnapura both estimates are in same magnitude due to high wind maximization factor.
- When true values of rainfall are used to calculate PMP, both estimates yield comparable results at the two stations. (Table 8.3)

# CHAPTER NINE

## CONCLUSIONS

### 9.1 Main Conclusions

The following main conclusions can be drawn from this research:

a) The PMP values for Anuradhapura and Ratnapura using the method of storm maximization are 425mm and 1025mm. The corresponding results obtained by the statistical method are 625mm and 1120mm.

b) The value of PMP estimated by the storm maximization is about 32% lower than that given by the statistical analysis for Anuradhapura.

c) If true rainfall values are considered in storm maximization, PMP values increase up to 623mm and 1027mm for Anuradhapura and Ratnapura respectively and this shows almost identical results for both methods, which is certainly noteworthy.

d) The ratio of true to fixed observational unit should be used in the storm maximization method, if true rainfall data is not available to get maximum rainfall.



e) The value of 1.143 of the above ratio for any time interval of same length was exceeded in one observed storm. Hence, it can be tentatively concluded that the value should be increased.

f) Incorporating only the moisture maximization factor is inadequate for the estimation of PMP. The estimated values do not agree with the statistical method because the wind also brings moisture for different locations in the island.

g) Inaccuracies in estimating the wind maximization ratio may be attributed to insufficient wind records, incorrect direction of critical wind direction, and wind velocity.

h) For Anuradhapura and Ratnapura, the maximum 24-hour persisting dew-point temperatures were 26.2 and 26.1°C respectively. This temperature could be a representative figure for much of the island.

i) The frequency factor in the statistical analysis varied from 13.9 in wet zone to15.3 in dry zone.

j) Results on PMP do not warrant replacement of storm maximization method by Hershfield's statistical method. For major structures involving minimum risk of failure and economics, a comparison of the results would be appropriate.

## 9.2 Recommendations for Further Research

The following recommendations for further research will be of considerable usefulness:

a) The frequency factor in the statistical analysis should be studied further in order to identify the values clearly for dry zone and wet zone.
b) The relationship between sea surface temperature and the maximum 24-hour persisting dew-point temperature should be identified to get the dew-point temperature easily.
c) The true to fixed ratio should be analysed in depth, thus, the maximum 24-hour rainfall could be calculated from fixed observational rainfall.

## LIST OF REFERENCES


1. American Meteorological Society as quoted in Wiesner, C. J., (1970), ***Hydrometeorology,*** Chapman and Hall Ltd., London
2. Arumugam, S., (2003), "Water for people and nature", in Arumugam Commemoration Volume, ***Sri Lanka water Heritage***, History of water Conservation, Volume 2, Vishva Lekha publication, Sri Lanka.
3. Benson, M. A., " Thoughts on the Design of Design Floods" in the proceedings of the Second International Symposium in Hydrology, (1973), ***Floods and Droughts,*** Water resources Publications, Fort Collins, Colorado, U.S.A., pp 27-33
4. Department of Meteorology, (1974), ***Annual Report for 1974***
5. Fernando, S., (2002), ***Wind Resources Assessment in the Puttalam region, Knuckles Range and Ambewela***, Consultancy Report for Ceylon Electricity Board.
6. Gilman, C. S., "Rainfall" in Chow, V. T. (ed.), (1964), ***Handbook of Applied Hydrology,*** McGraw Hill, New York
7. Hershfield, D. M., (1961), ***Estimating the Probable Maximum Precipitation***, Proceedings American Society of Civil Engineers, Journal Hydraulics Division, Vol.87, pp 99-106
8. Hershfield, D. M., (1965), ***Method for Estimating the Probable Maximum Precipitation,*** Journal American Waterworks Association, Vol.57, pp 965-972
9. Jowett, I. G., (1979), ***Clutha Flood of October 1978***, Journal of Hydrology, Vol.18, No. 2, pp 121-140
10. Koutsoyiannis, N., (1999), ***A Probabilistic View of Hershfield's Method for Estimating Probable Maximum Precipitation,*** Water Resources Research, Vol. 35, No. 4, pp 1313 - 1322
11. Malmgren, B. A., et.al., (2003), ***Precipitation trends in Sri Lanka since the 1870s and relationships to El Nino Southern Oscillation,*** International Journal of Climatology, 23, pp 1235-1252
12. Miller, J.F., (1973), "Probable Maximum Precipitation – The Concept, Current Procedures and Outlook", in the Proceedings of the Second International Symposium in Hydrology, ***Floods and Droughts***, Water Resources Publications, Fort Collins, Colorado, U.S.A, pp 50-61

13 Mutreja, L.N. (1986), ***Applied Hydrology***, Tata McGraw Hill Publishing Company Limited, New Delhi.

14 Nakagawa, N. et. al., "Long-term Hydrometeorological data in Sri Lanka" in the data book of ***Hydrological cycle in humid tropical ecosystems,*** Part I

15 Piper, B.S. et al., (1994), ***The Victoria Project, Sri Lanka Hydrological Analysis for Victoria Dam,*** Proc. Institution of Civil Engineers, Water, Maritime and Energy, 106, March, pp 43-52

16 Rezacova, D., et,al.,(1999), ***Estimation of Probable Maximum Precipitation over the catchments in the Czech Republic,*** Abstract in Proc. 4th European Conference on Applications of Meteorology (ECAM), 228-229

17 Riddell, D. C., (1980), ***Flood Hydrology of the Motu River***, Journal of Hydrology (N.Z.), Vol.19, No. 1, pp 35-48

18 Sirinanda, K. U., "Rainfall Variability Patterns and Agricultural Production in Sri Lanka" in Yoshino, M. M. (ed.), (1983), ***Climate, Water and Agriculture in Sri Lanka,*** Ibarak, Japan, pp 83 - 110

19 Solak, M. E., et.al.,(2000), ***Innovative design approaches for the South Platte Reservoir,*** Association of State Dam Safety Officials, West Region Annual Conference, Portland, Oregon. http://www.nawcinc.com/splatte.pdf.

20 Somasekeram, T., et.al., (1997), ***Arjuna's Atlas of Sri Lanka***, Arjuna Consulting Co. Ltd., Sri Lanka

21 Svensson, C., and Rakhecha, P. R., (1998), ***Estimation of Probable Maximum Precipitation for Dams in the Hongru River Catchment, China***. Theoretical and Applied Climatology, 59, pp 79-91

22 Tingsanchali, T. and Taesombut, V. (2001), ***Probable Maximum Flood for Pantabangan Dam in the Philippines,*** Water Resources Journal, June.

23 U. S. Corps of Engineers as quoted in Varshney, R. S., (1979), ***Engineering Hydrology***, New Chand & Bros. Roorkee (U. P.)

24 Varshney, R. S., (1979), ***Engineering Hydrology***, New Chand and Bros., Roorkee (U.P.)

25 Weiss, L. L., (1964), ***Ratio of true to fixed interval maximum rainfall,*** Proceedings of the American Society of Civil Engineers, Journal Hydraulics Division, Vol. 90

26 Wiesner, C. J. (1970), ***Hydrometeorology,*** Chapman and Hall Ltd., London

27 World Meteorological Organization, (1969), ***Estimation of Maximum Floods***, WMO – No. 233, TP.126, Technical Note No. 98, pp83-116

28 World Meteorological Organization (1986), ***Manual for Estimation of Probable Maximum Precipitation,*** Operational Hydrology, Rep. 1 (WMO No. 332), 2d ed., Geneva, Switzerland

29 WMO, Guide to hydrological practices as quoted in Chow, V. T. et al., (1988), ***Applied Hydrology,*** McGraw Hill, New York

30 Yoshino, M. M., "Wind and its Effects on Air Temperature, Humidity and Rainfall in Sri Lanka" in Yoshino, M. M. (ed.), (1983), ***Climate, Water and Agriculture in Sri Lanka,*** Ibarak, Japan, pp 181 - 190

## ANNEX 1

Table A.1.1 – Precipitable water (mm) between 1000 mb surface and indicated pressure (mb) in a saturated pseudo-adiabatic atmosphere as a function of the 1000mb dew point

| | 1000mb dew point temperature (°C) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Press: (mb)** | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| **990** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **980** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| **970** | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| **960** | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| **950** | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 |
| **940** | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 |
| **930** | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 |
| **920** | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 |
| **910** | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 |
| **900** | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 |
| **890** | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 |
| **880** | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 | 12 |
| **870** | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 | 12 | 13 |
| **860** | 4 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 12 | 13 |
| **850** | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 11 | 12 | 13 | 14 |
| **840** | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 |
| **830** | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| **820** | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 15 | 17 |
| **810** | 5 | 6 | 6 | 7 | 8 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| **800** | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 12 | 13 | 15 | 16 | 17 | 18 |
| **790** | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 |
| **780** | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 |
| **770** | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 |
| **760** | 6 | 7 | 7 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 19 | 21 |
| **750** | 6 | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 |
| **740** | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 22 |
| **730** | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 |
| **720** | 7 | 7 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 15 | 16 | 17 | 18 | 20 | 22 | 23 |
| **710** | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 22 | 24 |
| **700** | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 24 |
| **690** | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 25 |
| **680** | 7 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 20 | 22 | 24 | 25 |
| **670** | 7 | 8 | 9 | 10 | 11 | 11 | 12 | 14 | 15 | 16 | 17 | 19 | 20 | 22 | 24 | 26 |
| **660** | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 24 | 26 |
| **650** | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 |
| **640** | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 25 | 27 |
| **630** | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 20 | 22 | 24 | 26 | 28 |
| **620** | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 |
| **610** | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 |
| **600** | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 29 |
| **590** | 8 | 9 | 10 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 29 |
| **580** | 8 | 9 | 10 | 11 | 11 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 |
| **570** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 20 | 21 | 23 | 25 | 27 | 30 |
| **560** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 26 | 28 | 30 |
| **550** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
| **540** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 31 |
| **530** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 31 |
| **520** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 29 | 31 |
| **510** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 29 | 31 |
| **500** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 27 | 29 | 32 |
| **490** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 22 | 25 | 27 | 29 | 32 |
| **480** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 32 |
| **470** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 32 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **460** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 32 |
| **450** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 32 |
| **440** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **430** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **420** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **410** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **400** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **390** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **380** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **370** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **360** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **350** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **340** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **330** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **320** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **310** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **300** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **290** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **280** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **270** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **260** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **250** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **240** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **230** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **220** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **210** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **200** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |



| **mb** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** | **27** | **28** | **29** | **30** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **990** | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **980** | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| **970** | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 7 | 8 |
| **960** | 4 | 5 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 |
| **950** | 6 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 10 | 11 | 12 | 12 | 13 |
| **940** | 7 | 7 | 7 | 8 | 9 | 9 | 10 | 10 | 11 | 12 | 12 | 13 | 14 | 15 | 16 |
| **930** | 8 | 8 | 9 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 14 | 15 | 16 | 17 | 18 |
| **920** | 9 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 14 | 15 | 16 | 17 | 19 | 20 | 21 |
| **910** | 10 | 10 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 | 22 | 23 |
| **900** | 11 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 22 | 23 | 24 | 26 |
| **890** | 12 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 | 22 | 24 | 25 | 27 | 28 |
| **880** | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 21 | 23 | 24 | 26 | 27 | 29 | 30 |
| **870** | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 29 | 31 | 33 |
| **860** | 14 | 15 | 16 | 18 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 36 |
| **850** | 15 | 16 | 18 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 |
| **840** | 16 | 17 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 |
| **830** | 17 | 18 | 19 | 21 | 22 | 24 | 26 | 27 | 29 | 31 | 33 | 35 | 38 | 40 | 43 |
| **820** | 18 | 19 | 20 | 22 | 24 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 40 | 42 | 43 |
| **810** | 19 | 20 | 21 | 23 | 25 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 44 | 47 |
| **800** | 19 | 21 | 22 | 24 | 26 | 28 | 29 | 32 | 34 | 36 | 38 | 41 | 44 | 46 | 49 |
| **790** | 20 | 22 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 38 | 40 | 43 | 46 | 49 | 52 |
| **780** | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 45 | 48 | 51 | 54 |
| **770** | 22 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 38 | 41 | 43 | 46 | 49 | 53 | 56 |
| **760** | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 45 | 48 | 51 | 55 | 58 |
| **750** | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 38 | 41 | 44 | 47 | 50 | 53 | 57 | 60 |
| **740** | 24 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 45 | 48 | 51 | 55 | 59 | 62 |
| **730** | 24 | 26 | 28 | 30 | 33 | 35 | 38 | 40 | 43 | 46 | 50 | 53 | 57 | 60 | 64 |
| **720** | 25 | 27 | 29 | 31 | 34 | 36 | 39 | 42 | 45 | 47 | 51 | 55 | 58 | 62 | 65 |
| **710** | 26 | 28 | 30 | 32 | 36 | 37 | 40 | 43 | 46 | 49 | 53 | 56 | 60 | 64 | 68 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **700** | 26 | 28 | 31 | 33 | 35 | 38 | 41 | 44 | 47 | 50 | 54 | 58 | 62 | 66 | 72 |
| **690** | 27 | 29 | 31 | 34 | 36 | 39 | 42 | 45 | 48 | 52 | 55 | 59 | 63 | 68 | 72 |
| **680** | 27 | 30 | 32 | 34 | 37 | 40 | 43 | 46 | 49 | 53 | 57 | 61 | 65 | 69 | 74 |
| **670** | 28 | 30 | 33 | 35 | 38 | 41 | 44 | 47 | 51 | 54 | 58 | 62 | 67 | 71 | 76 |
| **660** | 29 | 31 | 33 | 36 | 39 | 42 | 45 | 48 | 52 | 55 | 60 | 64 | 68 | 73 | 78 |
| **650** | 29 | 31 | 34 | 37 | 39 | 42 | 46 | 49 | 53 | 57 | 61 | 65 | 70 | 75 | 80 |
| **640** | 29 | 32 | 35 | 37 | 40 | 43 | 46 | 50 | 54 | 58 | 62 | 67 | 71 | 76 | 81 |
| **630** | 30 | 32 | 35 | 38 | 41 | 44 | 47 | 51 | 55 | 59 | 63 | 68 | 73 | 78 | 83 |
| **620** | 30 | 33 | 36 | 38 | 42 | 45 | 48 | 52 | 56 | 60 | 65 | 69 | 74 | 79 | 85 |
| **610** | 31 | 33 | 36 | 39 | 42 | 45 | 49 | 53 | 57 | 61 | 66 | 71 | 76 | 81 | 87 |
| **600** | 31 | 34 | 37 | 40 | 43 | 46 | 50 | 56 | 58 | 62 | 67 | 72 | 77 | 82 | 88 |
| **590** | 32 | 34 | 37 | 40 | 43 | 47 | 51 | 55 | 59 | 63 | 68 | 73 | 78 | 84 | 90 |
| **580** | 32 | 35 | 38 | 41 | 44 | 48 | 51 | 55 | 60 | 64 | 69 | 74 | 80 | 85 | 91 |
| **570** | 32 | 35 | 38 | 41 | 45 | 48 | 52 | 56 | 61 | 65 | 70 | 75 | 81 | 87 | 91 |
| **560** | 33 | 36 | 39 | 42 | 45 | 49 | 53 | 57 | 61 | 66 | 71 | 77 | 82 | 88 | 94 |
| **550** | 33 | 36 | 39 | 42 | 46 | 49 | 53 | 58 | 62 | 67 | 72 | 78 | 83 | 90 | 96 |
| **540** | 33 | 36 | 39 | 43 | 46 | 50 | 54 | 58 | 63 | 68 | 73 | 79 | 85 | 91 | 97 |
| **530** | 34 | 37 | 40 | 43 | 47 | 50 | 55 | 59 | 64 | 69 | 74 | 80 | 86 | 92 | 99 |
| **520** | 34 | 37 | 40 | 43 | 47 | 51 | 55 | 60 | 64 | 70 | 75 | 81 | 82 | 93 | 100 |
| **510** | 34 | 37 | 40 | 44 | 48 | 51 | 56 | 60 | 65 | 70 | 76 | 82 | 88 | 95 | 102 |
| **500** | 34 | 37 | 41 | 44 | 48 | 52 | 56 | 61 | 66 | 71 | 77 | 83 | 89 | 96 | 103 |
| **490** | 35 | 38 | 41 | 45 | 48 | 52 | 57 | 61 | 66 | 72 | 78 | 84 | 90 | 97 | 104 |
| **480** | 35 | 38 | 41 | 45 | 49 | 53 | 57 | 62 | 67 | 73 | 79 | 85 | 91 | 98 | 105 |
| **470** | 35 | 38 | 42 | 45 | 49 | 53 | 58 | 62 | 68 | 73 | 79 | 85 | 92 | 99 | 106 |
| **460** | 35 | 38 | 42 | 45 | 49 | 54 | 58 | 63 | 69 | 74 | 80 | 84 | 93 | 100 | 108 |
| **450** | 35 | 39 | 42 | 46 | 50 | 54 | 58 | 63 | 69 | 74 | 81 | 87 | 94 | 101 | 109 |
| **440** | 35 | 39 | 42 | 46 | 50 | 54 | 59 | 64 | 69 | 75 | 81 | 88 | 95 | 102 | 110 |
| **430** | 36 | 39 | 42 | 46 | 50 | 55 | 59 | 64 | 70 | 76 | 82 | 88 | 96 | 103 | 111 |
| **420** | 36 | 39 | 43 | 46 | 50 | 55 | 60 | 65 | 70 | 76 | 82 | 89 | 96 | 104 | 112 |
| **410** | 36 | 39 | 43 | 47 | 51 | 55 | 60 | 65 | 71 | 77 | 83 | 90 | 97 | 105 | 113 |
| **400** | 36 | 39 | 43 | 47 | 51 | 55 | 60 | 65 | 71 | 77 | 84 | 90 | 98 | 105 | 114 |
| **390** | 36 | 39 | 43 | 47 | 51 | 56 | 60 | 66 | 71 | 77 | 84 | 91 | 98 | 106 | 115 |
| **380** | 36 | 39 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 78 | 85 | 92 | 99 | 107 | 115 |
| **370** | 36 | 40 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 78 | 85 | 92 | 100 | 108 | 116 |
| **360** | 36 | 40 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 79 | 86 | 93 | 100 | 108 | 117 |
| **350** | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 73 | 79 | 86 | 93 | 101 | 109 | 118 |
| **340** | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 73 | 79 | 86 | 93 | 101 | 109 | 118 |
| **330** | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 73 | 79 | 86 | 94 | 102 | 110 | 119 |
| **320** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 67 | 73 | 80 | 87 | 94 | 102 | 111 | 120 |
| **310** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 67 | 73 | 80 | 87 | 94 | 102 | 111 | 120 |
| **300** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 67 | 74 | 80 | 87 | 95 | 102 | 111 | 121 |
| **290** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 80 | 87 | 95 | 103 | 112 | 121 |
| **280** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 80 | 88 | 96 | 103 | 113 | 121 |
| **270** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 122 |
| **260** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 122 |
| **250** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 122 |
| **240** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 123 |
| **230** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 123 |
| **220** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 123 |
| **210** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 105 | 114 | 123 |
| **200** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 105 | 114 | 123 |



*Source: WMO (1986)*

Table A.1.2 – Precipitable water (mm) between 1000mb surface and indicated height (m) above that surface in a saturated pseudo-adiabatic atmosphere as a function of the 1000mb dew point (°C)

| Height (m) | 1000mb temperature (°C) | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **0** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** |
| **200** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| **400** | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 |
| **600** | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 6 | 7 | 7 |
| **800** | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 |
| **1000** | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 10 | 11 |
| **1200** | 4 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 | 11 | 12 | 13 |
| **1400** | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 |
| **1600** | 5 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 15 | 16 |
| **1800** | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 12 | 13 | 14 | 15 | 17 | 18 |
| **2000** | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 |
| **2200** | 7 | 7 | 8 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 |
| **2400** | 7 | 8 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 22 |
| **2600** | 7 | 8 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 20 | 21 | 23 |
| **2800** | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 22 | 24 |
| **3000** | 8 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 25 |
| **3200** | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 23 | 24 | 26 |
| **3400** | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 24 | 26 |
| **3600** | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 23 | 25 | 27 |
| **3800** | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 |
| **4000** | 8 | 9 | 10 | 11 | 11 | 12 | 14 | 15 | 16 | 17 | 19 | 21 | 22 | 24 | 26 | 28 |
| **4200** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 29 |
| **4400** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 20 | 21 | 23 | 25 | 27 | 29 |
| **4600** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 25 | 28 | 30 |
| **4800** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
| **5000** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 | 30 |
| **5200** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 29 | 31 |
| **5400** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 29 | 31 |
| **5600** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 22 | 24 | 27 | 29 | 32 |
| **5800** | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 22 | 25 | 27 | 29 | 32 |
| **6000** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 32 |
| **6200** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 32 |
| **6400** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **6600** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **6800** | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| **7000** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **7200** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **7400** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **7600** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **7800** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| **8000** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 30 | 33 |
| **8200** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 30 | 33 |
| **8400** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 30 | 33 |
| **8600** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 30 | 33 |
| **8800** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 30 | 33 |
| **9000** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 31 | 33 |
| **9200** | 8 | 9 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 31 | 33 |
| **9400** | | | | | | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 31 | 33 |
| **9600** | | | | | | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 31 | 33 |
| **9800** | | | | | | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 31 | 33 |
| **10000** | | | | | | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 26 | 28 | 31 | 33 |
| **11000** | | | | | | | | | | | 21 | 23 | 26 | 28 | 31 | 33 |
| **12000** | | | | | | | | | | | | | | | | 33 |

| Height (m) | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **200** | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 |
| **400** | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 10 | 11 | 12 |
| **600** | 7 | 8 | 8 | 9 | 10 | 10 | 11 | 11 | 12 | 13 | 14 | 15 | 15 | 16 | 17 |
| **800** | 10 | 10 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| **1000** | 12 | 13 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 | 22 | 23 | 25 | 26 | 28 |
| **1200** | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 23 | 24 | 26 | 27 | 29 | 31 | 32 |
| **1400** | 16 | 17 | 18 | 19 | 20 | 22 | 23 | 24 | 26 | 28 | 29 | 31 | 33 | 35 | 37 |
| **1600** | 17 | 19 | 20 | 21 | 23 | 24 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 |
| **1800** | 19 | 20 | 22 | 23 | 25 | 26 | 28 | 30 | 32 | 34 | 36 | 39 | 41 | 43 | 46 |
| **2000** | 21 | 22 | 24 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 42 | 44 | 47 | 50 |
| **2200** | 22 | 24 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 40 | 42 | 45 | 48 | 51 | 54 |
| **2400** | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 40 | 43 | 45 | 48 | 51 | 54 | 57 |
| **2600** | 24 | 26 | 28 | 30 | 32 | 33 | 37 | 40 | 42 | 43 | 48 | 51 | 55 | 58 | 61 |
| **2800** | 26 | 27 | 30 | 32 | 34 | 36 | 39 | 42 | 43 | 48 | 51 | 54 | 58 | 61 | 65 |
| **3000** | 27 | 29 | 31 | 33 | 35 | 38 | 41 | 44 | 47 | 50 | 53 | 57 | 61 | 64 | 68 |
| **3200** | 28 | 30 | 32 | 34 | 37 | 40 | 42 | 45 | 49 | 52 | 56 | 59 | 63 | 67 | 71 |
| **3400** | 29 | 31 | 33 | 36 | 38 | 41 | 44 | 47 | 51 | 54 | 58 | 62 | 66 | 70 | 74 |
| **3600** | 29 | 32 | 34 | 37 | 39 | 42 | 45 | 49 | 52 | 56 | 60 | 64 | 68 | 73 | 77 |
| **3800** | 30 | 32 | 35 | 38 | 41 | 44 | 47 | 50 | 54 | 58 | 62 | 65 | 70 | 75 | 80 |
| **4000** | 31 | 33 | 36 | 39 | 42 | 45 | 48 | 52 | 56 | 60 | 64 | 68 | 73 | 78 | 83 |
| **4200** | 32 | 34 | 37 | 40 | 43 | 46 | 49 | 53 | 57 | 61 | 65 | 70 | 75 | 80 | 85 |
| **4400** | 32 | 34 | 37 | 40 | 44 | 47 | 51 | 54 | 58 | 63 | 67 | 72 | 77 | 82 | 87 |
| **4600** | 32 | 35 | 38 | 41 | 44 | 48 | 52 | 56 | 60 | 64 | 69 | 74 | 79 | 84 | 90 |
| **4800** | 33 | 36 | 39 | 42 | 45 | 49 | 53 | 57 | 61 | 65 | 70 | 75 | 81 | 86 | 92 |
| **5000** | 33 | 36 | 39 | 42 | 46 | 50 | 54 | 58 | 62 | 67 | 72 | 77 | 82 | 88 | 94 |
| **5200** | 34 | 37 | 40 | 43 | 47 | 50 | 54 | 59 | 63 | 68 | 73 | 78 | 84 | 90 | 96 |
| **5400** | 34 | 37 | 40 | 44 | 47 | 51 | 55 | 60 | 64 | 69 | 74 | 80 | 85 | 92 | 98 |
| **5600** | 35 | 38 | 41 | 44 | 48 | 52 | 56 | 60 | 65 | 70 | 76 | 81 | 87 | 93 | 100 |
| **5800** | 35 | 38 | 41 | 45 | 48 | 52 | 57 | 61 | 65 | 71 | 77 | 82 | 88 | 95 | 101 |
| **6000** | 35 | 38 | 42 | 45 | 49 | 53 | 57 | 62 | 67 | 72 | 76 | 84 | 90 | 95 | 103 |
| **6200** | 35 | 38 | 42 | 45 | 49 | 54 | 58 | 63 | 68 | 73 | 79 | 85 | 91 | 93 | 104 |
| **6400** | 35 | 39 | 42 | 46 | 50 | 54 | 58 | 63 | 68 | 74 | 80 | 86 | 92 | 99 | 108 |
| **6600** | 36 | 39 | 42 | 46 | 50 | 54 | 59 | 64 | 69 | 74 | 80 | 87 | 93 | 100 | 107 |
| **6800** | 36 | 39 | 42 | 46 | 50 | 55 | 60 | 65 | 70 | 75 | 81 | 87 | 94 | 101 | 108 |
| **7000** | 36 | 39 | 43 | 46 | 50 | 55 | 60 | 65 | 70 | 76 | 82 | 88 | 95 | 102 | 110 |
| **7200** | 36 | 39 | 43 | 47 | 51 | 55 | 60 | 65 | 71 | 76 | 82 | 89 | 96 | 103 | 111 |
| **7400** | 36 | 39 | 43 | 47 | 51 | 56 | 61 | 66 | 71 | 77 | 83 | 90 | 97 | 104 | 112 |
| **7600** | 36 | 39 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 77 | 83 | 90 | 93 | 105 | 113 |
| **7800** | 36 | 39 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 78 | 84 | 91 | 98 | 106 | 114 |
| **8000** | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 72 | 78 | 85 | 92 | 99 | 107 | 115 |
| **8200** | 36 | 40 | 43 | 47 | 52 | 57 | 62 | 67 | 73 | 78 | 85 | 92 | 100 | 108 | 115 |
| **8400** | 36 | 40 | 43 | 47 | 52 | 57 | 62 | 67 | 73 | 79 | 65 | 92 | 100 | 108 | 116 |
| **8600** | 36 | 40 | 43 | 47 | 52 | 57 | 62 | 68 | 73 | 79 | 86 | 93 | 101 | 109 | 117 |
| **8800** | 36 | 40 | 43 | 47 | 52 | 57 | 62 | 68 | 73 | 79 | 86 | 93 | 101 | 109 | 118 |
| **9000** | 36 | 40 | 43 | 47 | 52 | 57 | 62 | 68 | 74 | 80 | 86 | 94 | 102 | 110 | 118 |
| **9200** | 36 | 40 | 43 | 48 | 52 | 57 | 62 | 63 | 74 | 80 | 87 | 94 | 102 | 110 | 119 |
| **9400** | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 80 | 87 | 94 | 102 | 110 | 119 |
| **9600** | 36 | 40 | 44 | 48 | 52 | 57 | 63 | 68 | 74 | 80 | 87 | 94 | 102 | 111 | 120 |
| **9800** | 36 | 40 | 44 | 48 | 52 | 57 | 63 | 68 | 74 | 80 | 87 | 95 | 103 | 111 | 120 |
| **10000** | 37 | 40 | 44 | 48 | 52 | 57 | 63 | 68 | 74 | 80 | 87 | 95 | 103 | 112 | 121 |
| **11000** | 37 | 40 | 44 | 48 | 52 | 57 | 63 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 122 |
| **12000** | 37 | 40 | 44 | 48 | 52 | 57 | 63 | 68 | 74 | 81 | 88 | 96 | 103 | 114 | 123 |
| **13000** | | | | | 52 | 57 | 63 | 68 | 74 | 81 | 88 | 97 | 105 | 114 | 124 |
| **14000** | | | | | 52 | 57 | 63 | 68 | 74 | 81 | 88 | 97 | 105 | 115 | 124 |
| **15000** | | | | | | | | | | 81 | 88 | 97 | 106 | 115 | 124 |
| **16000** | | | | | | | | | | 81 | 88 | 97 | 106 | 115 | 124 |

*Source: WMO (1986)*

## ANNEX 2

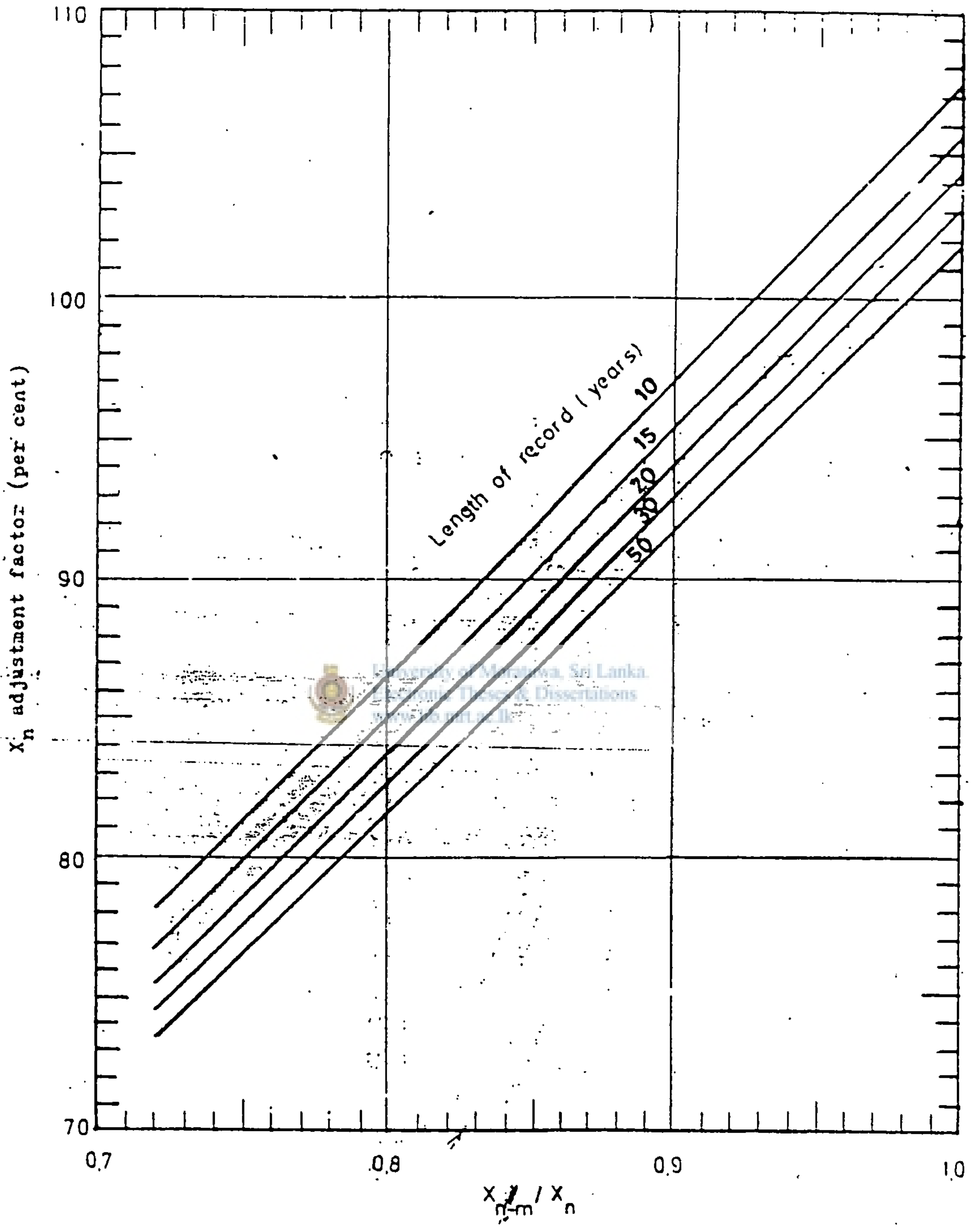



Figure A.2.1. – Adjustment of mean of annual series for maximum observed rainfall

*Source: WMO, 1986*

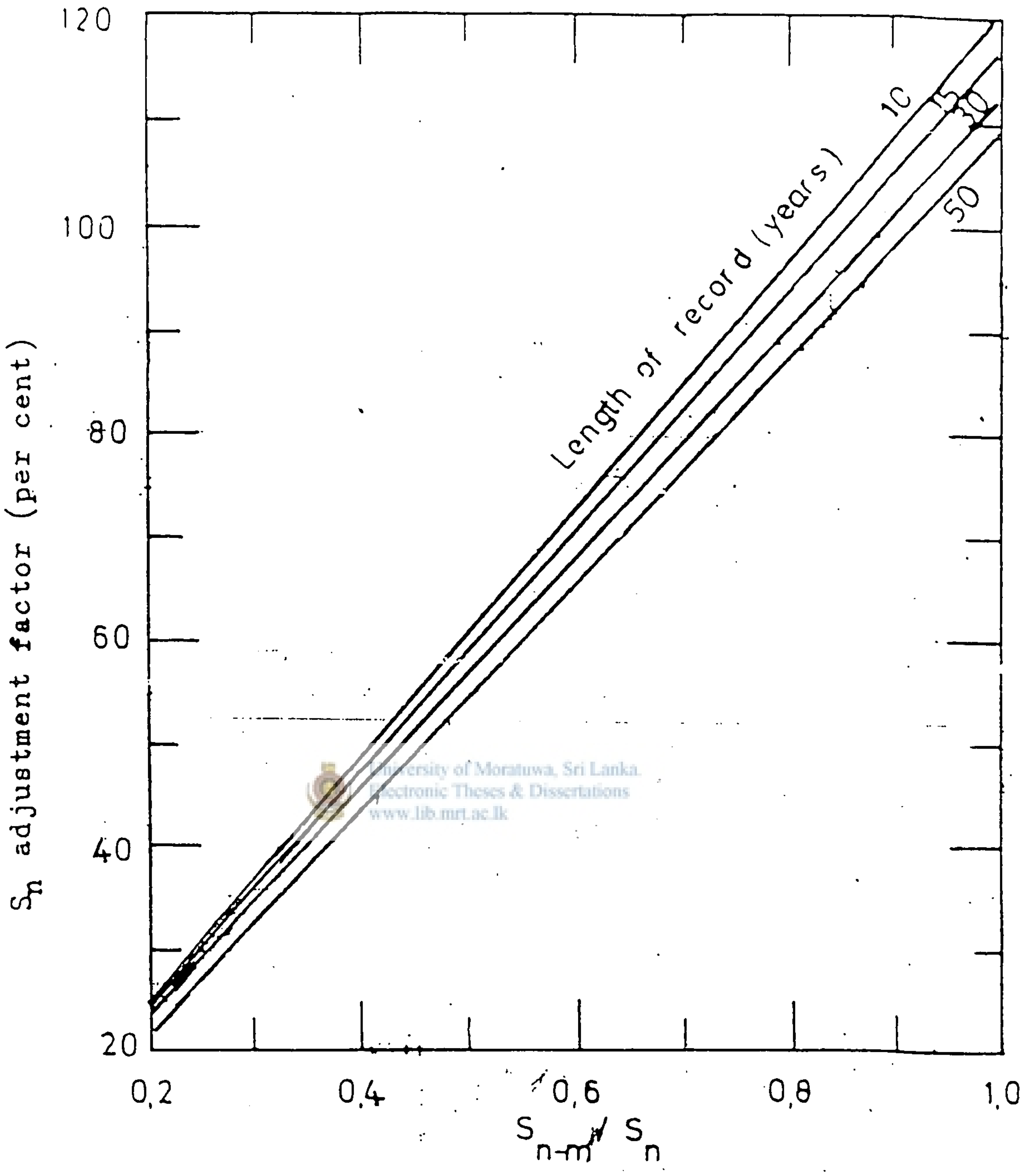





Figure A.2.2. – Adjustment of standard deviation of annual series for maximum observed rainfall

*Source: WMO, 1986*

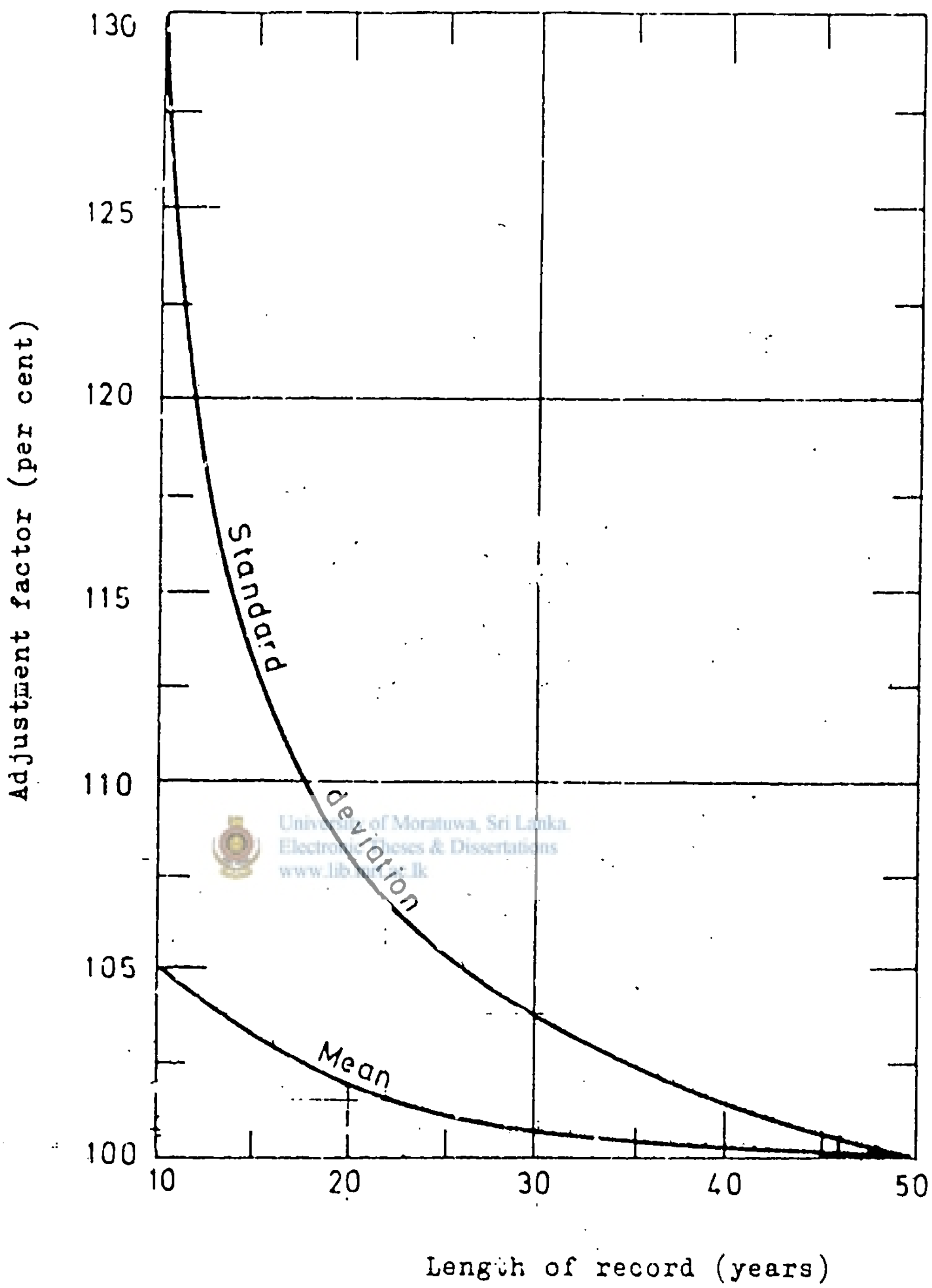



Figure A.2.3. – Adjustment of mean and standard deviation of annual series for length of record

*Source: WMO, 1986*

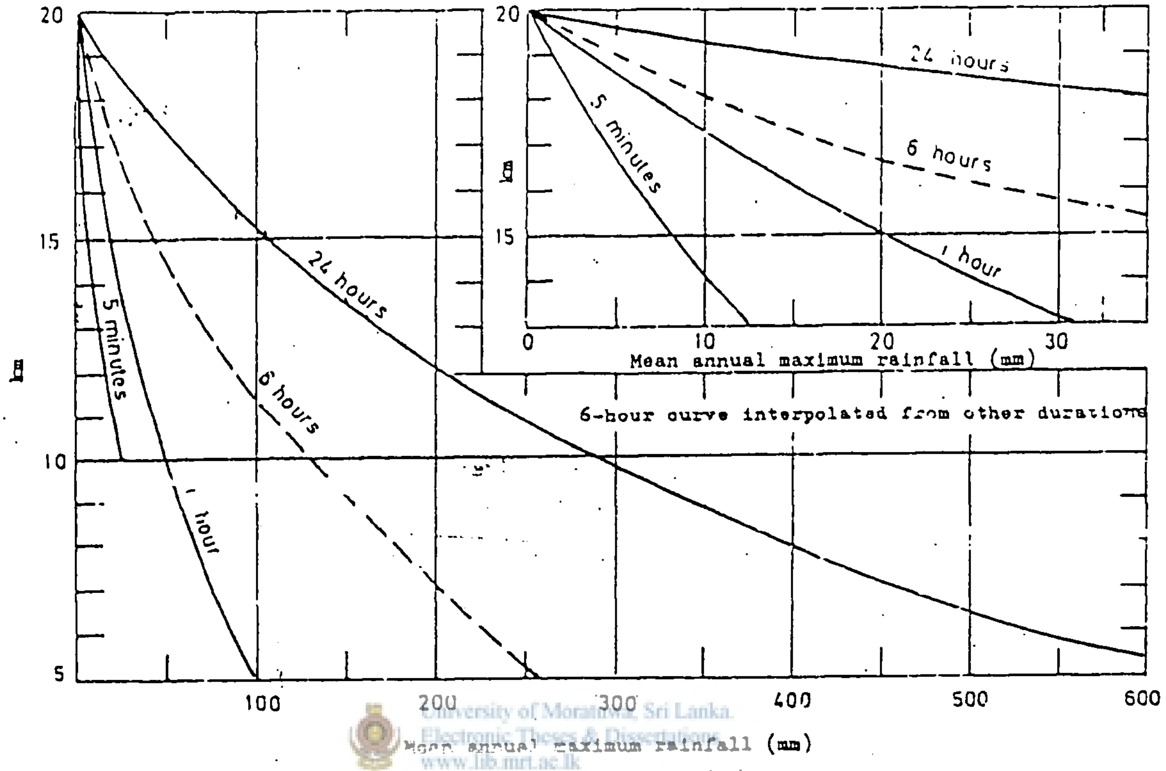




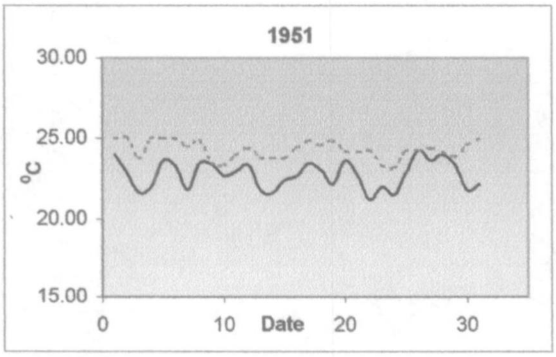

Figure A.2.4. – $K_m$ as a function of rainfall duration and mean of annual series

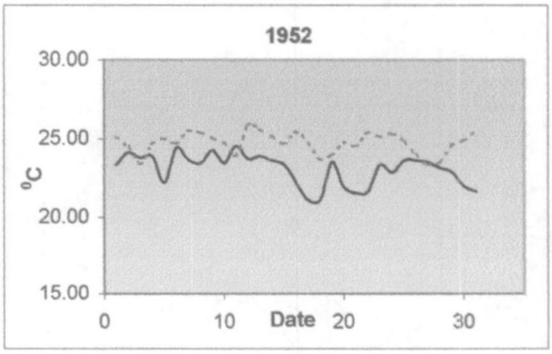
*Source: WMO, 1986*

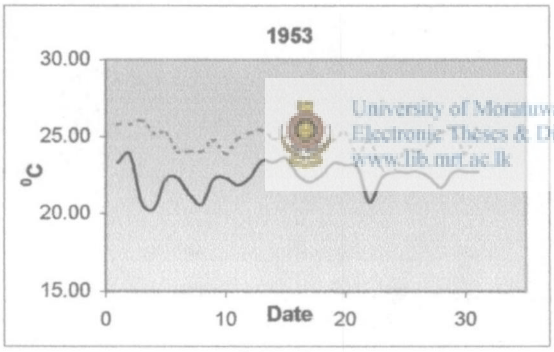
# ANNEX 3

Annex 3 shows all daily wet bulb temperatures in June and December for each year during 1951-2000 for Ratnapura and Anuradhapura respectively.

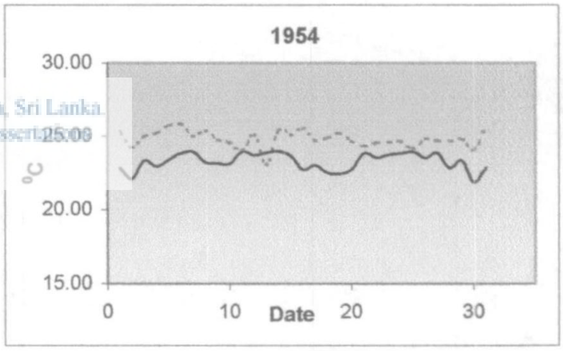
Legend Anuradhapura - ————————
Ratnapura - - - - - - - - - - - - -

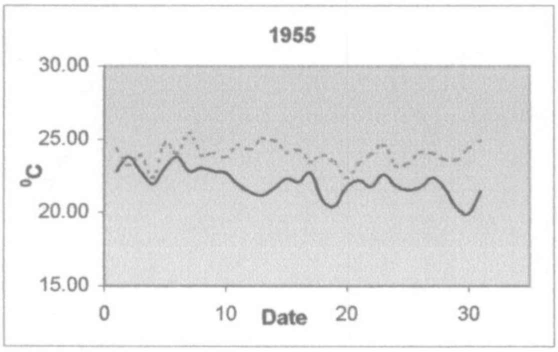


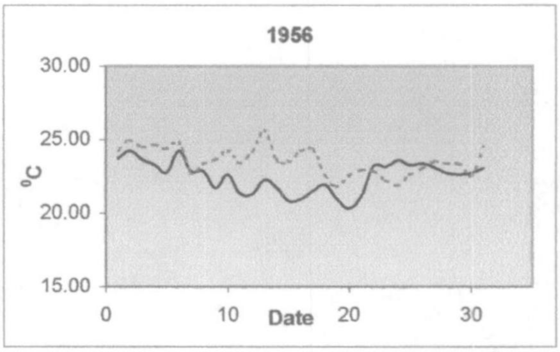



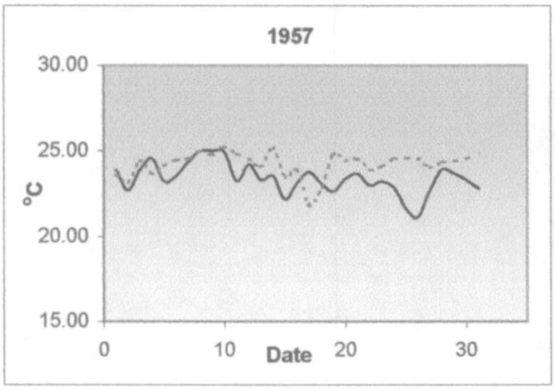



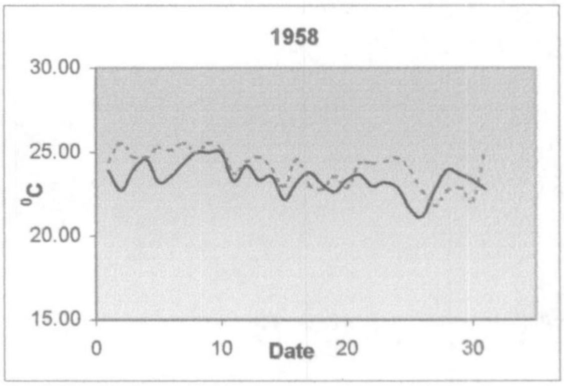


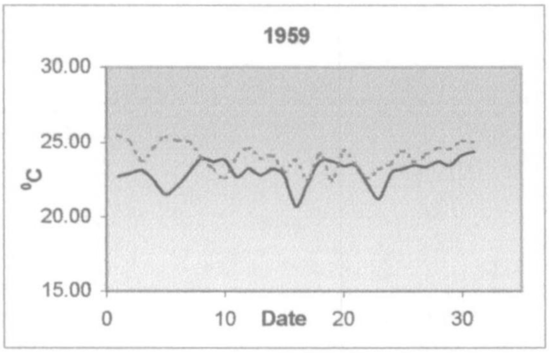



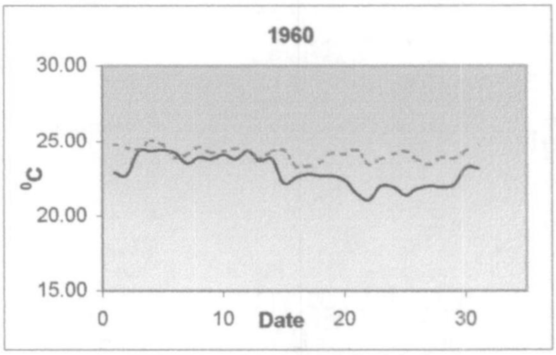



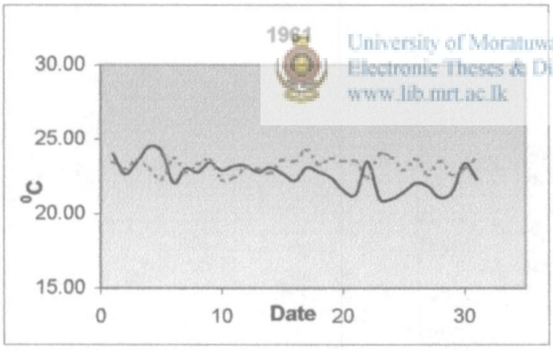

1957
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

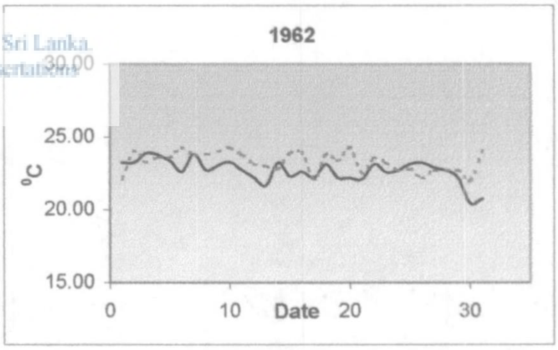

1958
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

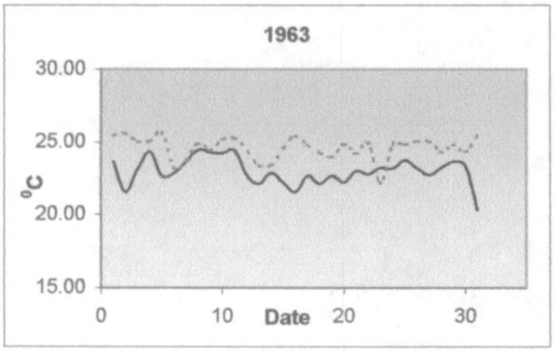

1959
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

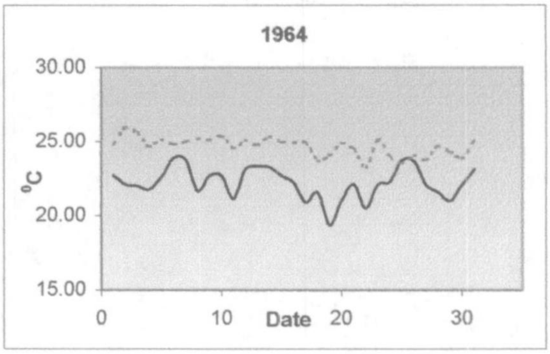

1960
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

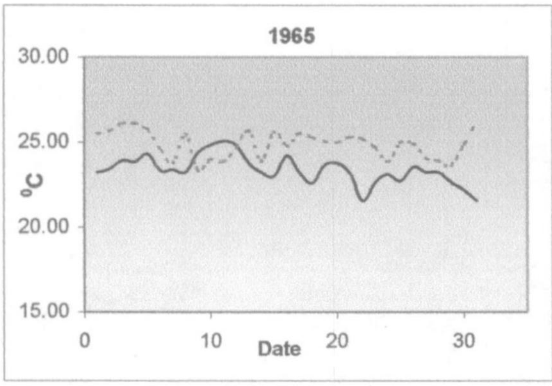


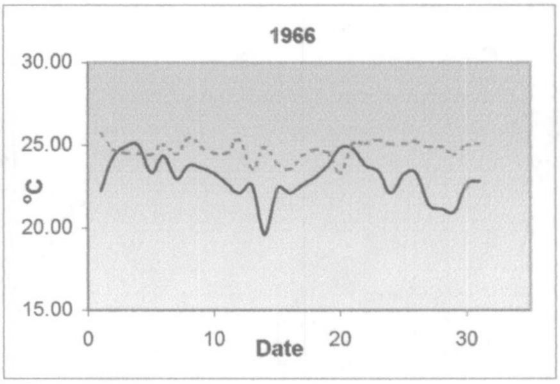

1961
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

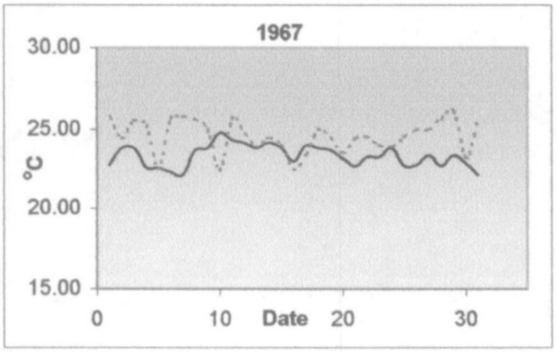

1962
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

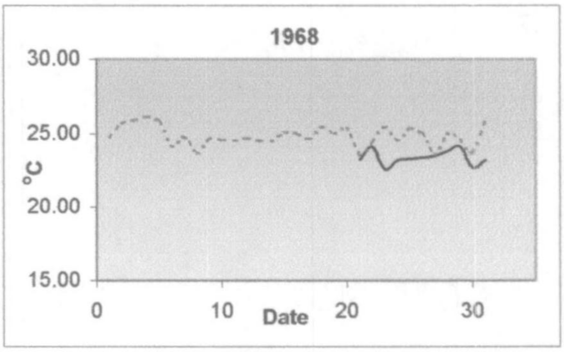

1963
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

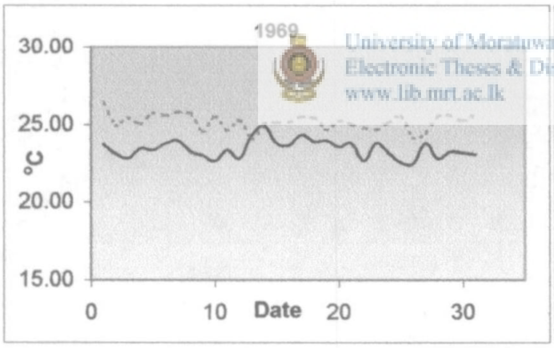

1964
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30


1965
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

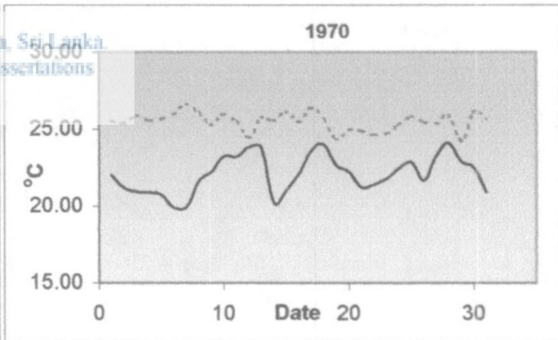

1966
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

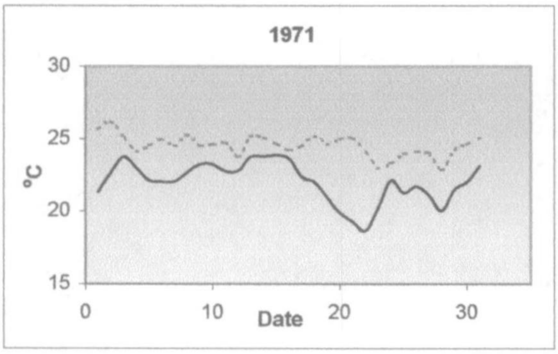

1967
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

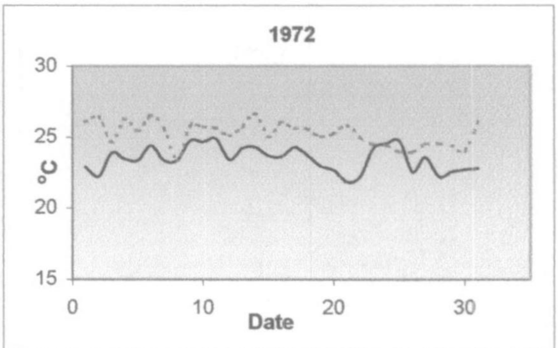

1968
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

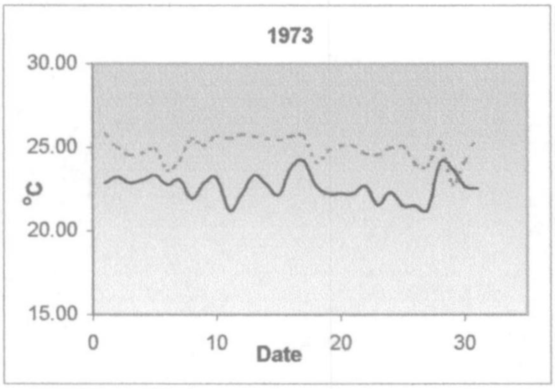

1969
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

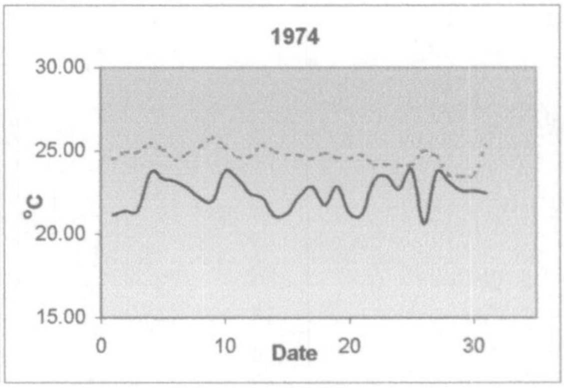


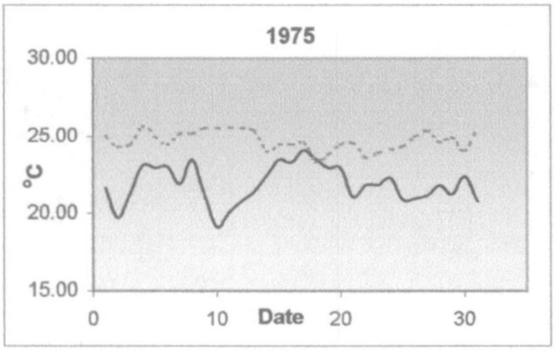

1970
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

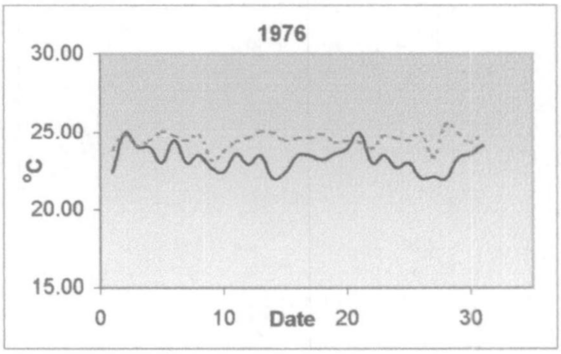

1971
30
25
20
15
°C
0
10
20
30
Date

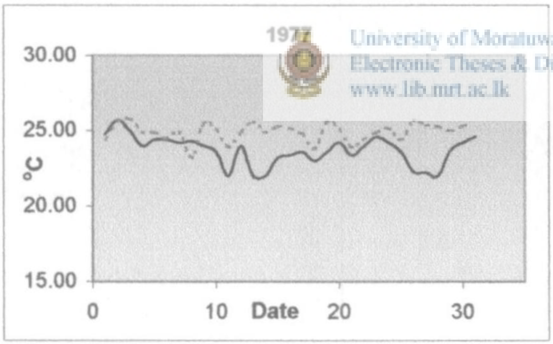

1972
30
25
20
15
°C
0
10
20
30
Date


1973
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

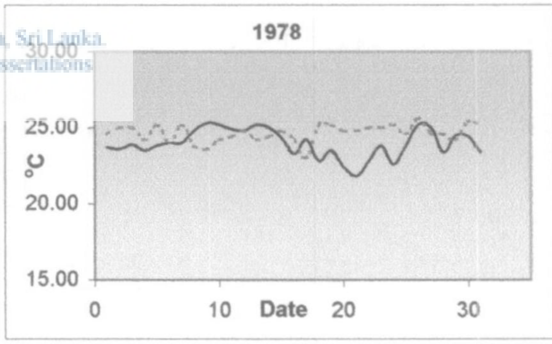

1974
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

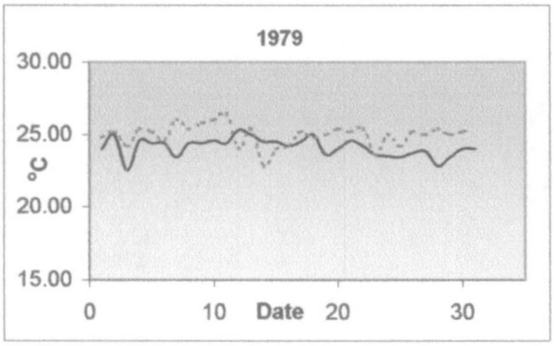

1975
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

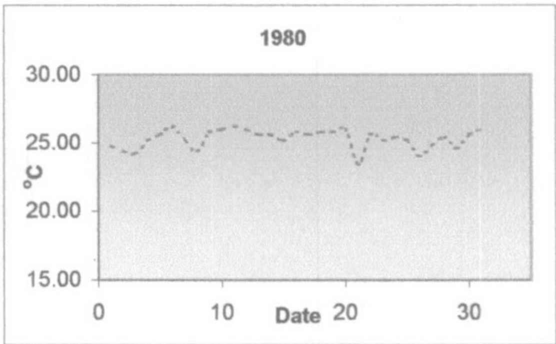

1976
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

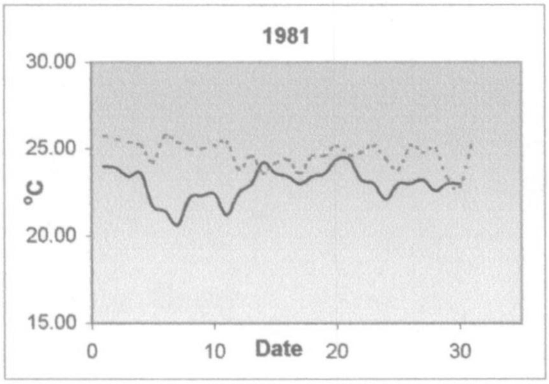

30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

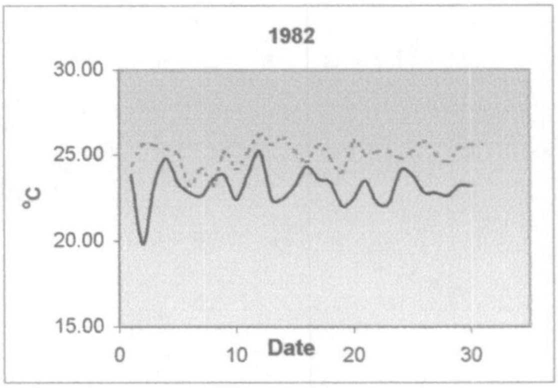


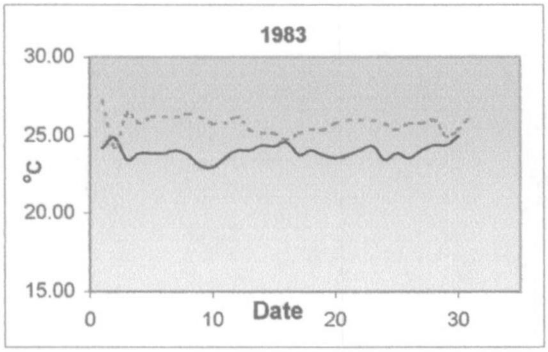

1978
25.00
20.00
15.00
°C
0
10
20
30
Date

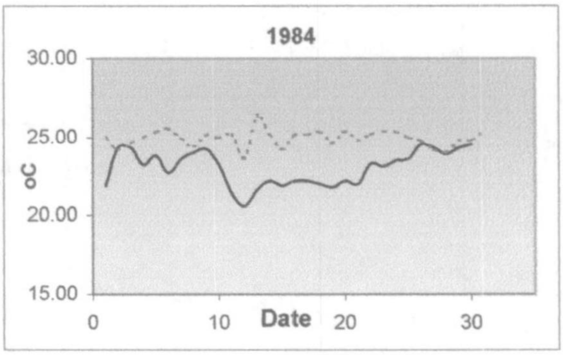

1979
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date

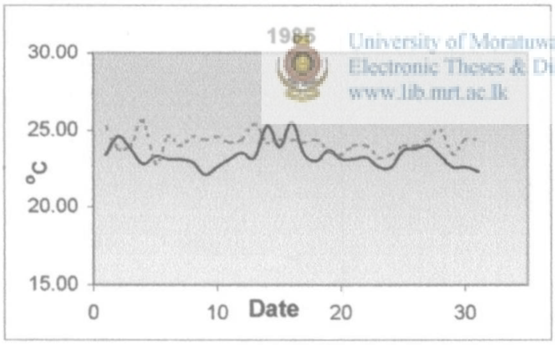

1980
30.00
25.00
20.00
15.00
°C
0
10
20
30
Date


1981
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

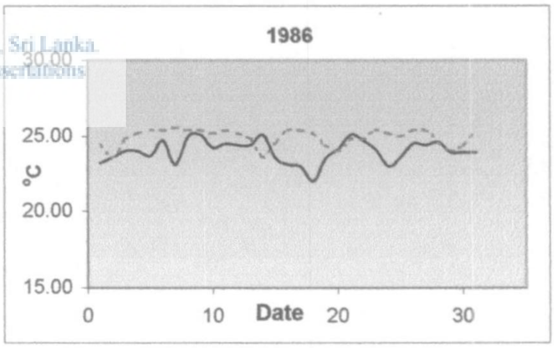

1982
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

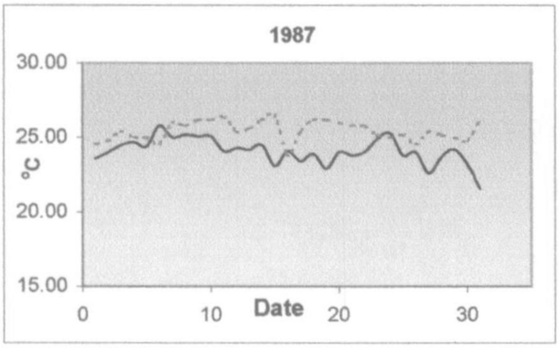

1983
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

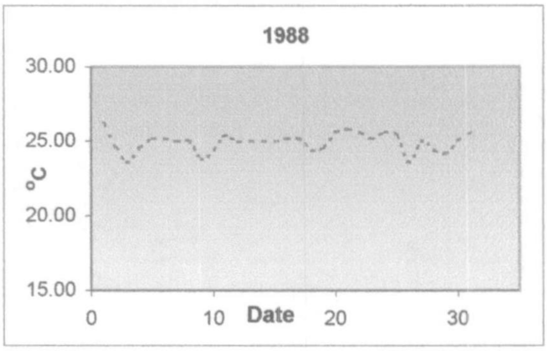

1984
30.00
25.00
20.00
15.00
oC
0
10
Date
20
30

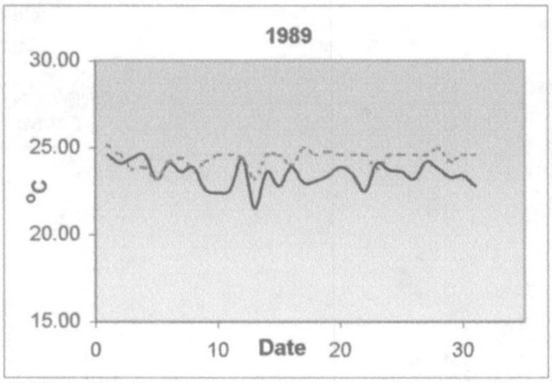

1985
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

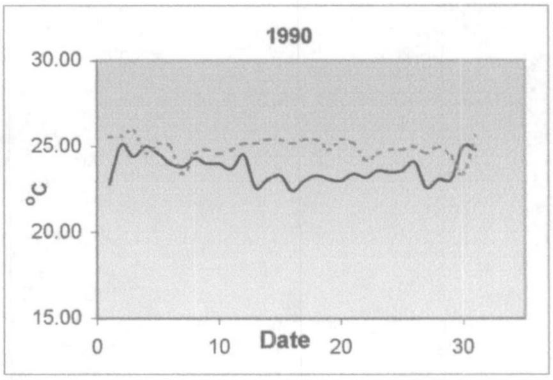


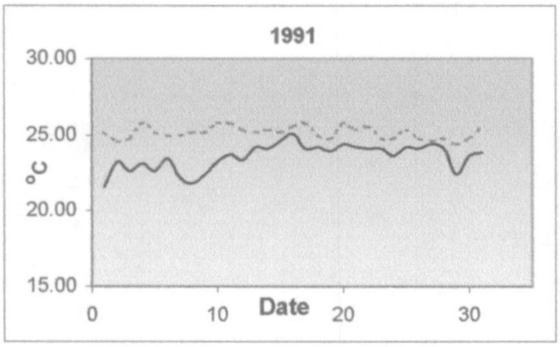

1986
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

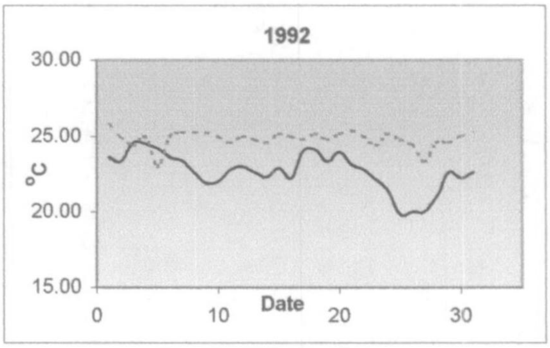

1987
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

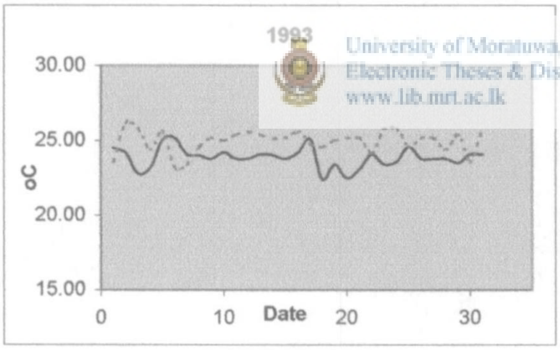

1988
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30


1989
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

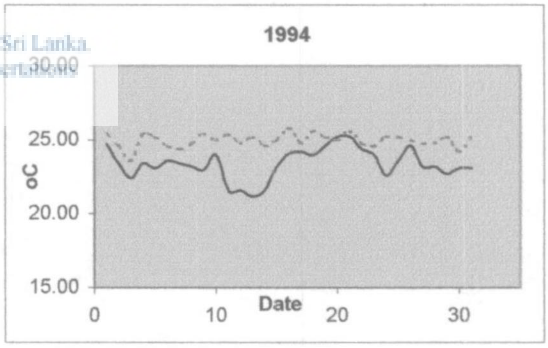

1990
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

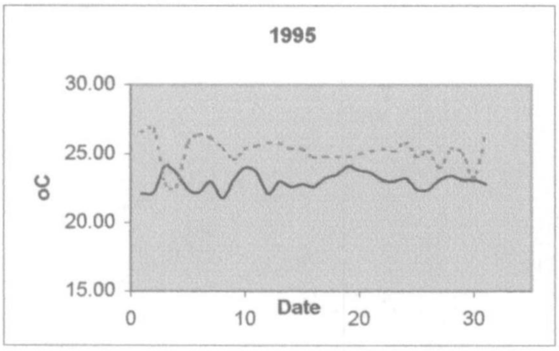

1991
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

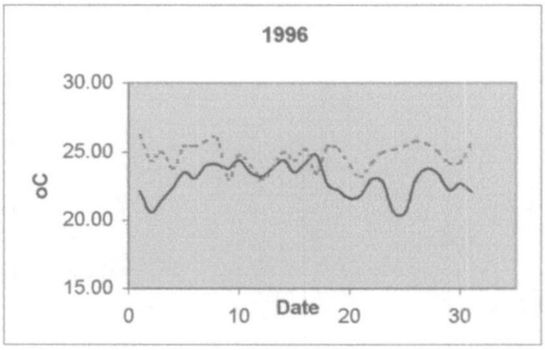

1992
30.00
25.00
20.00
15.00
°C
0
10
Date
20
30

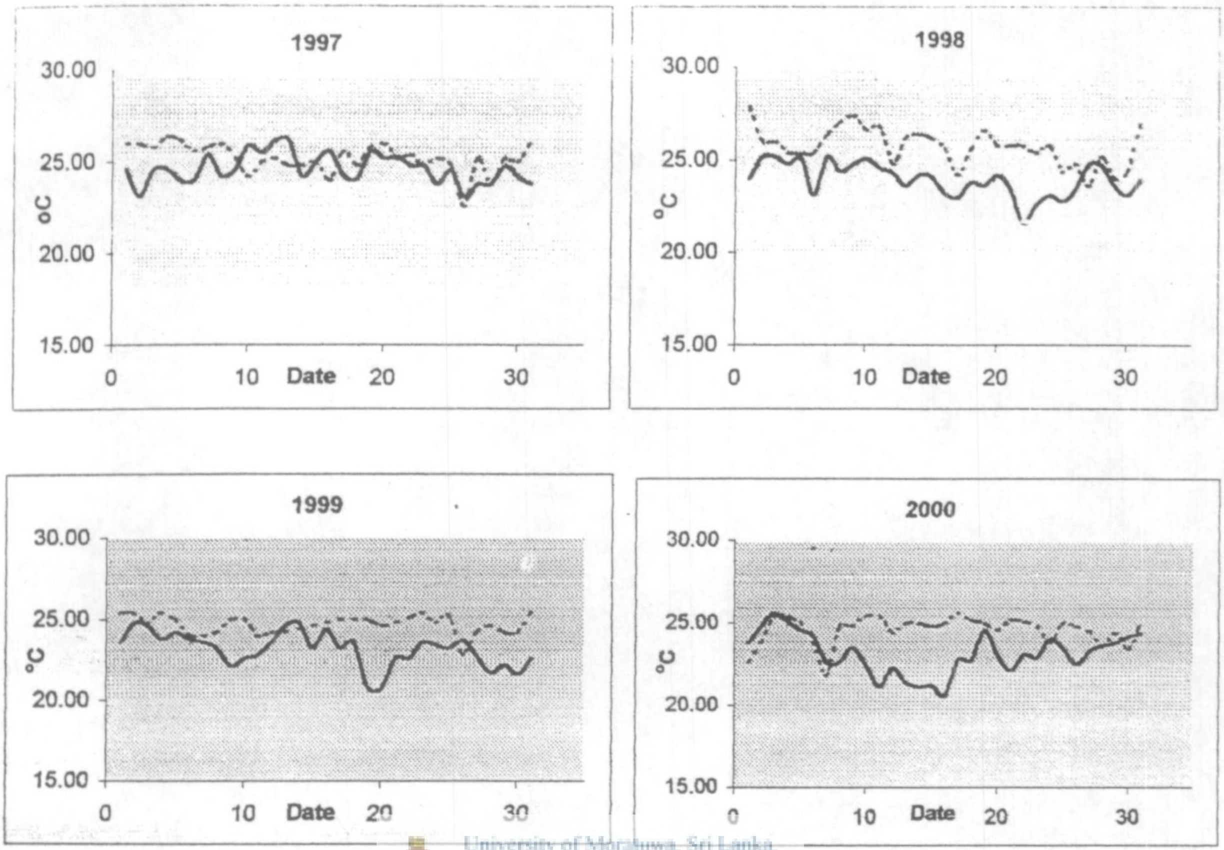

1993
30.00
25.00
20.00
15.00
oC
0
10
Date
20
30




1994
30.00
25.00
20.00
15.00
oC
0
10
Date
20
30


1995
30.00
25.00
20.00
15.00
oC
0
10
Date
20
30


1996
30.00
25.00
20.00
15.00
oC
0
10
Date
20
30


1997
1998
1999
2000
30.00
25.00
20.00
15.00
oC
°C
0
10
Date
20
30

## ANNEX 4

Annex 4 presents the paper published in the proceedings of the International Conference on Sustainable Water Resources Management in the Changing Environment of the Monsoon Region which was organized by the United Nations University, and was held in Colombo from 17th November to 19th November, 2004.

# SOME ISSUES IN THE ESTIMATION OF PROBABLE MAXIMUM PRECIPITATION

Kumari Fernando[1)] and S.S.Wickramasuriya[2)]

1) Department of Civil Engineering
General Sir John Kotelawala Defence Academy,
Ratmalana, Sri Lanka
2) Department of Civil Engineering
University of Moratuwa, Moratuwa, Sri Lanka

E-mail of Corresponding author: thiliku@yahoo.com

## ABSTRACT

The estimation of extreme rainfall continues to pose a challenge in hydrologic design. In projects where risk of failure has to be minimized, a reliable estimate of Probable Maximum Precipitation (PMP) is required for the computation of the Probable Maximum Flood (PMF). The paper focuses on two well known methods; one based on storm maximization or a hydro-meteorological method and the other using the statistical procedure developed by Hershfield.

The stations considered for the analysis are Anuradhapura and Ratnapura, which are representative of the dry zone and wet zone respectively. Daily rainfall data for the last 105 years have been considered in the research, which has afforded an opportunity to investigate how extreme values might be affected by possible climatic changes, at least at a preliminary level.

The storm of 219.7mm on 25[th] December 1957 at Anuradhapura and the heavy rainfall of 392.5mm on 8[th] June 1996 at Ratnapura have been used for storm maximization. These have yielded a PMP of 428 mm and 1055 mm at the two locations. The corresponding values based on the statistical method were 625mm and 1120mm respectively. The statistical method could prove to be most useful in developing maps of PMP.



## INTRODUCTION

Floods occurring in Sri Lanka are caused by weather patterns associated with monsoons, depressions and cyclones. One of the worst flood disasters in recent times was the flood of May 2003. The damage due to inundation was not confined to the Ratnapura District but covered vast extents of the Southern Province such as Galle, Matara and Hambantota Districts and some areas of the Kalutara District in the Western Province. The magnitude of the flood was such that it also resulted in enormous landslides and a total of 214 lost their lives and 175,000 families were rendered homeless.

Another major flood, which caused extensive damages to many irrigation systems and other infrastructure, was the flood of December 1957 in the North Central Province. Many areas of the city of Anuradhapura were inundated and major dams such as Nachchaduwa, Kalawewa and Huruluwewa breached. [Arumugam, 2003]. In the context of Sri Lanka, the flood events of 1907 and 1978 (Batticaloa), 1947 and 1996 (Ratnapura) and 1992 (Colombo) are also noteworthy. [Somasekaram, 1997]

It must be noted, that in the case of floods, "extreme rainfalls" are of critical importance and some of those values are shown in Table 1.

**Table 1:** The Greatest daily rainfall recorded upto 2003

| Station | Rainfall (mm) | Date |
|---|---|---|
| Vavuniya (Nedunkerni) | 805.6 | 16.12.1877 |
| Mullaitivu | 792.0 | 19.12.1911 |
| Balangoda | 755.9 | 17.05.1940 |
| Watawala | 524.5 | 05.10.1913 |
| Jaffna | 520.2 | 17.11.1918 |
| Kalutara (Neboda) | 511.8 | 09.08.1939 |
| Colombo | 493.7 | 05.06.1992 |
| Ratnapura | 394.5 | 15.07.1942 |
| Anuradhapura | 319.5 | 31.12.1948 |
| Hambantota | 296.9 | 06.05.1975 |

*Source: Department of Meteorology, Sri Lanka*

The design of a hydraulic structure such as a spillway requires a design flood estimate. This estimate carries with it a certain degree of "risk", due to the uncertainty of estimating the design rainfall or design flood which is based on concepts of probability. For major projects where the risk of failure has to be kept at a minimum, the design criteria are based on the Probable Maximum Flood (PMF). The probable maximum flood is defined as "the flood discharge that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in the region" [Varshney, 1979].

For the computation of the probable maximum flood, an estimate of the Probable Maximum Precipitation (PMP) is required, which has been defined as "the theoretical greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year" [WMO, 1986].

The main objective of the paper is to focus on two well-known methods recommended by the WMO, which are commonly used to estimate the daily PMP, for the purpose of comparison.



## METHODOLOGY

The following methods can be used to estimate PMP [Wiesner, 1970]

1. Storm model approach.
2. Maximization and transposition of actual storms.
3. Use of generalized data or maximized depth, duration, area data from storms.
4. Use of empirical formulae determined from maximum depth, duration, area data.
5. Use of empirical relationships between the variables in particular valleys.
6. Statistical analysis of extreme rainfalls.

Out of these methods, the maximization of actual storms and the statistical method developed by Hershfield were selected to estimate PMP.

### Storm Maximization

The goal of the hydrometeorological method, which is recommended by the World Meteorological Organization is to increase the available rainfall data to get maximum possible moisture either "in-situ" or by "transposition". If there are inadequate records of rainfall within the area, then it is possible to transpose storms from other meteorologically similar areas to the project area. However, in Sri Lanka, an extensive rainfall network has been maintained and hence this study is limited to in-situ maximization.

In-situ maximization can be done in two ways; namely moisture maximization and wind maximization. In many studies it can be seen that moisture maximization alone is used to adjust the rainfall data. But wind maximization can also be used in non-orographic regions, when moisture maximization gives inadequate or unrealistic results. [WMO, 1986].

The moisture maximization factor (MMF) is the ratio of the maximum precipitable water (Wm) to the precipitable water for the storm (Ws) where the precipitable water can be used to express the moisture charge.

$$MMF = \frac{W_m}{W_s} \quad (1)$$

Sea-level dew point temperature is the best tool to evaluate precipitable water and it can also be used for the comparison of dew points at different stations and at different elevations. However, the dew point should not be a single reading, but it should persist hours rather than minutes. In addition, for a storm of D hour duration, it is possible to select the highest D hour persisting dew point or the highest dew point that can persist for D consecutive hours. [Wiesner, 1970].

Precipitable water can be calculated by the summation from sea level to an elevation of 12,200m (200 mb pressure) by assuming that dew point in an air column changes with the altitude having a pseudo-adiabatic lapse rate. In general, the moisture availability above the elevation 12,200m is very little and hence not considered. Due to the seasonal monsoon variation in storm structure, the envelope of the maximum 24-hour persisting dew point is drawn by considering only the respective month in which the storm has occurred.

Wind maximization factor (WMF) is the ratio of the maximum daily wind run for the critical direction ($F_m$) to the observed daily wind run for the same direction ($F_s$) in the storm being maximized. Therefore,

$$WMF = \frac{F_m}{F_s} \qquad (2)$$

In Sri Lanka, considering the wind climate, both wind direction and wind speed are largely characterized by the monsoon system [Fernando, 2002]. Hence selecting the critical direction plays a vital role in deriving the wind maximization ratio. In addition, to determine the maximum wind speed, a long record of wind observations is necessary. Both maximization factors are used to calculate PMP as follows;

$$PMP = P_{obs} \times (MMF) \times (WMF) \qquad (3)$$

where $P_{obs}$ is the highest observed storm rainfall for a particular duration (24 hours), and PMP is the probable maximum precipitation of the same duration.

**Statistical Estimate – Hershfield Method**

Hershfield's method, which is a statistical method to estimate PMP, is selected as it has received the widest acceptance. Hershfield's statistical method is based on the generalized frequency equation,

$$X_m = \mu_n + K_m S_n \qquad (4)$$

where $X_m$ is the maximum observed rainfall amount at the site of interest, $\mu_n$ and $S_n$ are the mean and the standard deviation of a series of n annual rainfall maxima at that site, and $K_m$ is the frequency factor.

Records from 2645 stations of 24-hour rainfall were considered to compute $K_m$ and it was found that the maximum observed value of $K_m$ was 15. [Hershfield, 1961] Hence, to estimate PMP, $K_m$=15 can be substituted in (4). Later, Hershfield [1965] considered rain durations shorter than 24-hours and constructed a nomograph, which indicates that $K_m$ varies between 5 and 20.

The introduction of an unusually large event, which is called an outlier, may have an effect on the mean and the standard deviation of the annual series. Therefore, to compensate for outliers, it is necessary to calculate a ratio of mean and the standard deviation where the numerator does not include the maximum observed event and the denominator includes all values. Hershfield [1961] found that a 50-year record could be used as a reference standard to adjust other short records. However, large sample sizes such as 60-70 years showed negligible difference with a 50-year mean.

Most rainfall observations are made using non-recording gauges, so that the rainfall during a fixed interval is less than the value during the true interval. Weiss [1964] showed that the conversion factor of true amount to observational amount for any time interval of same length to be 1.143 and hence the PMP is adjusted accordingly.

Recent studies considering the statistical approach done by Koutsoyiannis [1999] have demonstrated Hershfield's method as a reliable tool in hydrologic design. In cases where available rainfall records are limited to a few years, this method provides first approximation to estimate PMP.

## DATA COLLECTION

In this research, the stations Anuradhapura and Ratnapura, which are representative of the dry zone and wet zone respectively, were selected. Table 2 describes the geographical co-ordinates and the elevations of those stations.

**Table 2:** Geographical Data

| Station | Anuradhapura | Ratnapura |
|---|---|---|
| Geographical Coordinates<br>Latitude<br>Longitude | <br>$8^0$ 21' N<br>$80^0$ 23' E | <br>$6^0$ 41' N ( $6^0$ 43')*<br>$80^0$ 24' E ($80^0$ 24')* |
| Elevation (m) | 89.9 | 34.45 (86.294)* |

*Source: Department of Meteorology, Sri Lanka*

*The meteorological station at Ratnapura was moved to a new site in August 1993. The data presented in parenthesis is after moving the station.

**Rainfall Data**

Daily rainfall data are available from 1889 to 2000 for Anuradhapura and from 1895 to 2000 for Ratnapura but there was no data during 1941-1950 for Anuradhapura. In the method of storm maximization, the selected period is 1951-2000 (50 years). Fig.1 and 2 show the series of annual maxima in Anuradhapura and Ratnapura respectively.

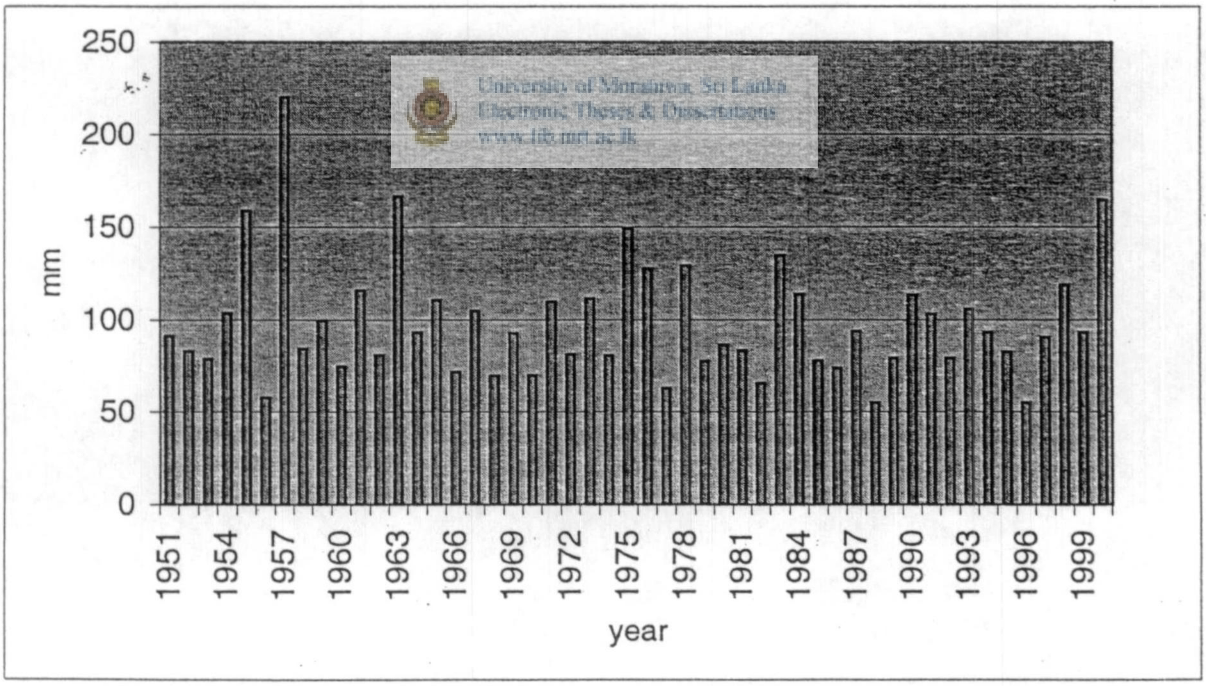



**Fig. 1:** Annual Maximum Daily Precipitation in Anuradhapura

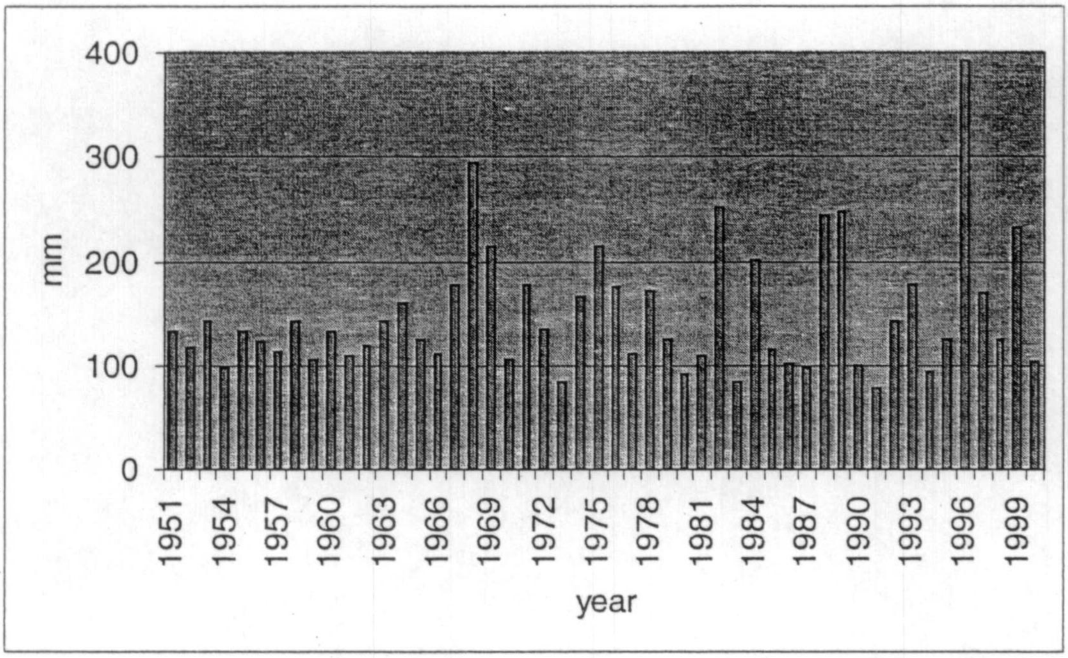



**Fig.2:** Annual Maximum Daily Precipitation in Ratnapura

From these two figures, the most significant storms were identified for both stations. The storm of 219.7mm on 25th December 1957 at Anuradhapura and the heavy rainfall of 392.5mm on 8th June 1996 at Ratnapura have been used for storm maximization.



**Dew Point Temperature Data**

Since there is a seasonal variation in precipitation, dew point values were extracted for the months in which the major storms have occurred. Therefore for the period 1951-2000, all December values for Anuradhapura and all June values for Ratnapura were obtained. Due to the non-availability of daily dew point temperatures, wet bulb temperatures were selected in order to calculate 24-hour persisting dew point values. These values were found by drawing the graphs considering all daily wet bulb temperatures in December for Anuradhapura and during June for Ratnapura in each year covering 1951-2000. Fig. 3 and 4 were compiled to get the maximum persisting dew point for Anuradhapura and Ratnapura respectively.

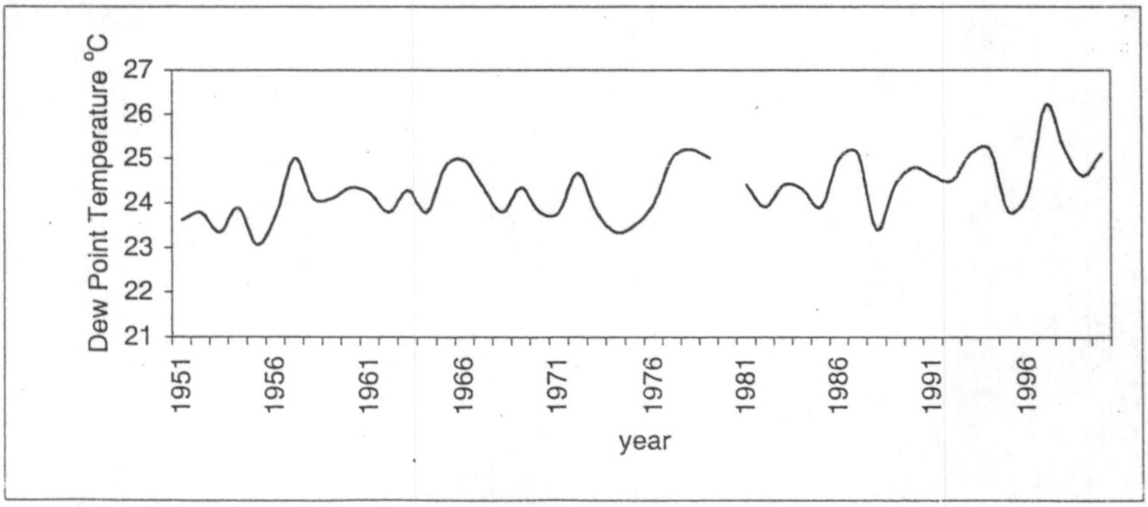



**Fig.3:** Maximum persisting 24-hour dew point temperature – Anuradhapura
Maximum 24-hour persisting dew point temperature = 26.2°C

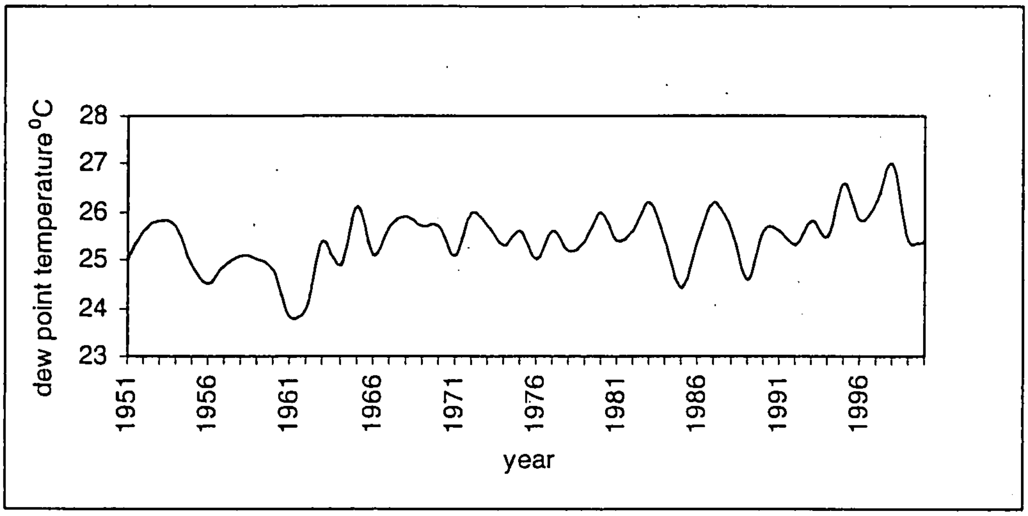



**Fig.4:** Maximum persisting 24-hour dew point temperature – Ratnapura
Maximum 24-hour persisting dew point temperature = 27.0°C

**Table 3:** The dew point temperature values for both stations.

| Description | Anuradhapura (°C) | Ratnapura (°C) |
|---|---|---|
| 1. During the storm. | | |
| a. Wet bulb temperature | 21.6 | 26.0 |
| b. Surface dew point | - | 25.1 |
| c. Average | - | 24.4 |
| 2. Maximum 24 – hour persisting dew point temperature | 26.2 | 27.0 |

*Source: Department of Meteorology, Sri Lanka*



### Wind Data

To estimate the maximum daily wind run, records of wind run were observed during 1951 – 2000 at Anuradhapura selecting the critical directions from NE – NW quadrant. However, in Ratnapura only 7 years of wind run data were available since the station had been relocated. For this period, the selected directions were N-NW. Wind data measured during the storm and the maximum wind run data are tabulated in Table 4.

**Table 4:** Daily Wind run (km) measured for critical directions.

| Description | Anuradhapura | Ratnapura |
|---|---|---|
| During the storm | 338 (NW) | 173 (N) |
| Maximum wind run | 440 (NW) | 415 (N) |

Source: Department of Meteorology, Sri Lanka

### Air Temperature

The minimum air temperatures during the selected storms were

i. 21.9°C in Anuradhapura
ii. 26.08°C in Ratnapura

## DATA ANALYSIS

Though daily rainfall data for the last 105 years are available, only the 50-year record 1951- 2000 was selected considering the requirement of dew point temperature and wind data. A depth-area-duration analysis has not been done for the selected major storms, since the objective was to calculate 24 hour, point PMP.

### Storm Maximization

A precondition for this method is that the surface dew point of the storm should not be higher than the minimum air temperature within the period [Wiesner, 1970]. When comparing dew point temperature and air temperature, it can be seen that the above condition is satisfied at both stations.

To compute the moisture maximization factor, the values of precipitable water were calculated using available charts. [WMO, 1986] These values vary with dew point temperature and altitude. The following steps were used to estimate precipitable water for the representative storm and the maximum during the selected period.

1. Total precipitable water for a moisture column with base at 1000 mb and top at 200 mb.
2. Precipitable water for the column with base at 1000 mb and top at the elevation of the station.
3. Residual precipitable water (Table 5)

**Table 5:** Precipitable Water, W (mm) calculations

| | Anuradhapura | | Ratnapura | |
|---|---|---|---|---|
| | 25.12.1957 | Max. during 1951 - 2000 | 08.06.1996 | Max. during 1951-2000 |
| W 1000 mb – 200 mb | 60.0 | 89.6 | 81.7 | 96.0 |
| W 1000 mb – elevation | 1.8 | 2.2 | 2.1 | 2.2 |
| Residual W | 58.2 | 87.4 | 79.6 | 93.8 |
| Moisture maximization factor | 87.4 / 58.2 = 1.5 | | 93.8 / 79.6 = 1.12 | |



Wind maximization factor (WMF) is the ratio of maximum daily wind run to daily wind run during the storm. Hence, WMF for Anuradhapura is 440/338 = 1.3 and for Ratnapura it is 415/173 = 2.4

Thus applying both maximization factors on the observed rainfall, the PMP would be 428.4 mm (219.7 x1 .5 x 1.3) for Anuradhapura and 1055 mm (392.5 x 1.12 x 2.4) for Ratnapura.

### Statistical Method

In the statistical approach, precipitation data were analysed according to sample sizes of 20, 30 and 50 years and it is expected that a long record of data yields more reliable PMP values than a short record. [WMO, 1986]

**Table 6:** Summary of statistical analysis in Anuradhapura.

| Period | 1921 - 1940 | 1961-1990 | 1891 - 1940 | 1951 – 2000 |
|---|---|---|---|---|
| Length of record (years) | 20 | 30 | 50 | 50 |
| Maximum daily rainfall (mm) | 160.7 | 166.3 | 236.7 | 219.7 |
| $\mu_n$ | 106.96 | 95.96 | 107.95 | 98.31 |
| $\mu_{n-m}$ | 104.13 | 93.53 | 105.32 | 95.83 |
| Adjusted mean | 110.19 | 97.40 | 107.41 | 97.82 |
| $S_n$ | 27.37 | 27.06 | 32.04 | 32.09 |
| $S_{n-m}$ | 24.93 | 23.99 | 26.37 | 27.16 |
| Adjusted standard deviation | 31.04 | 28.14 | 28.20 | 29.52 |
| $K_m$ | 14.5 | 16.3 | 14.9 | 15.2 |
| Unadjusted PMP | 560.27 | 556.08 | 527.59 | 546.52 |
| PMP (mm) | 640.39 | 635.60 | 603.04 | 624.68 |

**Table 7:** Summary of statistical analysis in Ratnapura.

| Period | 1901-1920 | 1911-1940 | 1901 - 1950 | 1951 - 2000 |
|---|---|---|---|---|
| Length of record (years) | 20 | 30 | 50 | 50 |
| Maximum daily rainfall (mm) | 269.2 | 302.3 | 394.4 | 392.5 |
| $\mu_n$ | 144.22 | 162.96 | 163.80 | 148.76 |
| $\mu_{n-m}$ | 137.64 | 158.16 | 159.09 | 143.78 |
| Adjusted mean | 146.37 | 164.59 | 162.16 | 147.27 |
| $S_n$ | 44.50 | 48.63 | 66.19 | 61.10 |
| $S_{n-m}$ | 34.30 | 41.62 | 57.81 | 50.47 |
| Adjusted standard deviation | 42.77 | 48.05 | 62.22 | 54.99 |
| $K_m$ | 13.8 | 13.2 | 13.1 | 13.7 |
| Unadjusted PMP | 736.60 | 798.85 | 977.24 | 900.63 |
| PMP (mm) | 841.93 | 913.08 | 1117.0 | 1029.42 |

## RESULTS AND DISCUSSION

The statistical estimates of PMP show a remarkable degree of consistency, which is certainly a striking feature. The estimates have been computed for varying lengths of record (20, 30 and 50 years) and considered over different time periods. This is true for both Anuradhapura and Ratnapura which are typical dry zone and wet zone stations. As for Ratnapura, the consistency of the PMP estimates improves with sample size. Accordingly, statistical estimates of PMP in the order of 600-625mm for Anuradhapura and 900-1120mm for Ratnapura seem justifiable.

The 24hour point PMP calculated by storm maximization yields 428mm and 1055mm at Anuradhapura and Ratnapura respectively. This value for Anuradhapura is about 32% less than the statistical estimate, while the corresponding figure for Ratnapura is only 6%. The relatively large deviation in the Anuradhapura result warrants further analysis and this leads to a very interesting observation. The daily rainfall data, which is measured for fixed time intervals (0830 hrs to 0830 hrs) was used to maximize the storm. However, there may be instances where the maximum 24-hour rainfall does not coincide with the above fixed time interval. To account for this, the method developed by Weiss (1964: 77-82) is applied in the statistical approach. The value of the conversion factor, which is the factor of true to observational amount for any time interval of same length, is 1.143. This factor is not included in WMO procedure for storm maximization. However if it is included and applied, then the revised estimates of PMP will be 489 mm and 1206 mm respectively.



Daily precipitation records show that the true 24-hour maximum rainfall for Anuradhapura was 319.53 mm (from 1730hrs. on 24.12.1957 to 1730hrs. 25.12.1957) and the same at Ratnapura was 393.5mm. (from 0600hrs.on 08.06.1996 to 0600hrs. on 09.06.1996 )With these two values of precipitation, the PMP obtained by storm maximization increases up to 623 mm and 1058 mm respectively. Therefore, if true maximum values are considered in the analysis, the estimates of PMP obtained by both methods will agree well and this is certainly a key aspect of this research.

All PMP results calculated by both methods are tabulated in table 8.

**Table 8:** Comparison of PMP in Anuradhapura and Ratnapura

| Station | Storm Maximization | | | Statistical Analysis | |
|---|---|---|---|---|---|
| | With fixed rainfall | With Weiss factor | With true rainfall | Lower | Upper |
| Anuradhapura | 428 | 489 | 623 | 600 | 625 |
| Ratnapura | 1055 | 1206 | 1058 | 1000 | 1120 |

## CONCLUSIONS

Based on the statistical method, the estimates of PMP at Anuradhapura and Ratnapura are 625mm and 1120mm respectively. The estimate for Anuradhapura a dry zone station, obtained by storm maximization is 32% lower than the statistical estimate. As for Ratnapura a wet zone station, there is a remarkable degree of agreement between the two estimates, the equivalent figure being only 6%. It is most interesting to note that both methods yield almost identical results, if storm maximization is based on true rainfall. It is appropriate and essential that wind maximization too be incorporated in the storm maximization process.

The research strongly suggests that the statistical method of estimating PMP is an efficient and promising area of study in the context of Sri Lanka. The technique offers speed and ease in analysis, and hence is useful in the context of design. Since a vast database of precipitation is available, the method can be used together with a geographic information system to rapidly develop maps of PMP for the Country. Further work in comparing the statistical and hydrometeorological methods and exploring the suitability of the frequency factors within the local climate, could also be a rewarding endeavour.

## ACKNOWLEDGEMENT

The rainfall and other meteorological data used in this study were obtained from the Meteorology Department of Sri Lanka.

## REFERENCE

Arumugam, S. (2003) "Water for people and nature" in Arumugam Commemoration Volume, *Sri Lanka Water Heritage*, 2, Vishva Lekha publication, Sri Lanka, 1-16.

Fernando, S. (2002) *Wind Resources Assessment in the Puttalam region, Knuckles Range and Ambewela*, Consultancy Report for Ceylon Electricity Board

Koutsoyiannis, D. (1999) *A Probabilistic View of Hershfield's Method for Estimating Probable Maximum Precipitation*, Water Resources Research, 35, 4, 1313-1322.

Hershfield, D.M. (1961) *Estimating the Probable Maximum Precipitation*, Proceedings American Society of Civil Engineers, Journal Hydraulics Division, 87, 99-106.

Hershfield, D. M. (1965) *Method for Estimating the Probable Maximum Precipitation*, Journal American Waterworks Association, 57, 965-972.

Somasekeram, T. (1997) *Arjuna's Atlas of Sri Lanka*, Arjuna Consulting Co. Ltd., Sri Lanka, 76pp.

Varshney, R. S. (1979) *Engineering Hydrology*, New Chand and Bros., Roorkee (U.P.) 663pp.

Weiss, L. L. (1964) *Ratio of true to fixed interval maximum rainfall*, Proceedings of the American Society of Civil Engineers, 3758, Journal Hydraulics Division, 90, 77-82.

Wiesner, C. J. (1970) *Hydrometeorology*, Chapman and Hall Ltd., London 152pp, 213-225

World Meteorological Organization (1986) *Manual for Estimation of Probable Maximum Precipitation*, Operational Hydrology , report 1, 332, 2nd ed. WMO, Geneva, Switzerland