THE UNIVERSITY OF CALGARY

A Spatial Study of Precipitation in Calgary

by

Jean Clara Andrey

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOGRAPHY

CALGARY, ALBERTA

JANUARY, 1980

THE UNIVERSITY OF CALGARY

FACULTY OF GRADUATE STUDIES

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A Spatial Study of Precipitation in Calgary," submitted by Jean Clara Andrey in partial fulfillment of the requirements for the degree of Master of Science.

Supervisor, Dr. Lawrence Nkemdirim
Department of Geography

Dr. Nigel Waters, Department of Geography

Dr. Valerious Geist, Faculty of Environmental Design

31 January 1980

ABSTRACT

The theme of this study is the examination of the spatial distribution of rainfall in Calgary and the assessment of the physical and environmental controls that influence the distribution.

To this end, precipitation data from a network of twenty rain gauges located within the city were collected from May to September 1978. Radar records from the Alberta Hail Project formed a supplementary data source.

Analysis of the data suggests that Calgary's precipitation regime was characterized by a high degree of spatial complexity. Two zones of relatively high precipitation receipt and one negative anomaly were identified. These were largely explained by storm track position, which in turn reflected local topography. The position of Glenmore Reservoir is believed to have influenced precipitation receipt in southwest Calgary. Precipitation enhancement, as a result of urban-industrial effects, is suspected in industrial southeast Calgary. Of secondary importance were the effects of wind and synoptic conditions on the spatial patterns of rainfall.

ACKNOWLEDGEMENTS

As I near completion of my thesis project, I am reminded of all those people who aided me in this endeavour. To my supervisor, Dr. Lawrence Nkemdirim, I extend my heartfelt thanks for the guidance and time which he generously gave me. Thanks also to Dr. Nigel Waters and Mr. Jim Crowley for their academic advice and encouragement. In addition, I am grateful to Mr. Ted Rhodes for his endless hours of instruction on technical details and to Beth and Dave Szplett for their aid in statistical matters.

During the course of data collection I received much appreciated cooperation from many people, in particular Sharon Forster, Julie Cursley, Bert Miller and Joyce Kuntz. To these people I would like to express my gratitude. In addition, I would like to thank the Alberta Weather Modification Board and Atmospheric Sciences Division of the Alberta Research Council for their assistance in the acquisition of the radar data. Thanks are extended in particular to B. Barge, R. Humphries, F. Bergwall, and B. Folliott.

For the financial assistance that I received from the University of Calgary Graduate Studies, National Research Council and Alberta Graduate Scholarship fund, I am grateful.

And lastly, but not leastly, thanks to Ray for his patience and understanding.

TABLE OF CONTENTS

	Page
List of Tables	viii
List of Figures	ix
Chapter One:Introduction	
1.1 Introduction	1
1.2 Factors Affecting the Spatial Distribution of Precipitation at a Microscale	3
1.3 Urban Precipitation Studies - Literature Review	5
1.4 The Study Area	
1.4.1 Calgary's Regional and Physiographic Setting	11
1.4.2 Calgary's Urban Complex	13
1.4.3 Calgary's Regional Climate	15
1.5 Objectives of the Study	19
1.6 The Study Period	21
Chapter Two:Data Sources and Quality	
2.1 Introduction	22
2.2 Rain Gauge Network Design	23
2.3 Logistics of Data Collection	30
2.4 Data Quality Controls	
2.4.1 Introduction	32
2.4.2 Site Exposure Examined	32
2.4.3 Experimentation with Variable Exposure in a Dense Network of Standard Gauges	41
2.4.4 Gauge Losses by Evaporation and Wetting	48
2.5 Missing Data	48
2.6 Rain Gauge Network Density-A Discussion	51
2.7 Summary	56
Chapter Three:Radar Data Analysis	
3.1 Introduction	58
3.2 Principles of Weather Radar	59
3.3 Data Base	60
3.4 A Comparison of Radar Estimated Rainfall and Gauge Estimated Rainfall	61
3.5 A Case Study of the July 19th Multicell Storm	
3.5.1 The Storm	65
3.5.2 A Comparison of RER and GER for July 19, 1978	68

TABLE OF CONTENTS
(continued)

		Page
	3.5.3 Sources of Errors in RER over Calgary	70
3.6	Utilization of Radar Data for Spatial Estimates of Precipitation	72
3.7	Summary	74
Chapter Four: Temporal Aspects of Rainfall in Calgary		
4.1	Introduction	77
4.2	Precipitation Histories	77
4.3	The Study Period - Temporal Characteristics	
	4.3.1 Introduction	80
	4.3.2 A Synoptic Classification of Storms	83
	4.3.3 The Distribution of Precipitation by Month	85
	4.3.4 The Distribution of Precipitation by Day of the Week	90
	4.3.5 The Distribution of Precipitation by Time of Day	96
4.4	A Study of the Relationship between Rainfall Duration and Rainfall Intensity	99
4.5	Summary	100
Chapter Five: The Spatial Distribution of Rainfall in Calgary		
5.1	Introduction	103
5.2	The Study Area - Is It Unique?	103
5.3	The Spatial Distribution of Precipitation in Calgary - The Study Period	107
5.4	The Spatial Distribution of Precipitation in Calgary - A Breakdown by Synoptic Type	110
5.5	The Spatial Distribution of Precipitation in Calgary - The Effect of Topography	
	5.5.1 Elevation	119
	5.5.2 The Spatial Distribution of Precipitation in Calgary - A Comment on Storm Tracks	122

TABLE OF CONTENTS
(continued)

Page

5.6 The Spatial Distribution of Precipitation in Calgary under various wind conditions
 5.6.1 The Role of Wind Direction 128
 5.6.2 The Role of Wind Speed 131
5.7 The Spatial Distribution of Precipitation in Calgary - The Effect of Glenmore Reservoir 135
5.8 The Effect of the Urban Complex on the Distribution of Precipitation in Calgary
 5.8.1 A Study of the Bonnybrook-Ogden Area 138
 5.8.2 An Examination of Cloud Development over the city of Calgary 143
5.9 The Spatial Distribution of Precipitation in Calgary - The Effects of Cloud Seeding 144
5.10 Summary 148

Chapter Six: Conclusions and Recommendations for Further Research
 6.1 Conclusions 149
 6.2 Recommendations for Further Research 154

Bibliography 155

Appendix One: Abbreviations and Symbols 165
Appendix Two: Locations of Rain Gauges in City Network 166
Appendix Three: Site Characteristics of Station 13 167
Appendix Four: The Degree of Variation in Precipitation Totals within Three Rain Gauge Networks 168
Appendix Five: Standard Errors of the Mean 169
Appendix Six: Dates and Times Used in Radar Analysis 172

LIST OF TABLES

		Page
1.3.1	A Comparison of Urban and Rural Precipitation	10
1.4.1	Mean Climatic Data for Calgary	16
2.4.1	Characteristics of the Recording Gauges .	35
2.4.2	Site Exposure Characteristics	37
2.4.3	Wind Direction Frequencies during Storms.	38
2.4.4	Potential Faulty Gauge Catch Sites	40
2.4.5	Per cent Loss by Evaporation and Wetting Combined	49
4.3.1	A Breakdown of Precipitation by Synoptic Type	84
4.3.2	Distribution of Precipitation by Month ..	86
4.3.3	Distribution of Precipitation by Month and Synoptic Type	88
4.3.4	Distribution of Precipitation by Day of the Week	91
4.3.5	Number of Days with Rain versus Day of the Week	92
5.4.1	The Gradients of Change in Rainfall Receipt from the CBD to Other Areas	114
5.5.1	Wind Direction Frequencies during Storms.	121

LIST OF FIGURES

		Page
1.4.1	Generalized Topography of Calgary	12
1.4.2	Schematic Land Use Map of Calgary	14
1.4.3	Distribution of Mean Annual Temperature in Calgary	17
2.2.1	Locations of Rain Gauges	31
2.4.1	Cumulative Frequency of Mean Wind Speeds during all Storms	39
2.4.2	Dense Rain Gauge Network	43
2.4.3	Gauge Losses by Evaporation and Wetting Combined	50
2.6.1	Standard Error of the Mean Versus Network Density	53
2.6.2	Standard Error of the Mean Versus Network Density - The General Case	55
3.4.1	Radar Estimated Rainfall Versus Gauge Estimated Rainfall	63
3.4.2	Cumulative Frequency of RER/GER Values ...	64
3.5.1	Radar Reflectivity Map, July 19, 1978	67
3.5.2	Accumulated Rainfall (mm) - Lag Adjusted .	69
3.6.1	Radar Estimated Rainfall, July 19	73
3.6.2	Gauge Estimated Rainfall, July 19	75
4.2.1	Locations of Sites used in Historical Analysis	79
4.2.2	Station Histories - Trends Examined	81
4.3.1	Mean Daily Precipitation by Month	89
4.3.2	Daily Distribution of Precipitation	93
4.3.3	Daily Distribution of Precipitation - August 15-17 Storm Removed	94
4.3.4	Number of Days with Rain by Day of the Week	95
4.3.5	Hourly Distribution of Precipitation	97
4.4.1	Rainfall Duration versus Intensity	101
5.2.1	Distribution of Precipitation Outside Calgary - Elevation Removed	105
5.3.1	Distribution of Precipitation in Calgary - May 16 to September 30, 1978	108
5.3.2	Per cent Deviation from the Airport Rainfall Total, May 16 to September 30, 1978 .	111
5.4.1	Distribution of Precipitation in Calgary - Cyclonic Storms	112

LIST OF FIGURES
(continued)

		Page
5.4.2	Distribution of Precipitation in Calgary- All Cyclonic Storms Except August 15-17 ..	115
5.4.3	Distribution of Precipitation in Calgary- Frontal Storms	116
5.4.4	Distribution of Precipitation in Calgary- Localized Convective Storms	118
5.5.1	Storm Tracks of Individual Cells	124
5.5.2	Generalized Storm Tracks	125
5.6.1	Distribution of Precipitation in Calgary- North and Northwesterly wind conditions ..	130
5.6.2	Distribution of Precipitation in Calgary- Easterly wind conditions	132
5.6.3	Distribution of Precipitation in Calgary when mean wind speeds were less than 5 metres per second	134
5.6.4	Distribution of Precipitation in Calgary when mean wind speeds exceeded 8 metres per second	136
5.8.1	Weekday Distribution of Precipitation- Station 20 versus the mean of Stations 4, 6, and 10	142
5.9.1	An Example of Storm Decay with Cloud Seeding - July 22	146
5.9.2	The Spatial Distribution of Precipitation in Calgary - Seeded Storms	147

CHAPTER ONE : INTRODUCTION

1.1 Introduction

The field of urban micro-climatology is a relatively new endeavour. Its development was triggered by the problems caused by adverse air quality conditions found in urban industrial areas at the turn of the century (Maisel, 1971). In recent decades, however, much attention has been focussed on the study of temperature fields in urban areas. In addition, recent detailed reports on the levels and distributions of humidity, wind, clouds, and precipitation in urban areas have also been carried out. Results indicate that both natural and man induced forces interact to create 'urban climates' that are somewhat unique from nearby rural areas.

Urban related precipitation anomalies were first reported in North America by Landsberg (1956). His work in Tulsa, Oklahoma led him to conclude that this city received more rainfall than the surrounding countryside and was experiencing an upward trend in precipitation receipt as time progressed. These anomalies were attributed to the impact of the city itself on precipitation processes.

Numerous investigations in other North American cities have occurred since the 1950's. The largest and most comprehensive of these, a project in the greater St. Louis area called Metromex (METROpolitan Meteorology

EXperiment), has allowed scientists to conclude that the built up area of this city does in fact modify precipitation processes (Changnon et al., 1971; Huff and Changnon, 1972; Atmospheric Sciences Section, Illinois State Water Survey, 1974; Auer and Dirks, 1974; Gatz, 1974; Huff and Schickedanz, 1974; Lowry, 1974; Semonin and Changnon, 1974; Huff, 1975; and Principal Investigators of Project Metromex, 1976).

The benefits of intensive urban precipitation studies, such as these, are many. Firstly, increased knowledge on cloud processes is gained. Secondly, there are practical implications. If the forces which control the distribution of precipitation in urban areas can be understood and if changes in the city or the city's site effect adjustments in precipitation which are consistent from city to city, then the spatial distribution of precipitation in urban areas may be predicted. Thus, intelligent decisions with respect to drainage and sewage systems, transportation facilities, and agricultural operations may be made. A contribution to hydrology may also be made by providing runoff estimates and water quality information from urban areas.

It is the aim of this thesis to perform an investigation into precipitation in Calgary, Alberta. The theme of the study is the documentation and explanation of the spatial distribution of precipitation in Calgary for the summer of 1978. The effects of a variety of natural and man created phenomena on the observed patterns are discussed.

1.2 Factors Affecting the Spatial Distribution of Precipitation at a Microscale

The rainmaking process is a complex one characterized by high variability over time and space. At a microscale, the spatial variability that one observes is related essentially to topographic, wind, synoptic and seasonal parameters. In addition, local precipitation regimes are affected by proximity to water bodies and urban areas.

Numerous studies in topographically diverse areas indicate that at a microscale, the distribution of precipitation may be strongly influenced by four topographic parameters: elevation, land orientation, slope angle, and exposure (Spreen, 1947; Reid, 1973). Elevation alone accounts for only a modest percentage of the variation in precipitation (Spreen, 1947; Schermerhorn, 1967). Its impact on precipitation receipt is largely controlled by the direction of moisture travel (Donley and Mitchell, 1939), land orientation (Smithson, 1974), and synoptic conditions (Williams and Peck, 1962; Duckstein et al.,1973; Longley, 1975). The impact of slope aspect and angle on precipitation receipt is a function of wind speed and direction as well as the ability of the land to funnel a storm or induce local convergence (Reid, 1973; Smithson, 1974). Exposure is particularly important when dealing with large topographic barriers (Donley and Mitchell, 1939; Schermerhorn, 1967).

As previously implied, the effect of wind direction on precipitation is strongly associated with topographic blocking, steering, and lifting mechanisms. Wind speed has been found to be particularly important in explaining precipitation patterns during orographic precipitation. A positive relationship between the amount of precipitation received during an orographic event and wind speed exists (Gilman, 1964). Zobel (1965) found no such relationship to exist between wind speed and rainfall rate for frontal storms.

Synoptic conditions affect the degree of spatial variability in precipitation. In Britain (Lawrence, 1973), western Canada (Canada, Department of Transport, 1967), and many other locations, the synoptic condition most strongly associated with the higher values of daily areal rainfall, is the cyclonic type. Although cyclones are known to be characterized by constant structural change, the growth-decay cycle through which the storm passes does not, because of the large storm size, result in extreme spatial variability of rainfall at a local scale. A convective type storm, on the other hand, can be a very local phenomenon. As a result, multicell convective storm rainfall of low duration is usually characterized by the sharpest spatial profiles (Huff and Stout, 1952; Craddock and Wales-Smith, 1977; and Keers, 1977). The areal distribution of frontal rainfall is more uniform than for convective types, as is precipitation induced by upslope motion (Linsley and Kohler, 1951). This is due to the increased simplicity of frontal and orographic precipitation in comparison to convective types.

The urban area alters atmospheric processes and so too affects the spatial distribution of precipitation.

> In general, the city through alterations of the local temperature, moisture, and wind fields plus the addition of nuclei from aerosols, acts to trigger and enhance cloud and rain activity.
>
> Changnon, 1979, p. 40

A detailed literature review of urban precipitation studies follows in Section 1.3.

1.3 Urban Precipitation Studies - Literature Review

The most comprehensive urban precipitation research to be carried out in North America is the project, Metromex. Its study area encompasses greater St. Louis, an area of 700 km^2 with a population of 1.8 million at the time of the project's inception (Auer and Dirks, 1974).

Direct impetus for the inception of Metromex came from anomalous findings by Changnon in the La Porte, Indiana area. These findings suggested an urban precipitation enhancement process that resulted in increased total precipitation and an increased number of days with rain, thunderstorms and hail since 1925 (Changnon, 1968).

The goals of Metromex are "to quantify and discover causes for, and to assess the consequence of urban-induced weather effects at St. Louis" (Principal Investigators of Project Metromex, 1976, p. 304).

Field work for the project began in 1971, with much of the work focussing on summer precipitation. Results to date suggest that a very real rainfall modification process is occurring as a result of the urban complex of St. Louis Some of the most important modifications are:

1. Various thunderstorm conditions increased by 10 to 115 %.
2. Hailstorm conditions increased by 3 to 330 %.
3. A tendency toward heavier rainfall by 35 to 100 % occurred.
4. Strong wind gusts increased by 90 to 100 %.

Radar enabled further observations to be made:

5. 44 % of all radar echoes (cloud images) that

crossed the urban area of St. Louis were affected by it. Thus, storms tended to be areally larger, more vigorous, and longer lasting. This is partially explained by the high incidence of echo merging that occurred over the urban area (Changnon, 1976).

6. Area-normalized frequency of first echo formation over the city and in the near downwind region was approximately a factor of two greater than for nearby rural regions (Braham and Dungey, 1978). This caused precipitation to occur up to three times as frequently (Braham, 1974).
7. The distribution of cloud heights over the urban area differed from the usual bimodal distribution found in rural areas (Braham and Wilson, 1978).

The centre of these anomalies was located 15-30 km downwind of the city core, although urban effects were evident up to distances of 40 km downwind of the city (Huff, 1975).

In general, the urban effect was found to be associated with the stimulation of ongoing storms, as opposed to an increase in the frequency of storm events (Huff and Vogel, 1978). Enhancement tended to occur mainly on weekdays (Braham and Dungey, 1978). The synoptic conditions most responsible for the anomalies include cold fronts, squall lines, and major convective entities (Vogel and Huff, 1978).

The causes of the enhancement process, as outlined by Changnon et al. (1976) are related to thermodynamic and mechanical changes induced by the urban area and to coalescence enhancement caused by added condensation and ice nuclei.

Less detailed studies have been carried out in the following major United States centres: Chicago, Cleveland, New Orleans, Houston, Indianapolis and Washington (Huff and Changnon, 1973). Results suggest that urban precipitation enhancement (increases in precipitation by 10-30 %) was related to city size, industrial nuclei generation and urban thermal effects.

In Washington, D.C., Harnack and Landsberg (1975) examined convective showers as they related to the urban heat island. In London, England, Atkinson (1971, 1975, 1977) concluded that the mechanical and thermodynamic effects of a city on air flow strongly influence the precipitation process. Studies in the Detroit-Windsor area showed a warm season rainfall increase of 20-30 %. This was attributed to increased particulate matter in the urban airshed and to the urban heat island (Sanderson et al., 1973; Sanderson and Gorski, 1978). In Bombay, India, Khemani and Murty (1973) examined the effects of urban industrial pollution on precipitation. The regime downwind of the urban industrial complex recorded an increase in rainfall of approximately 15 %. For the urban areas of

Amsterdam and Rotterdam, Buishand (1979) found evidence of an increase in precipitation with increased industrialization.

On a smaller scale, the effect of individual industrial operations on precipitation have been examined by Lowry and Probáld (1978) and Ogden (1969). However, both studies concluded that no significant effect due to the steelworks examined could be detected.

In summary, urban areas have the potential to modify precipitation processes in the following ways:

1. Atmospheric destabilization as a result of well-established urban heat islands.
2. Modification of microphysical and dynamic processes caused by the addition of cloud condensation and ice nuclei from industrial atmospheric discharges.
3. Increased low-level mechanical turbulence from urban created obstructions to airflow.
4. Modifications of low-level atmospheric moisture content, due to additions from industrial generated plumes emitted from stacks and cooling towers, along with changes in the evapotranspiration process within the city resulting from the high percentage of impervious surfaces in the core of urban areas.

Sources: Changnon et al.(1971); Huff and Changnon (1972); Schickedanz (1974); and Atkinson (1975).

A summary of urban versus rural precipitation is provided in Table 1.3.1.

TABLE 1.3.1

A COMPARISON OF URBAN AND RURAL PRECIPITATION

Element	City Value Compared to Rural Value
Precipitation	
Amount	5 - 30 % more
Days with less than 5 mm	10 % more
Days with more than 30 mm	50 - 100 % more
Thunderstorms	13 - 45 % more
Days with Hail	30 - 450 % more
Relative Humidity	
Mean	6 % lower
Cloud and Fog	
Cloud, amount	5 - 10 % more
Convective Cloud Base	300 - 600 meters higher
Fog, summer	5 % less

Sources: Huff and Changnon (1973); Changnon et al. (1976); Principal Investigators of Project Metromex (1976); and Changnon (1978).

1.4 The Study Area

1.4.1 Calgary's Regional and Physiographic Setting

Calgary (51^0N, 114^0W), a rapidly growing city (3.5 per cent annually) with a current population of over one-half million, is situated at the boundary between the western plains and foothills physiographic units. Its location is approximately 70 km east of the Front Ranges of the Rocky Mountains. As such, the city of Calgary is built on rolling topography that is characterized locally by a southeasterly downward trend in slope. The mean elevation of the city is just under 1100 m a.s.l. (Fig. 1.4.1). The difference between the highest and lowest point exceeds 200 m.

The most prominent physiographic features of the area include the Bow and Elbow River Systems, which converge just east of the Central Business District, Glenmore Reservoir on the Elbow River in southwest Calgary, and the prominant Broadcast and Nose Hills, located to the west and north of the city centre respectively. The terraced Bow valley is approximately 60 m deep, controlling the slope of the land to the southeast. The elevation rapidly increases perpendicular to the river valley giving the developed portion of the city the shape of an inclined, elongated bowl.

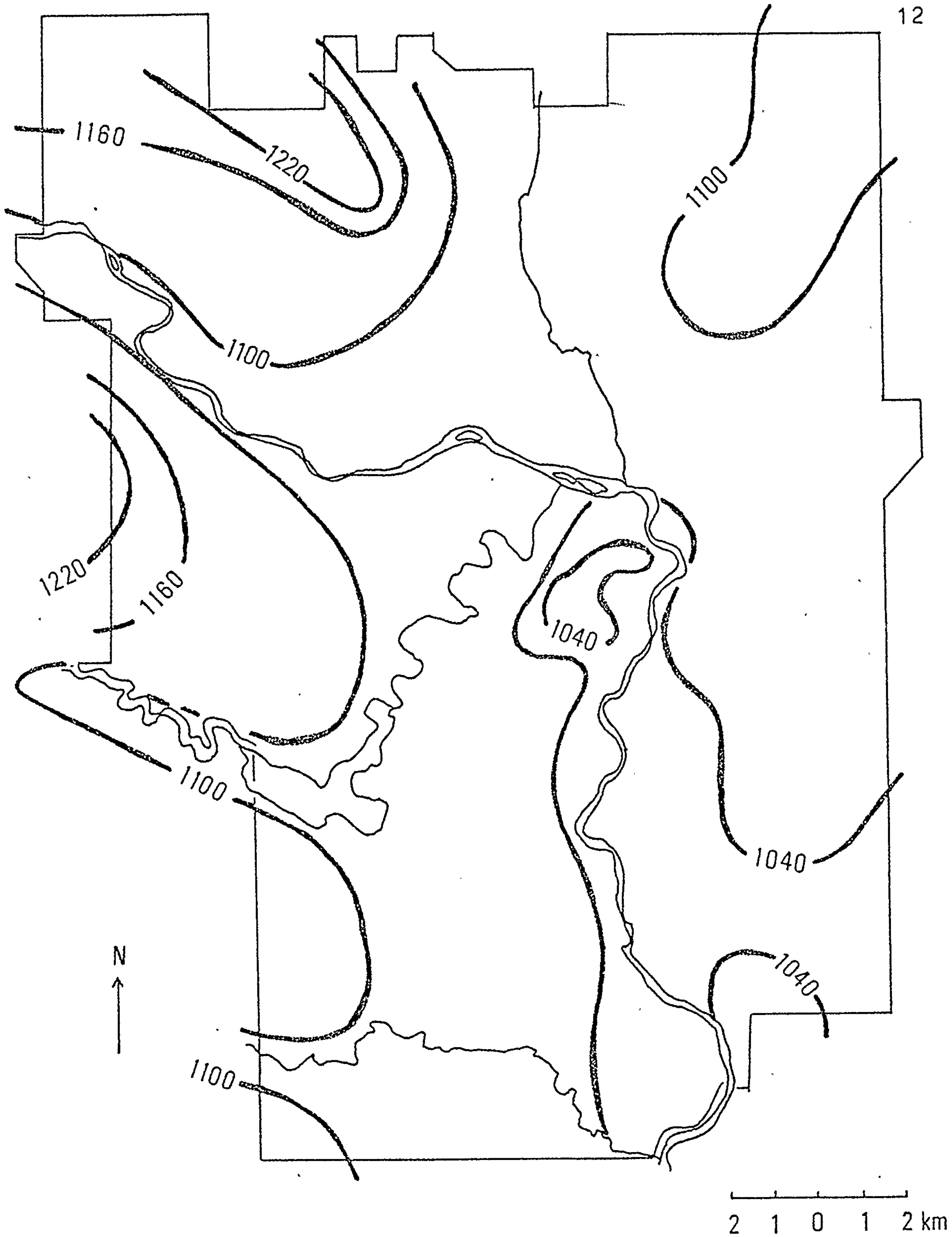


FIGURE 1.4.1

GENERALIZED TOPOGRAPHY (m)

1.4.2 Calgary's Urban Complex

Although Calgary has a modest population of one-half million, areally it boasts being the largest city in Canada, covering 419 km^2 (City of Calgary, 1977). The low population density, as well as the rapid population growth of approximately 3.5 % annually (1973-1978 mean), make Calgary unique among Canadian cities.

The land use patterns within the city show a high concentration of the commercial-retail sector in the downtown core area. Industrial zones tend to be located in the southeastern portion of the city with more recent developments of industrial parks in the northeastern part of the city. Large pockets of open space and public parks are located throughout the city. The most notable areas of open space are located within newly annexed regions near the periphery of the city, in the Nose and Broadcast Hills areas,and along Fish Creek and the southern stem of the Bow River (Fig. 1.4.2).

Climatic studies within the city have indicated that the structure of the city does appear to affect the local climate. Extensive investigation into Calgary's horizontal and vertical temperature distributions have revealed the development of a classical heat island under clear skies and low wind speeds. At ground level, higher temperatures were associated with the CBD and the industri-

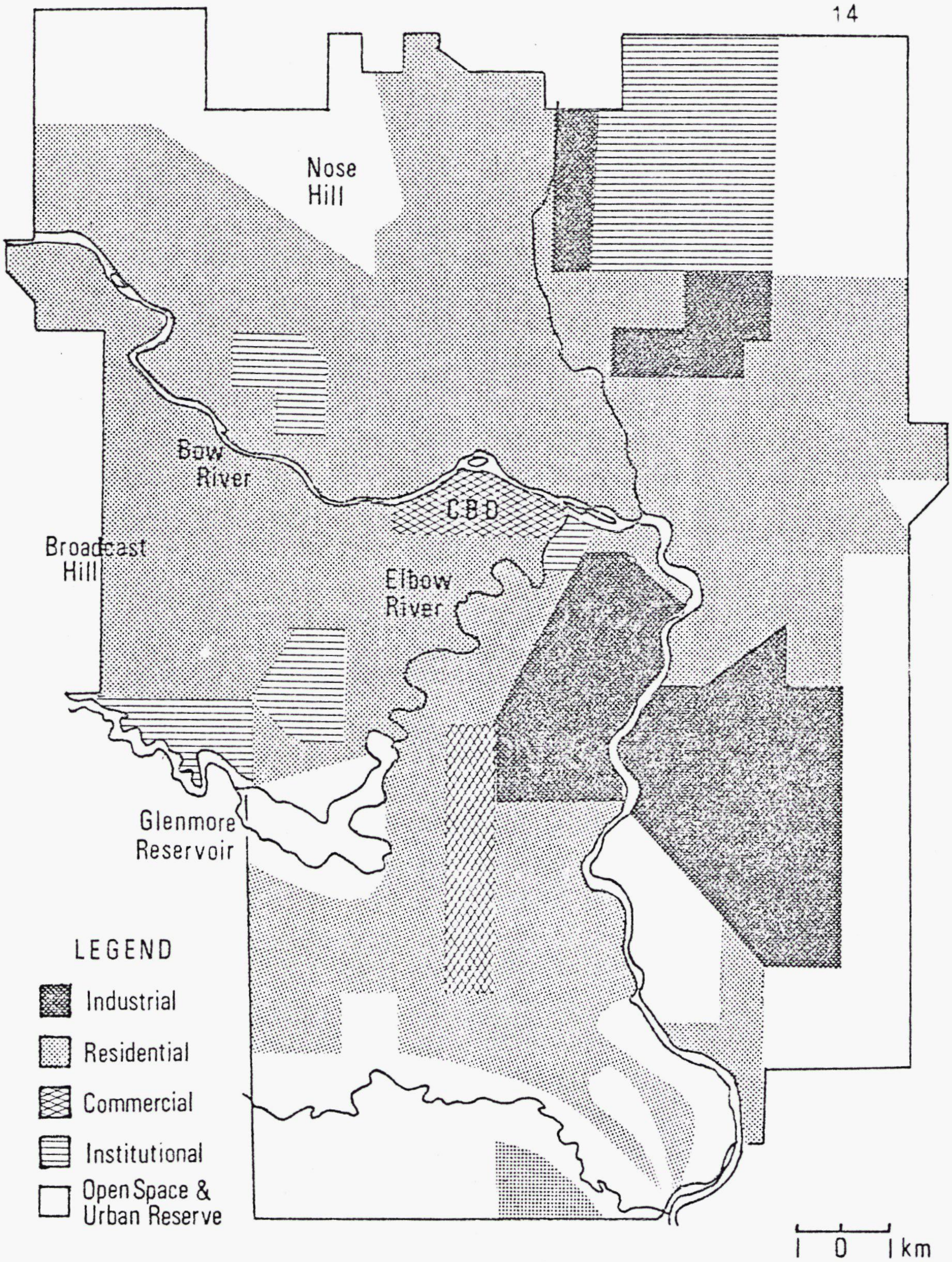


FIGURE 2.4.1

SCHEMATIC LAND USE MAP OF CALGARY
SOURCE: CITY OF CALGARY

al area of Ogden in SE Calgary (Truch, 1977; Nkemdirim et al., 1977) (Fig. 1.4.3). Peaks in mean mixing depth were also found to occur over the CBD and Ogden (Leggat, 1978).

Numerous researchers have also been engaged in air pollution studies within the city. These studies indicate that pollutants are stratified in Calgary's airshed. The situation appears to be one of nocturnal stratification and mainly daytime uniformity (Alberta Environment, 1976).

1.4.3 Calgary's Regional Climate

Calgary's climate is largely controlled by its continental location and proximity to the Rocky Mountains. In general, Calgary's climate may be described as being cold and temperate. The major climatic indicators, as recorded at Calgary's International Airport are summarized in Table 1.4.1.

Winters in the study area are best noted for their rapid changes within short periods of time. This variability is the result of oscillations between warm maritime polar air and invasions of cold continental arctic air. The former condition results in chinook weather, which is influential approximately 30 % of the time during the months of December, January, and February (Danielwicz, 1977).

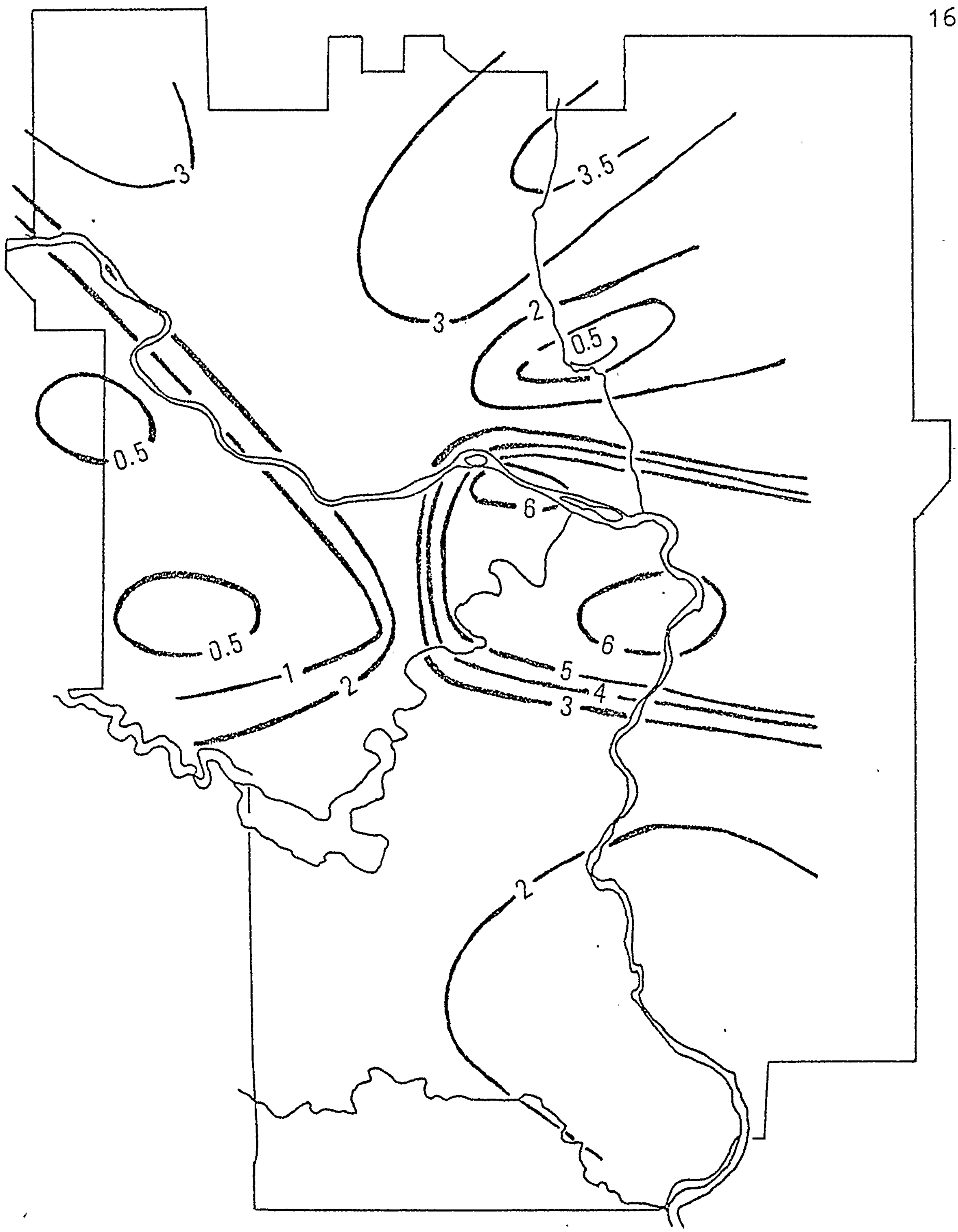


FIGURE 1.4.3

DISTRIBUTION OF MEAN ANNUAL TEMPERATURES IN CALGARY (°C)

NKEMDIRIM AND TRUCH (1977)

TABLE 1.4.1

MEAN CLIMATIC DATA FOR CALGARY

Month	Mean Daily Temperature (ZC)	Mean Daily Maximum Temperature	Mean Daily Minimum Temperature	Hours with Bright Sunshine	Mean Wind Speed (MPS)	Highest Frequency Direction	Mean Total Precipitation (mm)	Greatest Precipitation (mm)
Jan	-10.9	- 5.3	-16.7	101	4.5	W	17.0	25.4
Feb	- 7.9	- 1.6	-13.3	117	4.5	S	19.8	27.7
Mar	- 4.3	1.3	- 9.8	146	4.6	N-S	20.3	24.1
Apr	3.3	9.6	- 2.9	188	5.2	W	29.5	45.7
May	9.3	15.9	2.8	240	5.1	NNW	49.8	65.0
Jun	13.2	19.4	6.9	234	4.9	NNW	91.7	79.3
Jul	16.5	23.5	9.5	318	4.2	NNW	68.3	95.3
Aug	15.2	22.2	8.2	275	4.1	NNW	55.9	80.8
Sep	10.7	17.4	3.9	186	4.6	NNW	35.3	67.3
Oct	5.7	12.3	- 1.0	159	4.7	W	18.8	45.7
Nov	- 2.6	3.2	- 8.4	111	4.4	W	16.0	35.6
Dec	- 7.6	- 1.7	- 3.4	91	4.5	W	14.7	21.8
Year	3.4	9.7	- 2.8	2166	4.5	NNW	437.1	95.3

Sources: Canada Department of Transport (1968)
Environment Canada (1975 a, 1975 b, 1975 c)

Spring and autumn are very short transitional seasons. In general, spring is accompanied by relatively heavy precipitation (Table 1.4.1), due to cyclones passing south of the Calgary area. The transition from summer to winter is marked by a rapid deterioration of temperatures and a wind shift to a more westerly flow. This may occur anytime from early September to December, depending on the southward extension of the arctic continental air masses.

In summer, the general intensity of the circulation is much less than in other seasons. Variation in precipitation receipt is largely a function of the strength of the zonal circulation. Strong zonal flow reflects low precipitation and meridional flow high precipitation (Borchert, 1950). Summer days are warm but nights are cool (average minimum = $8.3^{\circ C}$), due to Calgary's high elevation.

Calgary's average annual precipitation is 437.1 mm. Approximately one-third falls as snow. Seventy per cent of the annual rainfall occurs in spring and early summer. June, the month with the most rainfall, produces an average of 91.7 mm. December, the driest month, averages less than 15 mm. July is characterized as the month of maximum thunderstorm and hail activity.

1.5 Objectives of the Study

Within the past six years, there has been extensive research into Calgary's temperature fields (Truch, 1977; Nkemdirim et al., 1977; Leggat, 1978). However, no attempt has been made to define or explain Calgary's precipitation regime.

Research in numerous American cities has shown that urbanism can have marked effects on the natural processes of precipitation. Other factors, such as topography, wind, and proximity to water bodies, have also been documented as having critically influenced the precipitation processes and the resultant spatial patterns of precipitation.

It is the goal of this thesis to investigate the distribution of precipitation in Calgary, Alberta. The objectives of the thesis are the examination of the spatial distribution of rainfall in Calgary and the assessment of the physical and environmental controls that influence this distribution. In this regard, information and analysis are presented to demonstrate:

1. the quality of rain gauge data used to define the observed patterns of precipitation
2. whether any temporal trends in precipitation

exist for Calgary or for rural localities peripheral to the city

3. temporal aspects of the data collected during the study period
4. how Calgary's precipitation regime compares to that of the surrounding rural areas
5. the effects of (a) synoptic and wind conditions
   (b) topography
   (c) storm track position
   (d) water bodies
   (e) the urban structure
   (f) intentional and unintentional cloud seeding

   on the spatial patterns of precipitation in Calgary.

A special study on the use of radar as a source of precipitation information is presented. It is shown that such information can contribute towards an understanding of storm structure, development and movement.

The contributions of this thesis to the field of microclimatology are twofold:

1. It provides information on the controls which define the precipitation patterns in the urban area of Calgary, and thus adds to man's

understanding of the controls which influence the spatial distribution of precipitation in urban areas in general.

2. Results from this investigation will form a basis for future studies designed to evaluate the effect of city growth on the spatial distribution of rainfall in Calgary.

1.6 The Study Period

The time period under investigation is May 16 to September 30 inclusive. During this period, a dense network of gauges was operated within the city of Calgary. Results from the network indicate that 51 storms, which spanned 74 days, occurred.

According to precipitation records from Calgary International Airport, the study period received approximately 25 % more precipitation than was normal. In general, the amount of precipitation that falls within this timeframe represents more than 60 % of the annual average.

2.1 Introduction

In chapter two, data sources and data quality are discussed. The objectives of the chapter are as follows:

1. To outline the sources of rain gauge data used in the study.
2. To establish the level of data quality.
3. To examine the effect of inadequate gauge exposure on data quality.
4. To determine the minimum gauge density that would be needed to reliably measure Calgary's mean precipitation.

Throughout the study period, a dense network of 20 rain gauges, distributed throughout the city of Calgary, was operated. The mean gauge density was approximately one gauge per 20 km^2 .

Of the 20 gauges used in the study, 15 were Canadian standard copper gauges, 4 were automatic recording tipping bucket gauges, and 1 was a weighing-type gauge with a recording device.

The ideal situation in a comparative study is to use only one style of gauge. However, automatic recording gauges were included in the network for two reasons:

1. To increase the gauge density to approximately one gauge per 20 km^2.

2. To provide information on the timing of rainfall events, rainfall intensities and durations.

In order to minimize the discrepancy between rainfall measurements by standard and tipping bucket gauges, the tipping bucket gauges at Stations 6, 10, and 20 were carefully calibrated on the basis of rainfall intensity. The resultant calibration curves were then used to interpret the records. Thus, the error effect caused by the tipping action of these automatic recording gauges was minimized. The tipping bucket gauge at Station 4 was supported by a standard gauge for corrective purposes.

2.2 Rain Gauge Network Design

The design of a precipitation network should incorporate two essentials:

1. The amount of rainfall caught by each individual gauge should approach the ideal of 'true catch', i.e. the catch inside the rain gauge should represent the amount of precipitation that actually fell at that location.
2. The network or composite of gauges should reflect the purpose of the study.

In consideration of the former, several guidelines, which must be rigidly adhered to in order to approach 'true catch', exist. Neglect of any of these considerations may lead to substantial error in gauge catch.

The major cause of error in precipitation gauge measurement is created by disturbed wind fields (Robinson and Rodda, 1969; Larson and Peck, 1974). This error increases with site wind speed and is a function of either:

1. site turbulence created by topographic variation or obstacle position, or
2. turbulence and increased wind speed in the vicinity of the gauge orifice, resulting from the obstacle of the gauge itself to the wind flow.

In the latter case, as the air rises to pass over the gauge, precipitation droplets that would normally have been caught by the gauge are instead deflected and carried further downwind. This results in an unrepresentative catch (Robinson and Rodda, 1969). Since, in general, wind speed increases with height above ground level, gauge catch errors also tend to increase with height. The relationship between gauge catch error and gauge height has been found to be exponential (Larson and Peck, 1974).

Although the use of wind shields has been recommended, work by Wilson (1954) and Larson and Peck (1974) suggests that shields have little beneficial effect for liquid precipitation measurement. The solution to gauge created wind error appears to lie in locating rain gauges at or near ground level (Stanhill, 1958). Since over rough terrain the aerodynamic boundary is approximately 30 cm above ground (Reynolds, 1971), the Canadian guideline for standard gauge placement, that of the gauge orifice being located 30.5 cm above ground level, appears reasonable. It is this guideline which has been applied in this study.

Wind error created by site turbulence or by near-by obstacles can give rise to either excess or deficient gauge catch (World Meteorological Organization, 1971). A guideline for gauge placement has been defined by the World Meteorological Organization (1971, VII.4):

> The gauge should be exposed with its mouth horizontal over level ground and surrounding objects should not be closer to the gauge than a distance equal to four times their height, but subject to this limitation, a site that is sheltered from the full force of wind should be chosen, provided however that the shelter does not provide larger disturbances in the wind field than the effects which one is trying to avoid.

Ideally, a naturally well-protected site is optimal (Larson and Peck, 1974).

Another source of gauge catch error is loss by evaporation (Gilman, 1964). The amount of loss by evaporation is a function of temperature and gauge characteristics, such as construction material and insulative properties. The material used for Canadian standard gauges is copper. Reynolds (1965) classified copper as being a good material, second only to ebonite. Nonetheless, there is an evaporative problem. Copper is characterized by high thermal conductivity, which leads to increased internal temperature by day with resultant evaporative losses, and to decreased temperature by night leading to deposition of dew. Another inherent problem in the use of copper is that during its life, copper's surface changes from a high polish with low radiative absorption and rapid runoff of water over the internal surface, to a dull finish with higher radiative absorption and more water being used to wet the inside of the cylinder (Maidens, 1965).

Canadian standard gauges were experimented with in order to estimate losses by evaporation and wetting for the study period involved. Results are discussed in Section 2.4.4.

Gauge rim sharpness is also important when considering possible catch errors. It is best to use a sharp rimmed gauge, which has the ability to split raindrops and thus reduce the problem of faulty catch. All gauges used in this study were of high quality. No problems with deformation of gauge orifices occurred.

The major criteria for obtaining true catch for individual gauges have been outlined. An example of a standard gauge, whose siting approaches optimum conditions, has been included to illustrate the points mentioned above (Plate 1):

Plate 1

This gauge, located in southwest Calgary (Station 14), was positioned in such a way so as to avoid problems caused by disturbed wind fields. The gauge was naturally well protected by its valley location. No major obstacles were located in close proximity to the gauge. The gauge itself was new and was mounted on a plywood platform in order to conform with Canadian standard gauge height placement guidelines. In addition, the gauge was equipped with a metal cover, which was used to shelter the gauge orifice when the lawn was being mowed or watered.

The network or composite of gauges was designed to best accommodate the theme of the study - the spatial distribution of precipitation in Calgary. Criteria used are discussed below.

The main objective of this thesis is to document and explain the spatial variation of precipitation in Calgary. In order to accomplish this task, the gauge network must be suitably designed for this purpose. A relatively uniform distribution of gauges, which fully represents the topographic diversity of the area would be ideal. This would ensure that all parts of the city were sampled. In addition, the effect of elevation on the spatial receipt of precipitation could be isolated.

To this end, the city was divided into 20 rectangular zones of 20 km^2 each. Into each zone one gauge was to be positioned. Although the complex city boundaries did not conform totally to this process, the fit was adequate. In order to provide information on rainfall intensities from each quadrant of the city, one tipping bucket gauge was allocated to each of the four city quadrants (i.e. the NW,NE,SW, and SE).

In positioning gauges within the zones, priorities were on ensuring good topographic representation and providing adequate gauge exposure. These priorities were sometimes compromised by decisions regarding accessibility and safety, however.

Even after provisions were made for daily access to the sites, protection from vandalism and other forms of human and animal intervention, and relatively good site exposure, the resultant distribution of gauges did approach uniformity and was representative of Calgary's topography.

Statistical tests were carried out in order to measure the degree of uniformity and the degree to which topography was expressed in the selection of gauge sites.

A chi-square test was used to measure topographic representation. The city was divided into topographic zones, each with a range of 38 m. The percentage of land that fell into each elevation zone was calculated. Ideally, the distribution of gauges throughout the city would represent the distribution of topographic zones. A chi-square test comparing the actual frequency of gauge placement within topographic zones to that expected by proportional representation indicated that at a significance level of .05, no statistical difference between the actual and theoretical frequencies existed. Examination of site elevations did reveal a slight tendency toward over representation of the lower and middle elevations and an under representation of the higher land, however. Hence, extrapolations of precipitation totals over the higher regions may be less reliable than for other parts of the city.

In order to measure the degree of uniformity in the distribution of gauges, a Kolmogornov-Smirnoff test of nearest neighbour distances was used. At a significance level of .05, the distribution of gauges varied significantly from randomness, tending toward uniformity.

Thus, a relatively uniform distribution of gauges, which for the most part represented Calgary's topography, was achieved (Fig. 2.2.1).

2.3 Logistics of Data Collection

The design for data collection was such that it would ensure an almost complete sample of rain storms for the study period. To this end, four 'check sites' were utilized, one in each of the four quadrants of the city. Each morning at 0700 MDT, a phone call was placed to each check site. At this point in time, a rain can was checked for any precipitation that might have fallen in the past 24 hours. If even a trace of precipitation was found at any of the four sites, or if any of the four reporters had visually observed a shower, then a complete tour of all 20 sites in the Calgary rain gauge network was undertaken to check for and/or measure the precipitation which may have fallen. This resulted in what has been estimated to be a complete sample for the 4½ month study period.

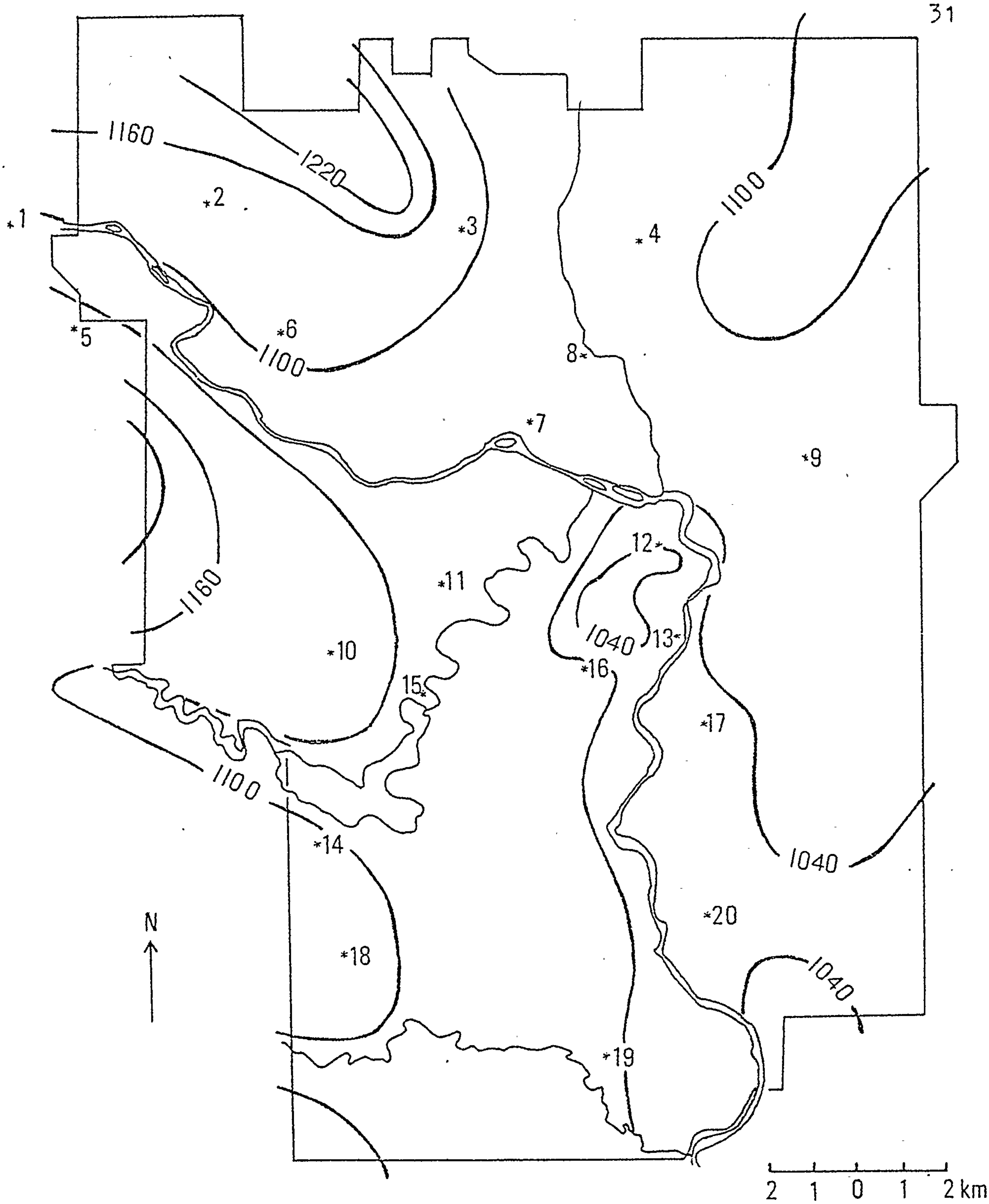


FIGURE 2.2.1

LOCATIONS OF RAIN GAUGES (TOPOGRAPY SUPERIMPOSED)

2.4 Data Quality Controls

2.4.1 Introduction

In order to get a measure of how large the gauge catch errors were as a result of improper exposure, or loss by evaporation and wetting, three controls were employed:

1. close examination of site exposures and wind conditions during precipitation events
2. experimentation with variable site exposure in a dense gauge network
3. experimentation with copper standard gauges to test for loss by evaporation and wetting.

2.4.2 Site Exposure Examined

Although in the absence of wind,gauge catch tends to approach 'true catch', studies indicate that rain storms are in general accompanied by considerable wind speed (Wilson, 1954). Thus, gauge exposure is a source of potential catch error that must be contended with and must be viewed in conjunction with wind data.

For the study period involved, continuous wind records from three sites at which cup anemometers were mounted were used. These included:

1. Station 4 - Calgary International Airport
   - mast height: 20 m
2. Station 6 - University Weather Research Station
   - mast height: 11 m
3. Station 20- CIL Explosives Plant
   - mast height: 8.6 m

Hourly wind speed and direction data were abstracted from the records for each site.

With regards to gauge position, 11 of the 15 standard gauges were positioned such that the gauge orifice was 30.5 cm a.g.l., according to Canadian standards. Gauges at Stations 3, 11 and 17 were located on top of wooden fences approximately 150 cm high. The reasons for this were twofold:

1. Buildings were located in close proximity to these gauges such that at ground level the gauges were underexposed. By elevating the gauges, an overall better exposure was achieved, i.e. the exposures more closely approached the recommended distance to obstacle-height of obstacle ratio of 4.0.
2. The gauges were located in areas where pedestrian and pet traffic were substantial. It was believed that both gauge safety and catch reliability would

have been threatened if the gauges had been positioned at ground level.

The gauge at Station 15 was located on top of the filtering beds at Glenmore Dam Waterworks, approximately 4.5 m a.g.l.. This gauge is part of a more permanent network within the city and therefore could not be moved. Due to the height of the gauge, wind error at this site may have caused substantial catch reduction, particularly when the local wind speed exceeded 4 m sec^{-1}, but catch losses were not quantified.

The gauge orifices for the recording instruments at Stations 4, 6, 10, and 20 were situated between 62 and 94 cm a.g.l. (Table 2.4.1). At Station 1, the gauge was a weighing-type gauge, standing 91 cm high. It was positioned on top of a building, giving the gauge mouth an altitude of approximately 7 m a.g.l.. This gauge was also part of the semi-permanent gauge network in Calgary. The loss in catch due to excessive winds at this height is believed to be substantial but again was not quantified. Any precipitation anomalies observed in the vicinity of Station 1 must be interpreted with caution.

In addition to the potential problems related to gauge height, the effects of nearby obstacles on gauge catch must also be considered. All obstacles located within a distance range of four times the height of the obstacle

TABLE 2.4.1

CHARACTERISTICS OF THE RECORDING GAUGES

Station No.	Gauge Mouth Diameter	Height of Gauge Mouth a.g.l.	Type of Gauge
1	36.8 cm	700 cm	Weighing Type
4	26.7 cm	61 cm	MSC Tipping Bucket
6	30.5 cm	95 cm	Belfort Tipping Bucket
10	24.1 cm	51 cm	P501-I Tipping Bucket
20	24.1 cm	51 cm	P501-I Tipping Bucket

were measured. Appropriate distance-height ratios were derived.

On the basis of exposure (Table 2.4.2) and wind (Table 2.4.3 and Fig. 2.4.1) a qualitative assessment of the reliability of gauge catch was made for each event. Any occurrence of sub-optimal exposure was considered to be a case of possible error. Those sites at which sub-optimal exposure was suspected were identified (Table 2.4.4). Only 9 of the 20 gauges were characterized by close to optimal exposure conditions during all storms (Table 2.4.4).

The gauges at Stations 1 and 15, located at 7 m and 4.7 m respectively, were constantly in danger of being overexposed. Work by Larson and Peck (1974) among others suggests that at a wind speed of approximately 4.5 m sec^{-1} catch deficiencies for liquid precipitation are approximately 10 %, increasing to 15 % at speeds of 6.5 m sec^{-1}. For the study period involved, the percentage of storms accompanied by a mean wind speed of greater than 5 m sec^{-1} varied inversely with the height of the anemometer above ground level (Fig. 2.4.1). At the lowest level measured, that of 8.6 m a.g.l., mean wind speed exceeded 5 m sec^{-1} during 10 % of all storms. At heights of 7 m and 4.8 m, wind speeds would in general be lower. Therefore, although catch error is suspect at Stations 1 and 15, errors of greater than 10 % are believed to have occurred less than 10 % of the time. No attempt to quantitatively estimate the

TABLE 2.4.2

SITE EXPOSURE CHARACTERISTICS

Station No.	Height of Gauge Orifice Above Ground Level (meters)	Comments	Approximate Distance - Height Ratios With Wind From the Following Directions* N	NW	W	SW	S	SE	E	NE	Minimum Distance - Height Ratio	Direction of Minimum Distance - Height Ratio	
1	7.00		4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
2	0.30	Site Quality Deteriorated as vegetation cover changed	1.7	2.7	4.0	4.0	4.0	3.0	4.0	1.8	1.0	160°	SSE
3	1.83		4.0	4.0	4.0	4.0	4.0	3.0	4.0	4.0	3.0	160°	SE
4			4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
5	0.30		4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
6			4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
7	0.30	Wire Fence & Trees to West	4.0	4.0	4.0	4.0	4.0	4.0	4.0	1.25	0.97	062°	ENE
8	0.30	Wire Fence to East	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
9	0.30		1.6	4.0	4.0	4.0	4.0	4.0	4.0	4.0	1.60	360°	N
10		Wire Fence to N, NW, NE	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
11	1.84		1.98	4.0	4.0	4.0	1.8	4.0	4.0	3.06	1.80	180°	S
12	0.30	Wire Fence to South	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.80	200°	SSW
13	0.30	Wire Fence surrounding gauge	4.0	2.91	3.09	4.0	4.0	4.0	4.0	4.0	1.87	079°	ENE
14	0.30	Located in Depression	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	3.0	345°	NNW
15	4.80	Wire Fence surrounding gauge	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
16	0.30		4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
17	1.83		2.9	4.0	4.0	4.0	4.0	2.0	4.0	2.1	1.3	122°	ESE
18	0.30		4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0		
19	0.30		4.0	4.0	2.96	3.92	1.46	4.0	1.7	2.0	0.89	340°	NNW
20			4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.80	064°	ENE

* Derived from Site Measurements.
Sample Site Depicted in Appendix 3.

TABLE 2.4.3

WIND DIRECTION FREQUENCIES DURING STORMS

	NW	W	SW	S	SE	E	NE	N
Per cent Storms with Given Direction as a Dominant Component	45.9	37.8	9.5	12.2	10.8	21.6	14.9	58.1

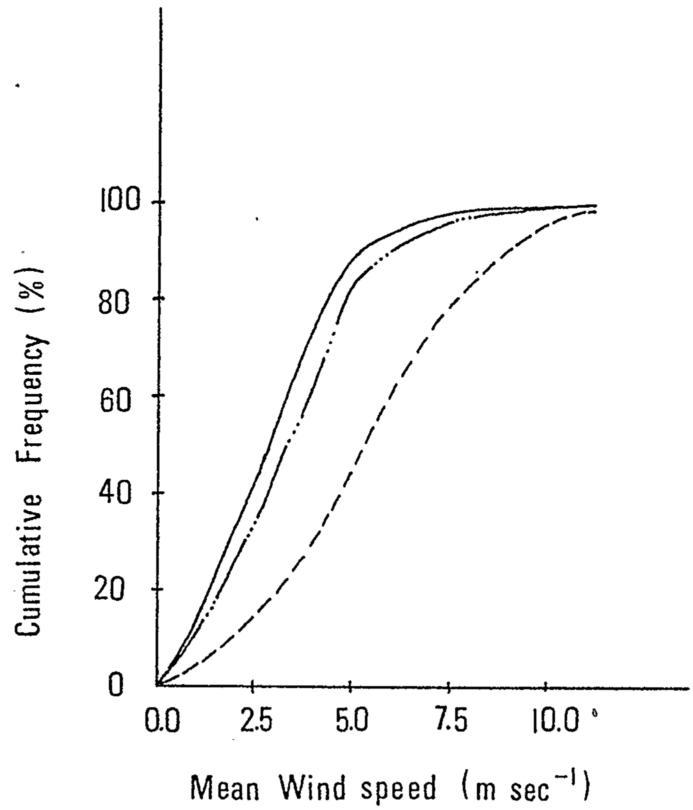


FIGURE 2.4.1

CUMULATIVE FREQUENCY OF MEAN WIND SPEEDS DURING ALL STORMS

TABLE 2.4.4

POTENTIAL FAULTY GAUGE CATCH SITES

(Denoted in table below as 'x')

EVENT		DOMINANT WIND DIRECTION	STATIONS																			
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
May	16	NW	x	x											x		x					
	23-24	E , NW	x	x											x		x				x	
	30-31	NW	x	x											x		x					
June	05-06	N	x	x							x		x				x		x			
	09-10	NW	x	x											x		x					
	11	V	x	x					x		x		x				x		x		x	
	13	W	x												x		x				x	
	15-16	NW	x	x											x		x					
	18	NW	x	x											x		x					
	20	S	x										x				x				x	
	21	SE	x	x	x										x		x		x			
	22	NE	x	x					x				x				x		x			
	23	SE	x	x	x										x		x		x			
	25-26	NW	x	x											x		x					
	29	W , SW	x												x		x		x			
July	01	NW	x	x											x		x					
	02	V	x	x					x		x		x				x		x		x	
	04	NW	x	x											x		x					
	05-06	N	x	x							x		x		x		x		x			
	07-08	NE, S	x	x					x				x				x		x		x	
	09-10	V	x	x					x				x				x		x		x	
	11-12	NW	x	x											x		x					
	17	NW	x	x											x		x					
	17-18	NW	x	x											x		x					
	18-19	NW	x	x											x		x					
	19	V	x	x					x		x		x				x		x		x	
	20	NW	x	x											x		x					
	21	NW	x	x											x		x					
	22	SE	x	x	x												x		x			
	28-29	V	x	x					x		x		x				x		x		x	
	29-30	V	x	x					x		x		x				x		x		x	
Aug	01	NW	x	x											x		x					
	07	NE	x	x					x				x				x		x		x	
	11	V	x	x					x		x		x				x		x		x	
	12-13	V	x	x					x		x		x				x		x		x	
	15-17	V	x	x					x		x		x				x		x		x	
	19-20	N	x	x							x		x				x		x			
	21	V	x	x					x		x		x				x		x		x	
	22-23	E, NE, NW	x	x					x				x		x		x		x		x	
	31	W	x												x		x				x	
Sept	05-08	V	x	x					x		x		x				x		x		x	
	11-13	V	x	x					x		x		x				x		x		x	
	14-16	NW	x	x											x		x					
	17-18	NW	x	x											x		x					
	19	NW	x	x											x		x					
	27	NW	x	x											x		x					

'V' indicates variable wind direction at lower levels gauge deficits at these sites was made because of the lack of wind data for these locations. Correlations between hourly wind magnitude measurements of neighbouring anemometer sites have been found to be uncertain (Vasanji and Gartshorne, 1978).

The 9 remaining sites had exposures that varied with wind direction. The amounts by which catch was underestimated at these sites was found to be a function of both wind speed and direction. For the most part, winds were northerly, northwesterly or westerly (Table 2.4.3). Gauge catch at Stations 2, 9, 11, 13, 14, 17, and 19 are most likely to have been adversely affected by flow from the above mentioned directions, when wind speed was sufficient to create a measurable effect. The gauges at Stations 3 and 7 were most likely to have experienced deficit catch when a dominant easterly wind component existed.

An attempt to quantify the effects of inadequate exposure on gauge catch was made by experimentation with a dense network of standard gauges (Section 2.4.3).

2.4.3 Experimentation with Variable Exposure in a Dense Network of Standard Gauges

From August 1 to September 30 inclusive, a dense network of 18 Canadian standard copper gauges was operated at the University of Calgary Weather Research Station.

The purpose for operating the network was twofold:

1. To examine the spatial variability of precipitation that exists within a dense network characterized by relatively uniform and supposedly optimal gauge exposure, and thus to quantify random errors involved in precipitation measurement.
2. To examine the spatial variability of precipitation that exists within a dense network of gauges characterized by variable exposure and thus to assess the effect of inadequate exposure on gauge catch efficiency.

The area covered was approximately 3230 m^2 in size, accommodating a mean gauge density of 1 gauge per 180 m^2. This was more than 100,000 times as dense as the network of gauges in the city. Its location was $51^{0}04'46''$N and $114^{0}08'26''$W. Its mean elevation was 1109.5 m a.s.l.. The area was relatively flat with a relief of 2.75 m. The vegetation cover was natural prairie grass.

The 18 gauges in the network were divided into two subnetworks. Eight gauges, randomly located in areas of adequate exposure (according to W.M.O.), comprised the control set of gauges. The other 10 gauges were positioned in areas of sub-optimal exposure. All 10 gauges were under exposed to a degree that was similar to or worse than was experienced in the city network (Fig. 2.4.2).

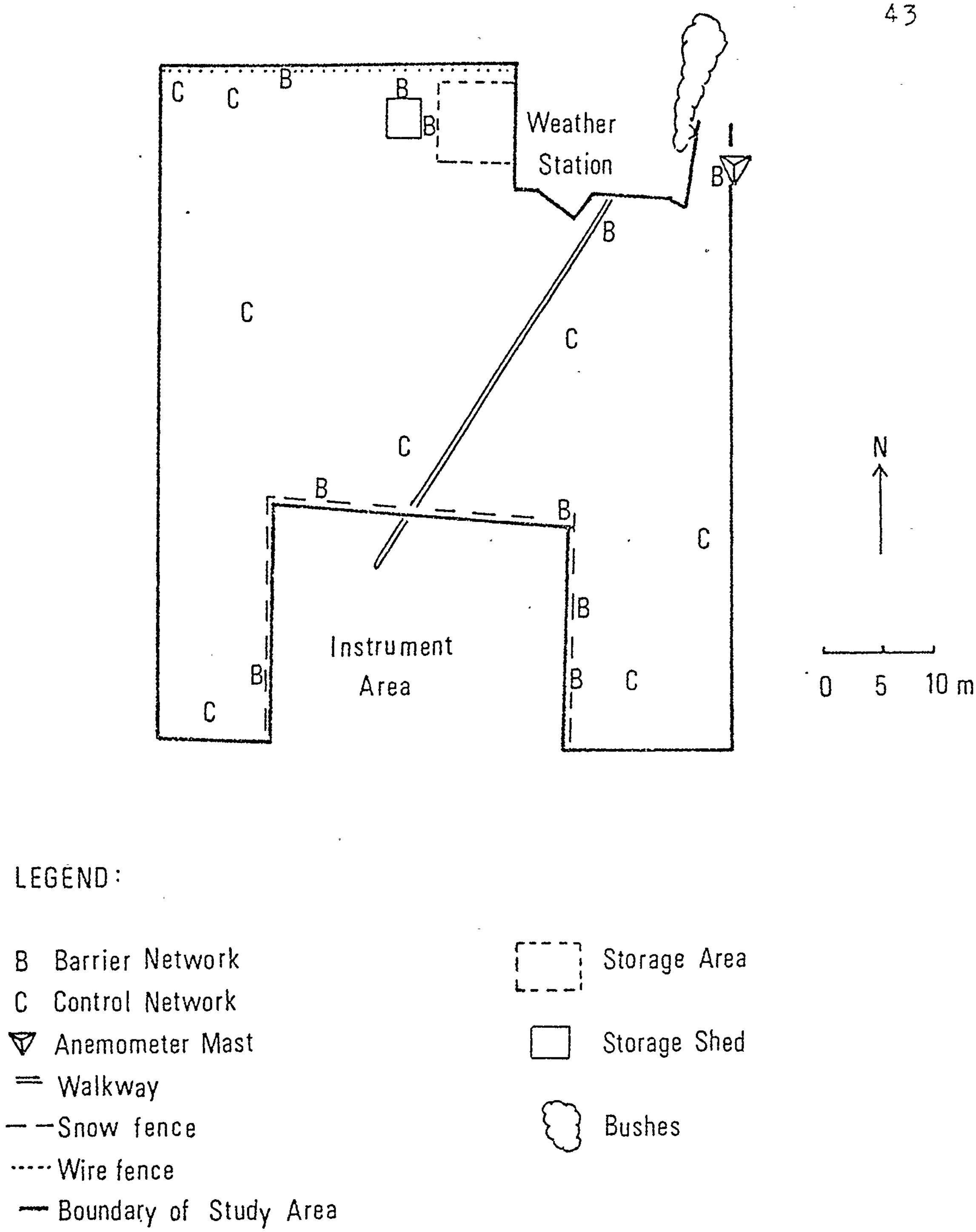


FIGURE 2.4.2

DENSE RAIN GAUGE NETWORK

Examination of the variation in rainfall catch within the dense network suggested that a dichotomy existed among the gauges. Those gauges given adequate exposure (the control set of gauges) and those characterized by inadequate, variable exposure (the barrier network) appeared to catch markedly different amounts of precipitation. A one-tailed t-test confirms this observation. At a significance level of .05, the accumulated rainfall catch within the barrier network was found to be statistically less than for the control gauges. In addition, there was a difference in variability of catch between the two sub-networks, and between the city network and each of the two sub-networks.

Examination of the degree of variation within these three networks for individual storms revealed the following:

1. The control set of gauges experienced relatively little variation in precipitation receipt. With a mean standard error[1] of less than 2.0 %, any of the 8 gauges in the network would be expected to give a good estimate of mean precipitation (within $\pm$ 4 % at a confidence level of 95%). Since the control gauges had nearly optimum exposure and were located in close proximity to one another, the observed variation in the control

[1] Since each gauge represents a sample catch from the total population of possible catches in the vicinity which the gauge represents, the use of standard errors of the mean is an appropriate index of variability about the population mean.

network is believed to be explained by random error.

2. The amount of variation in precipitation receipt in the control network was approximately 10 % of its city equivalent (Appendix 4). By extrapolation, it would appear that approximately 10 % of the variation observed in the city network would be related to random errors.

3. The barrier network, on average, experienced more than twice as much variation in precipitation receipt than did the control network. This increased variability in the barrier network over the control network is believed to be due to poor exposure. The amount of spatial variability in the barrier network was approximately 25 % of that observed in the city. Since exposures in the barrier network were in general considerably worse than in the city network, it is safe to say that the degree of spatial variation of precipitation recorded in the city is at least 75 % accurate after random and exposure related errors are removed.

A quantitative estimate of gauge catch deficits under different exposure conditions is highly desirable. This would allow data quality to be further evaluated. On the basis of the dense network data, an attempt to derive a descriptive model of gauge catch error, based on exposure and wind speed, was made with the use of multiple linear regression analysis. The multiple regression equation was of the form:

$$Y = a + b X_1 + c X_2$$

where Y represents GAUGE EFFICIENCY - the amount by which gauge catch differed from the mean of the control network of gauges, in per cent,

X_1 represents WIND SPEED - mean wind speed that occurred during a given storm at the University of Calgary Weather Research Station at a mast height of approximately 11 m ,

X_2 represents EXPOSURE - distance to obstacle-height of obstacle ratio for a given mean wind direction.

Although gauges characterized by exposure ratios of less than 4.0 consistently underestimated precipitation, no significant linear relationships were found to exist between mean wind speed and catch deficit [1] or between exposure and catch deficit at a significance level of .05. Combined, the two independent variables accounted for less than 1 % of the variation in catch deficit. As a result, no predictive tool for estimating the quantity of error caused by inadequate exposure could be derived.

[1] Theoretically, wind speed and gauge catch deficit are exponentially related. Work by Larson and Peck (1974) among others suggests, however, that at low wind speeds (less than 9 m sec^{-1}) the relationship approaches linearity Since mean wind speeds were for the most part less than 9 m sec^{-1}, a linear relationship was assumed.

This further emphasizes the fact that much of the observed variability in gauge catch is random.

A modest mean gauge catch deficit of 13.5 % was found for all underexposed gauges combined. Despite a high linear correlation between mean storm total and mean wind speed of .943, no tendency toward increased per cent loss occurred with increased wind speed.[1] Since gauges in the barrier network were generally more poorly exposed than those in the city network, the mean gauge deficit observed in the barrier network (13.5 %) is believed to provide an upper limit for exposure related errors in the Calgary network.

In conclusion, there are random errors associated with the measurement of precipitation. Approximately 10 % of the observed variation in precipitation in Calgary is believed to be due to random errors. Poor gauge exposure tends to increase the variability in gauge catch and decrease gauge catch totals. Experimentation with a barrier network of gauges indicates that exposure related errors in the Calgary network most likely accounted for less than 13.5 % of the variation observed. Thus, it is safe to say that the degree of spatial variation in precipitation recorded in the city network is at least 75 % accurate.

[1] Mean wind speed and total precipitation were highly correlated (r= .943) in the control network. The correlation between mean wind speed and mean rainfall in the city, for the entire study period, was less strong (r= .510).

2.4.4 Gauge Losses by Evaporation and Wetting

New copper gauges, identical to those used in the Calgary network, were experimented with in order to measure the loss of catch by evaporation from the gauge and by wetting of the gauge. An identical methodology was applied on three sets of days: July 27-28, August 03-04, and October 02-03.

Measured amounts of water were added to five rain gauges. The amounts were .25 mm, 2.5 mm, 5.0 mm, 7.5 mm, and 10.0 mm. After a period of 28 hours, the longest time that elapsed between the time when precipitation ended and was measured in the Calgary network, the experimental gauges were emptied and the amount of remaining water measured. The losses by evaporation and wetting combined were obtained (Table 2.4.5).

While the loss with trace-like precipitation was very high (70 %), for larger storms, losses decreased rapidly, levelling off to approximately 5 % (Fig. 2.4.3). Wetting was found to account for between .01 mm and 2.5 mm in all cases.

2.5 Missing Data

During the four and a half month study period, only a small percentage of the data from the 20 gauge network

TABLE 2.4.5

PER CENT LOSS BY EVAPORATION AND WETTING COMBINED

	Water Added to Gauge (mm)				
Date	.25	2.5	5.0	7.5	10.0
July 27-28	75%	15%	6.5%	6.0%	5.0%
Aug. 03-04	25%	10%	6.5%	5.0%	6.5%
Oct. 02-03	100%	10%	8.5%	6.7%	3.5%
$\bar{X}$	70%	12%	7.0%	6.0%	5.0%

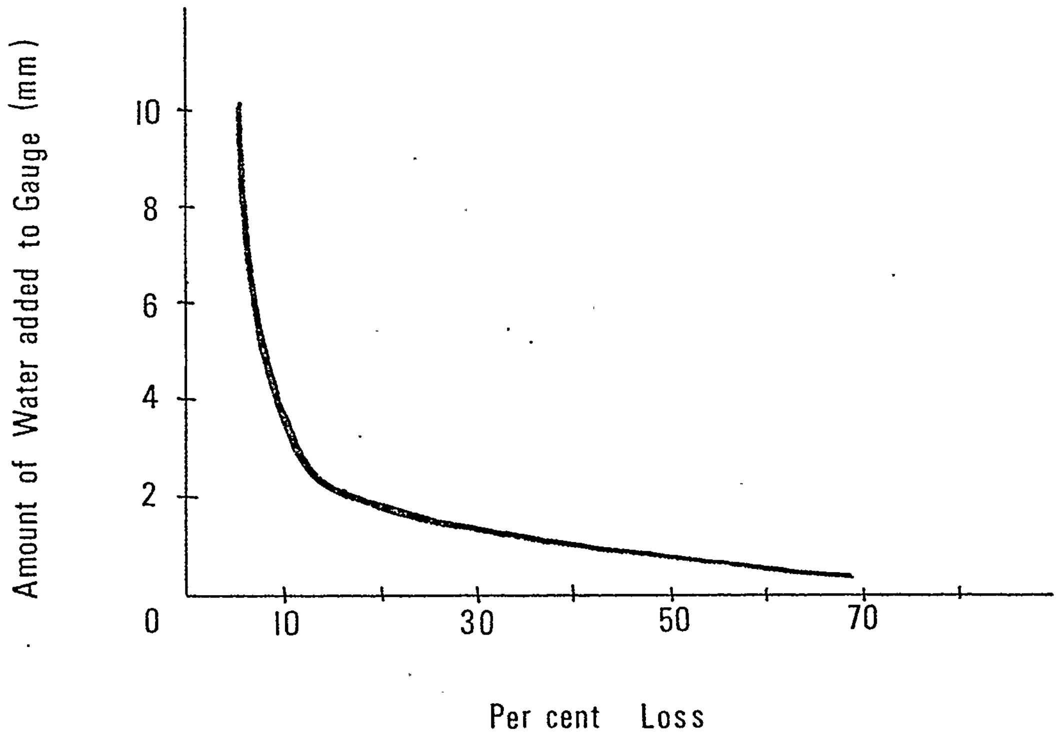


FIGURE 2.4.3

GAUGE LOSSES BY EVAPORATION AND WETTING COMBINED was missing or unreliable.

A total of 3.6 % of all storm totals were missing. In the case of missing data, totals were estimated by the distance-weighting interpolation technique. The three nearest sites to the missing data point that had data for the complete event were used in the interpolation. The importance or weight of each of the three sites was inversely proportional to its distance from the missing data point.

If a storm, for which there was missing data, spanned more than one day, the estimate of daily totals was derived by using the isopercental technique. Storm totals were interpolated by using the technique described above. To find the daily totals, the percentage of rain that fell on each of the days at the site nearest the missing data point was calculated and the estimated precipitation total at the missing data point then divided into daily amounts in the same proportion as at the neighbouring site.

Five and one-half per cent of all information on rainfall intensities was missing or unreliable. No attempts to interpolate missing intensities were made because of the complexity of intensity patterns over time.

2.6 Rain Gauge Network Density - A Discussion

Although the network of 20 gauges has been evaluated as giving a complete and relatively reliable measurement of Calgary's precipitation, it is not necessarily feasible to operate a network with such high density for long periods of time. Given the cost and logistics of operating dense ground networks, it becomes desirable to determine the minimum gauge density required to reliably measure Calgary's mean precipitation.

In order to accomplish this task, the standard errors of mean precipitation amounts were examined. It was observed that as gauge density decreased (gauge sites were randomly eliminated), the standard errors increased. The initial degree of variability about the mean was found to be a function of the time period and storm type involved (Fig. 2.6.1). For single precipitation events, the degree of variability about the mean was high, particularly for convective storms. Monthly totals, and to an even greater extent the study period totals, exhibited less variability. In general, cyclonic events showed the least amount of variability.[1]

For all cases, Station 10 was found to create anomalous patterns in the density-area decay function. This was caused by the existence of a real negative precipitation anomaly in the vicinity of Station 10. If a good estimate of Calgary's mean precipitation were to be achieved, a measurement from this anomalous zone would be

[1] See Appendix 5 for details on the standard errors of the mean for all events.

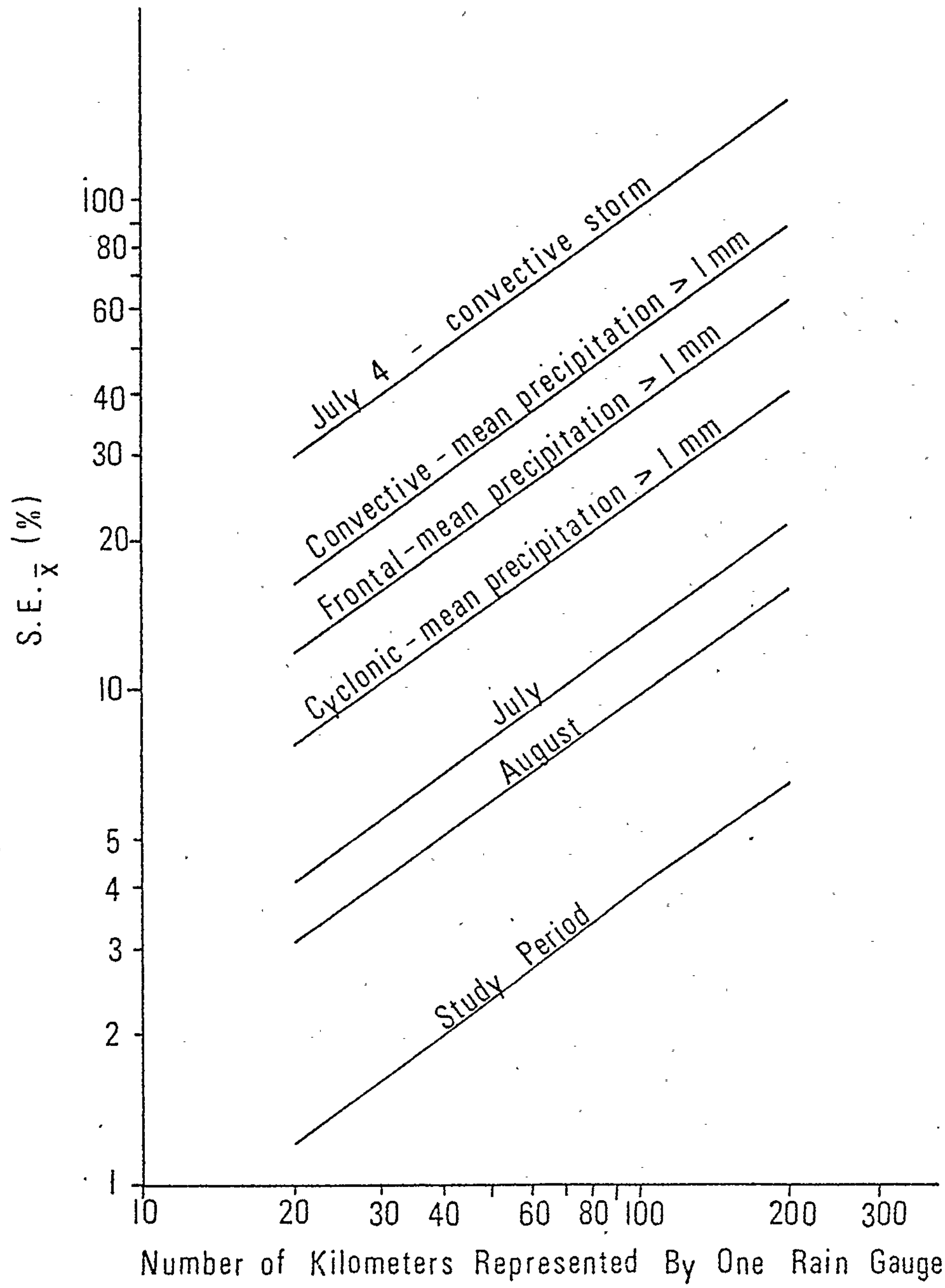


FIGURE 2.6.1

STANDARD ERROR OF THE MEAN VERSUS NETWORK DENSITY necessary.

In order to determine the optimal rain gauge network density, an examination of accuracy decay with decreasing gauge density was made. The decay in accuracy that occurred with decreasing gauge density is expressed in the standard error of the mean (S.E.$_{\bar{X}}$). As the standard error increased, estimates of the mean decreased in precision. The curve relating standard errors to network density has been defined for the general case in Fig. 2.6.2.

Maximum slope change occurs when the network is very dense (greater than one gauge per 20 km^2). Thus, the degree of improvement in the estimate of the mean afforded by each additional gauge in the network decreased with increasing gauge density.

At a density of one gauge per 50 km^2 (including one gauge in the vicinity of Station 10), the error involved in estimating the mean would be twice as large as with a 20 gauge network. This would increase the standard error to approximately 2.3 % for a summer study period, less than 10 % for monthly total estimates, and on average between 15 and 35 % for individual storms with a mean precipitation total of greater than 1 mm. Given these error levels, a network of 8 gauges is recommended for the acquisition of monthly or seasonal means.

For individual events, however, neither 8 nor 20 gauges provide an optimum network density. Each additional

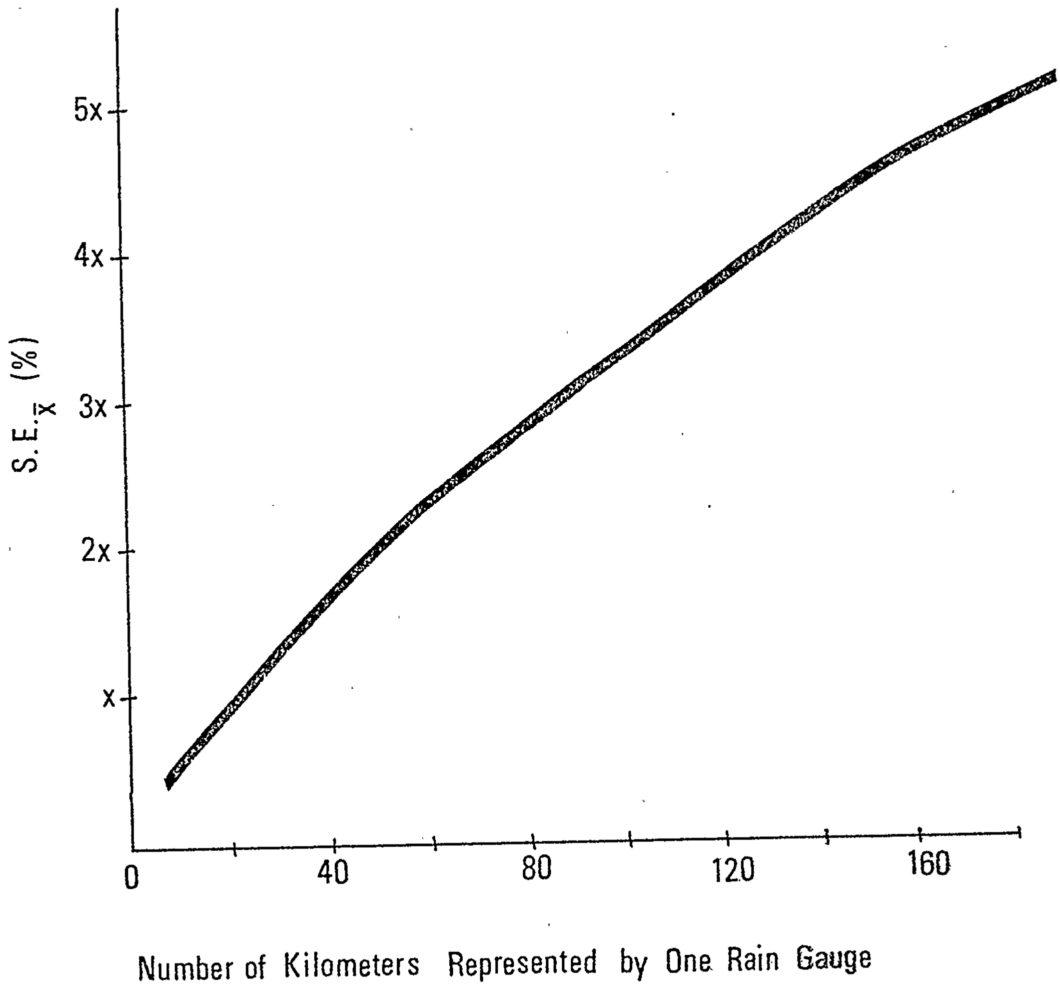


FIGURE 2.6.2

STANDARD ERROR OF THE MEAN VERSUS NETWORK DENSITY
THE GENERAL CASE

gauge in the 20 gauge network was found to contribute substantially toward increasing the accuracy of the estimate of the mean. But, even at this high density of one gauge per 20 km^2, the slope of the line appears capable of further rise. Thus, optimal density would appear to require more than 20 rain gauges.

The cost and time involved in operating a network whose density exceeds one gauge per 20 km^2 would be substantial. One alternative to expanding ground based gauge networks is to employ remote sensing techniques to compliment a ground network. A high correlation between weather radar returns and precipitation intensity has been established for summer rainfall in Alberta (Barge et al., 1978). Chapter 3 examines the ability of weather radar to contribute information regarding the spatial distribution of precipitation in Calgary for the study period involved.

2.7 Summary

This chapter has dealt essentially with data sources and data quality. The primary source of data was that of a city wide network of rain gauges, implemented specifically for the study. The criteria used to design the network include uniformity, topographic representation, and good site exposure.

The quality of the data collected from this network has been closely examined. Gauge catch errors resulting from wind and instrument inaccuracy have been assessed. Particular emphasis was placed on the evaluation of exposure related gauge catch error. Results suggest that the data base is at least 75 % accurate.

3.1 Introduction

To date, the most thorough investigation into the use of radar in providing spatial estimates of precipitation in Alberta has been carried out by the Atmospheric Sciences Division of the Alberta Research Council. Their finds have encouraged the use of radar to give spatial estimates of rainfall, particularly over large areas, such as is required in flood forecasting (Barge et al., 1978). All attempts to correlate radar estimates of precipitation with gauge estimated rainfall have been at distances from the radar site of less than 100 km, however.

Calgary is located at a mean distance of 128 km from Penhold, the nearest radar site offering the necessary information. Therefore, if radar data is to be incorporated into this spatial study of precipitation in Calgary, a need to establish the quality of the correlation between gauge and radar estimates of rainfall at this distance exists.

The objectives of the radar analysis are twofold:

1. To establish the degree of association between radar estimated rainfall (RER) and rain gauge estimated rainfall (GER) for precipitation over Calgary.
2. To conduct a case study in some detail in order to:
   a) Comment on the contribution that radar makes in defining and describing storm characteristics.

b)Analyze the quality of the correlation between RER and GER.

c)Comment on the quality of radar derived spatial rainfall estimates.

3.2 Principles of Weather Radar

A radar system is comprised of four essential components, a transmitter, antenna, receiver, and display unit. The transmitter produces pulses of electromagnetic waves whose wavelengths range from about 1 mm to 1 m. The waves are radiated in narrow beams by the radar antenna. When the beam of energy intercepts precipitation or any other object, a portion of the energy is backscattered in the direction of the antenna. This returning energy, known as backscattered power or the echo, is measured in decibels of reflectivity (dBZ) and is a measure of the precipitation intensity. Once the power is returned to the antenna, it passes into the receiver and is then displayed to the user on a Plan Position Indicator (PPI).

The distance to the precipitation is determined by measuring the time interval between transmission of the signal and reception of the echo. The antenna position determines the azimuth and elevation of the precipitation with respect to the radar site.

The data for this study were obtained from the Alberta Hail Project[1] S-band (10 cm wavelength) radar system, which is located at Penhold, Alberta.

The characteristics of the system are as follows:

frequency:	2.880 GHz
pulse repetition frequency:	480 sec^{-1}
pulse duration:	1.75 μs
typical peak power:	200 kW
beam width:	1.15^0 (all planes)
antenna gain:	43.2 dB (at pedestal)
antenna rotation rate:	8 RPM
elevation program:	spiral scan: 1^0 per revolution to 8^0 or 20^0.

(Leung, 1977)

3.3 Data Base

The S-band radar is the primary radar used for weather watch at the Alberta Hail Project. However, it is operated only during convectively active periods from June to September, when winds are not excessive. As a result of the limited coverage and the demand for completed records by other studies, S-band records were available for only 25 rain storms that occurred during the

[1]The Alberta Hail Project is a "cooperative investigation into phenomena associated with hailstorms in central Alberta. Its primary aim is to determine the causes and behaviour of hailstorms in Alberta and to devise models of hailstone growth as a basis for developing hail suppression techniques."

Lunn and Wojtiw (1977)

study period. Of these 25 storms, complete coverage occurred during 12 rain periods[1] (Appendix 6).

3.4 A Comparison of Radar Estimated Rainfall and Gauge Estimated Rainfall

Radar reflectivity measurements taken immediately above the four tipping bucket gauges in Calgary were converted to precipitation rates by the use of a radar calibration equation. Twenty-two precipitation periods were examined. The conversion equation used was:

$$Z = 200 R^{1.6}$$

where Z is the reflectivity factor and R represents precipitation rate. This relationship was derived by Marshall and Palmer (1948) for stratiform, summer rainfall in Eastern Canada.

Before radar estimated rainfall (RER) and gauge estimated rainfall (GER) can be compared, a qualifying remark is necessary. The spatial resolution of RER is determined by the beam width of the radar and the distance of the site being measured from the radar system. The Alberta Hail Project S-band radar has a beam width of 1.15^0.

[1] A rain period has been defined to include all the precipitation that fell within a time period which was separated from other rain activity by a minimum of three hours.

Penhold is approximately 128 km from Calgary. Therefore radar estimates of precipitation occurring over Calgary are the result of substantial spatial averaging of between 2.40 and 2.99 km^2. GER is a point measurement of precipitation. Thus, discrepancies between RER and GER for individual storms and individual stations are to be expected. Theoretically, RER/GER ratios should approach one.

A scattergram of GER versus RER for the 22 cases studied has been provided (Fig. 3.4.1). Mean RER/GER was .21. RER consistently underestimated precipitation. A relatively high frequency of RER=0 occurred. For all cases where RER=0, no radar echoes were observed. A problem in detecting very light precipitation by radar does exist due to the fact that the minimum detectable signal is 20 dBZ. Even upon removal of all cases where RER=0, however, RER/GER values were less than .18, fifty per cent of the time (Fig. 3.4.2).

When localized convective storms were considered in isolation, a substantial improvement was made. Radar was still responsible for a considerable underestimation of ground level precipitation, but RER/GER values exceeded .40 more than 45 % of the time (Fig. 3.4.2).

No significant relationship between mean total precipitation and mean RER/GER was found at a significance level of .05. Therefore, it is unlikely that

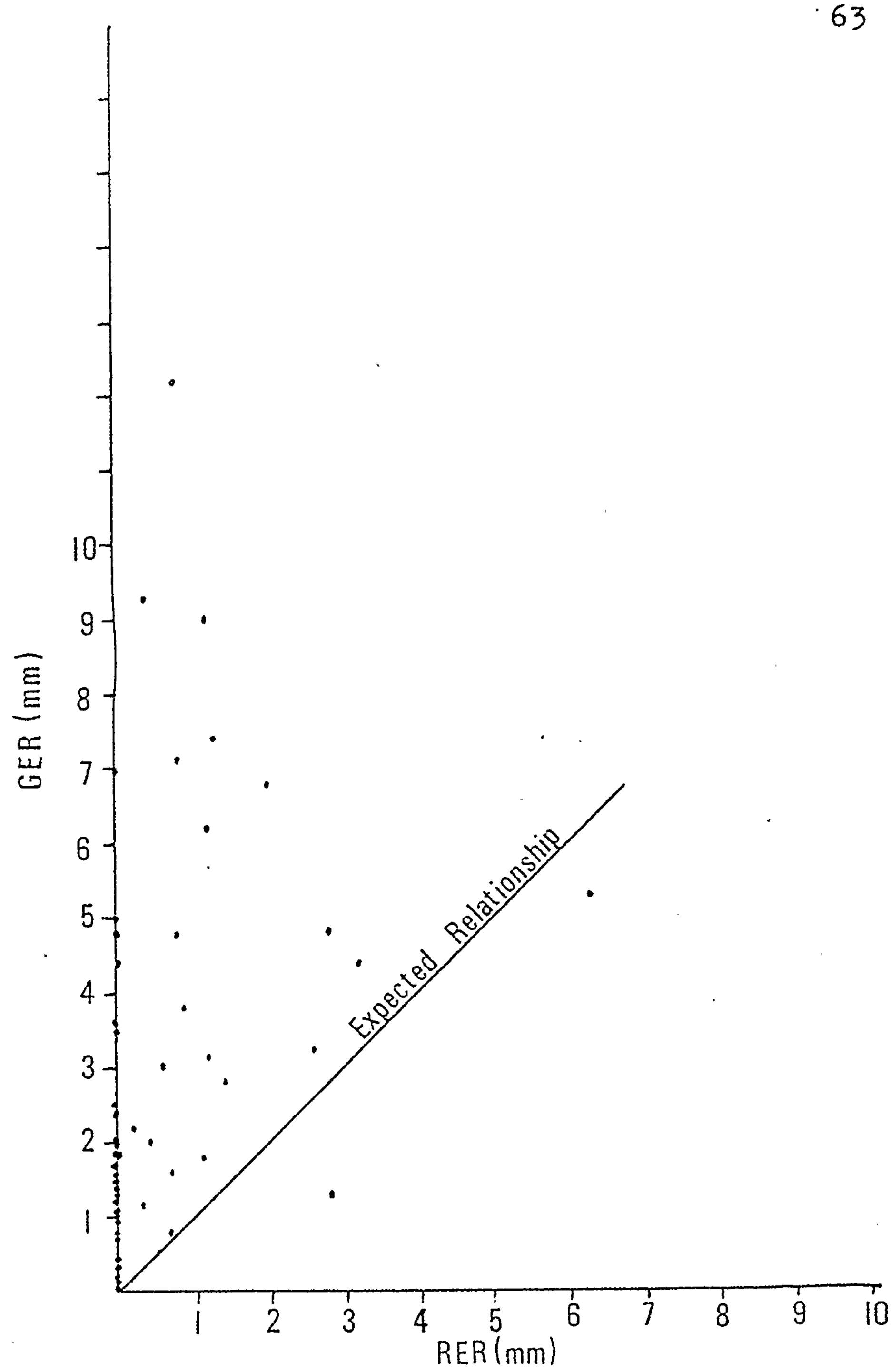


FIGURE 3.4.1

RADAR ESTIMATED RAINFALL VERSUS GAUGE ESTIMATED RAINFALL

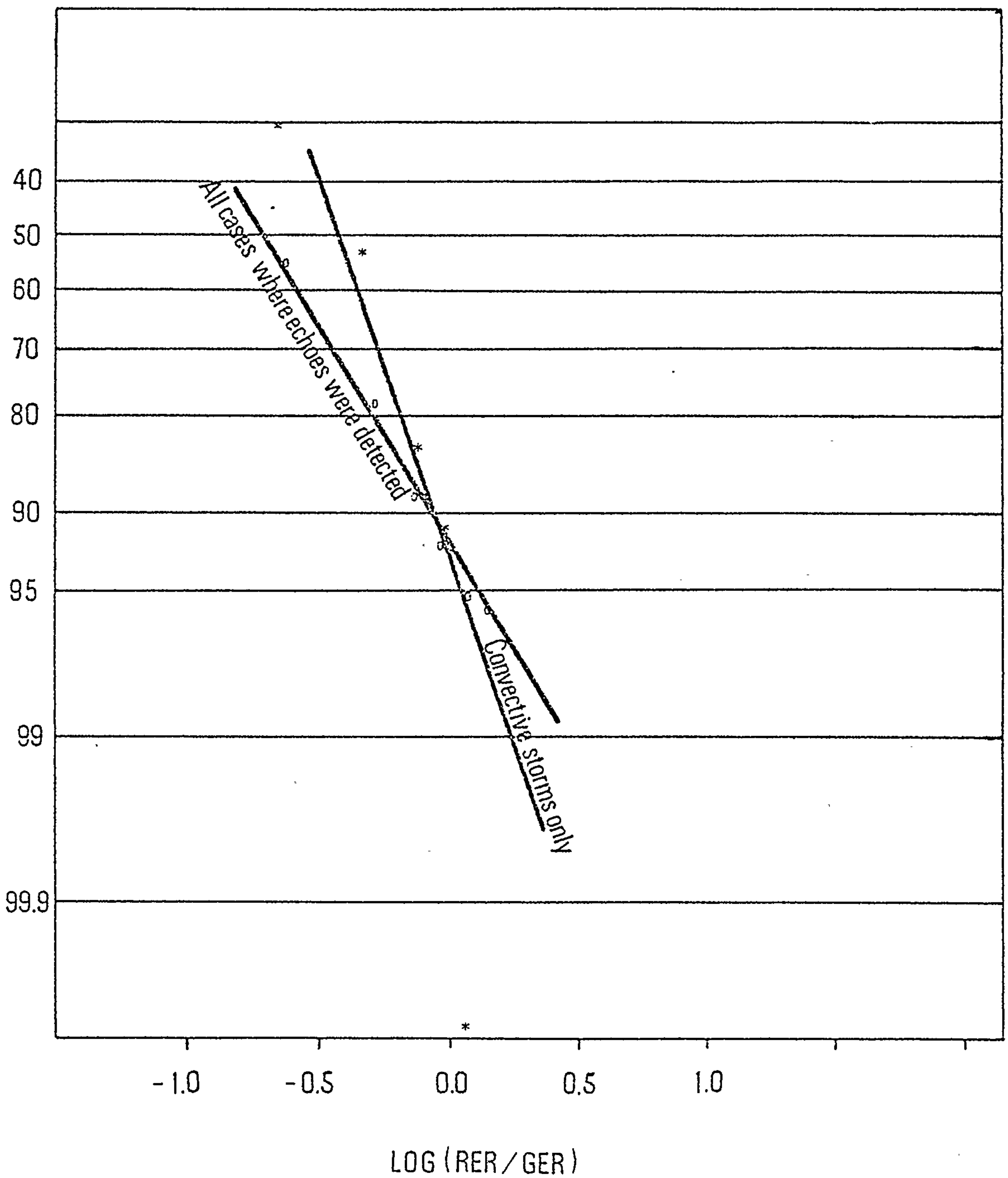


FIGURE 3.4.2

CUMULATIVE FREQUENCY OF RER/GER VALUES(%)

the discrepancy observed between localized convective storms and other synoptic types is a function of rainfall amounts.

Barge et al. (1978) found that for gauges located near Sundre, Alberta, which is approximately one-half the distance from Penhold, the mean RER/GER was 1.15. Collier (1975) suggests that the increase in distance that exists between Sundre and Calgary would cause a decrease in accuracy in the order of 15 %.

It would therefore appear that the radar estimates of precipitation in Calgary lack the expected accuracy. A case study of a convective storm is examined in detail in order to comment further on the quality of the correlation between RER and GER, to outline sources of error in RER, and to discuss the contribution of radar in defining and describing storm characteristics.

3.5 A Case Study of the July 19 Multicell Storm

3.5.1 The Storm

Continuous records from the four tipping bucket rain gauges in Calgary (Stations 4,6,10,20) indicated that intense precipitation had occurred in parts of Calgary between 1620 and 1810 MDT, July 19, 1978. The synoptic conditions for the period indicated a light NW flow, associated with low level, convectively unstable air containing patchy, lower level moisture.

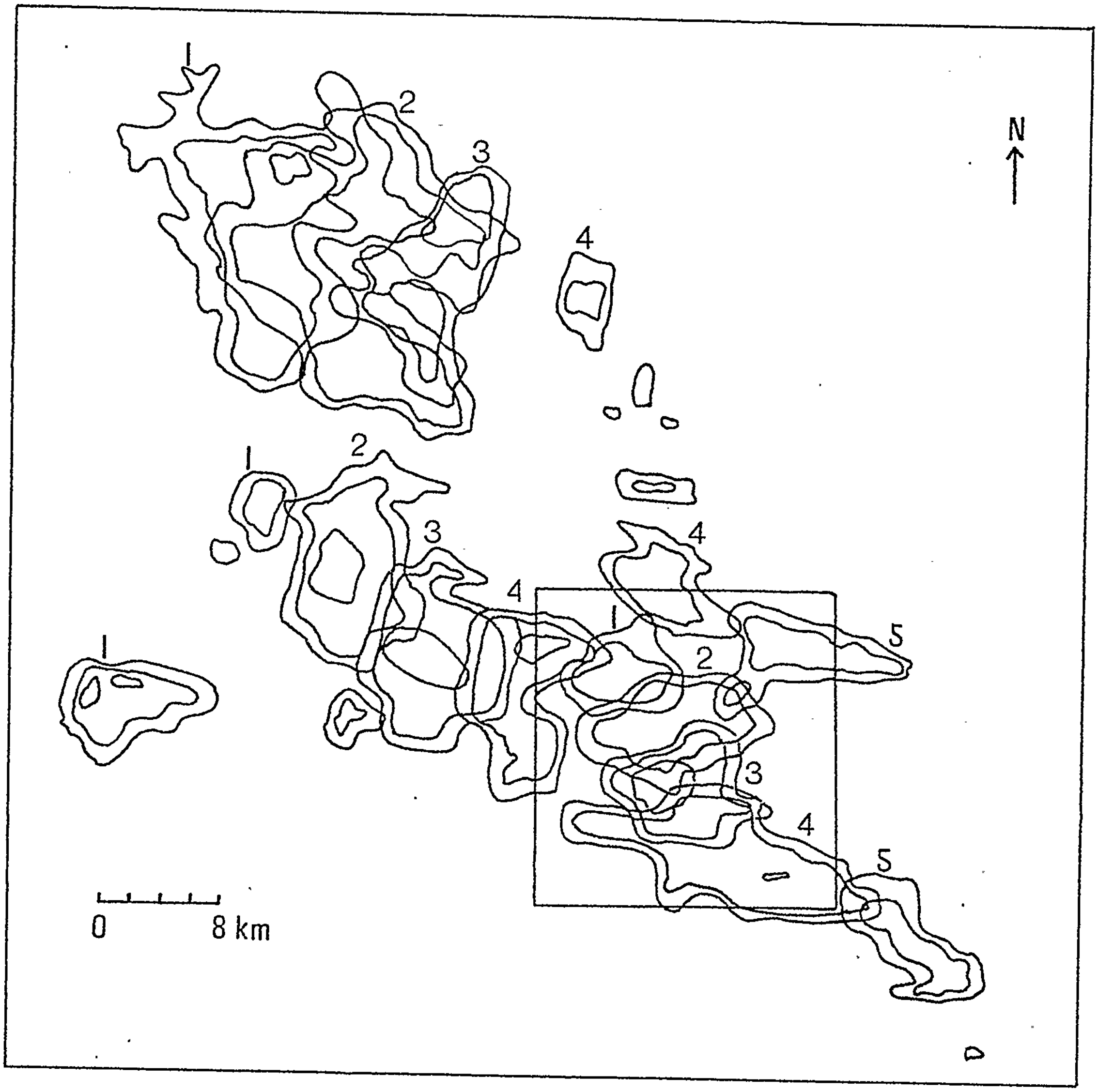
Radar reflectivity maps were collected for the duration of the storm at 10 min intervals and antenna elevations of 0.6^0, 1.6^0, 2.6^0, and 3.6^0. The echoes have been mapped at 20 min intervals and antenna positions of 0.6^0 or 0.7^0 (Fig. 3.5.1).

Three cells can be distinguished over the city. The first to affect the city was small in extent, approximately 2 km by 3 km. This cell entered Calgary from the NW and moved progressively SE across the city at a mean speed of 5.4 m sec^{-1}. Stations 10 and 20 received rainfall from this cell. The time of greatest rainfall intensity corresponded with the passage overhead of the highest reflectivity echoes.

Cell two, originating WNW of the city, matured and dissipated over NW Calgary. Its movement was relatively slow at an average rate of 3.7 m sec^{-1}. Station 6, located on the eastern edge of the cell, was the only tipping bucket gauge affected.

Cell three affected only Station 4. Originating and maturing north of Calgary, it traversed NE Calgary during its later stages. Again the time of the most intense rainfall corresponded with the time of highest radar reflectivity.

This initial discussion allows one conclusion to be



Time	Elevation
1. 1610:56	0.6^0
2. 1628:51	0.7^0
3. 1649:45	0.7^0
4. 1710:39	0.6^0
5. 1739:01	0.6^0

Reflectivity

Minimum ....20 dBZ
Contour Interval. 10 dBZ

FIGURE 3.5.1

RADAR REFLECTIVITY MAP

JULY 19, 1978

made. Radar has the ability to provide detailed information pertaining to the structure, development and movement of storms over Calgary.

3.5.2 A Comparison of RER and GER for July 19, 1978

A comparison of RER and GER for July 19, 1978 shows a substantial underestimation of precipitation by radar. The mean RER/GER ratio for the four stations combined was .4. This low value is largely a result of the extreme underestimation of precipitation by radar at Station 6 in NW Calgary. The mean ratio for the other three sites was .73.

Plots of the accumulated rainfall estimates by both gauges and radar were examined. In order to remove the lag effect that existed between GER and RER, time adjustments were made by the use of cross correlation analysis (Fig. 3.5.2).

One probable reason for the observed lag effect stems from the fact that gauge measurements were taken at ground level and radar estimates at approximately 1360 m a.g.l.. Other probable causes for the variable lags include improper clock checks, insensitive clock mechanisms on the gauge recorders, and wind factors.

Continuous records from three anemometers in Calgary indicate that during the July 19 event, low level winds

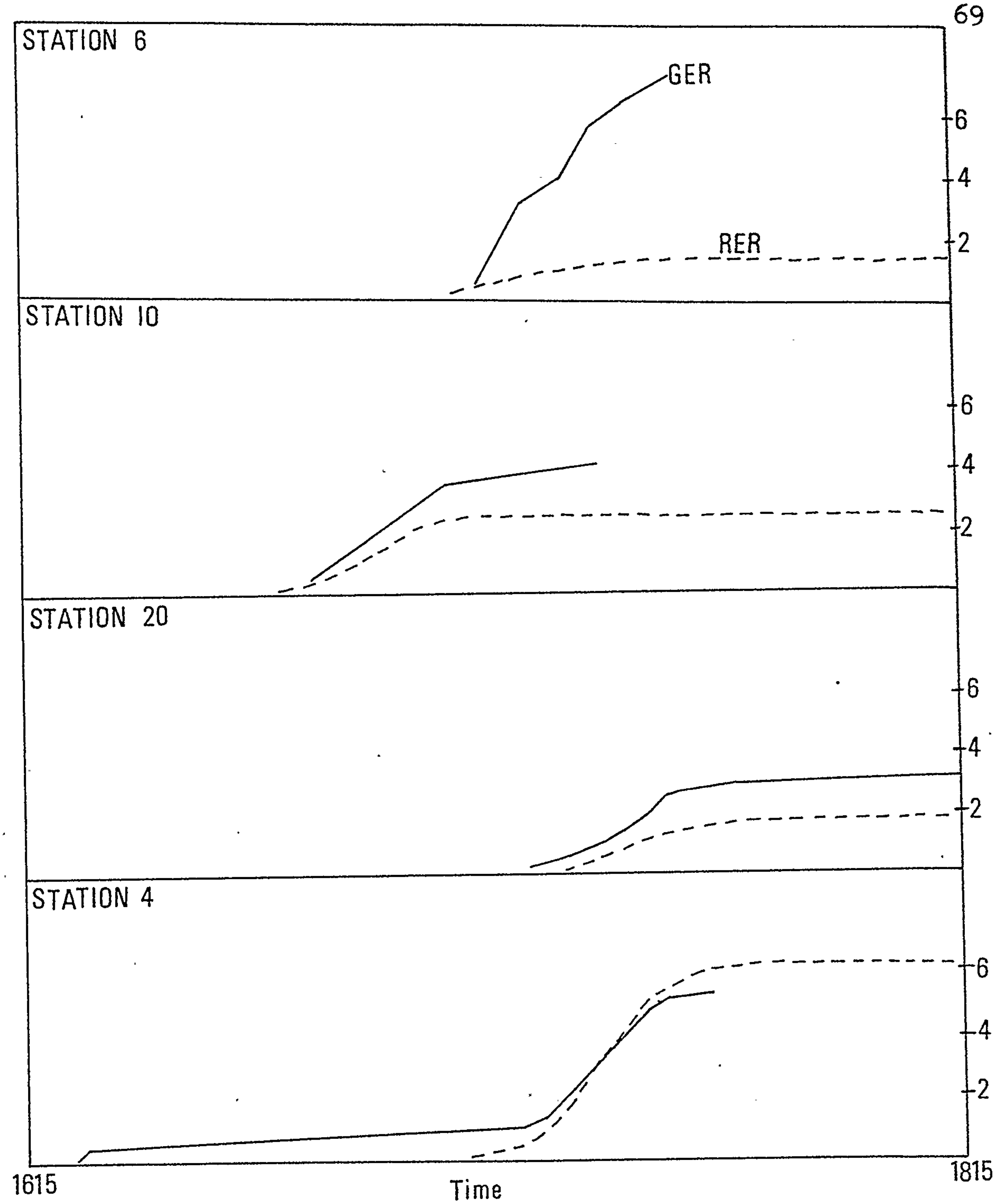


FIGURE 3.5.2

ACCUMULATED RAINFALL (mm) ; LAG ADJUSTED had a more easterly component in southern Calgary than in northern Calgary. This is believed to have resulted in an exaggeration of the lags between RER and GER, since all cells approached the city from the northwest. At Station 6 in northwest Calgary, maximum correlation between RER and GER occurred at zero lag position. The prevailing northwesterly flow is believed to have caused rain to occur over the gauge prematurely because the gauge was positioned downwind of the cell. Station 4's records show precipitation occurring at ground level prior to the detection of clouds overhead. The northwesterly flow appears to be partially responsible for this.

3.5.3 Sources of Error in RER over Calgary

The two most apparent reasons for the extreme underestimation of precipitation by radar at Station 6 are related to winds and spatial averaging (Andrey and Drakeford, 1979). At the time when cell two was most active, low-level winds in the northwest were westerly at 3 m sec^{-1}. Therefore it is probable that rain would have been carried downwind of its cloud source, causing heavy rainfall in the vicinity of Station 6.

The spatial averaging effect would also have depressed radar estimates of precipitation. This is due to the fact that the area to the east of Station 6, which received relatively less precipitation, would have been included in the spatial average. In order to substantiate this, RER values for 6 locations surrounding the gauges were obtained. These check sites were approximately 1.4 km apart latitudinally and 1.2 apart longitudinally. A sharp spatial gradient of decreasing precipitation from SW to NE was identified.

Other possible sources of error include the problems of attenuation and unrepresentative reflectivities caused by the bright band effect. On the 19th of July, between 1615 and 1815 MDT, the only clouds in the entire Alberta Hail Project study area were those over Calgary. Therefore attenuation would be negligible. Tephigram analysis shows the freezing level at just under 3000 m a.s.l.. RER values were based on an antenna elevation of 0.6^0, which would be under the zone where bright band distortion might have occurred.

A major source of error, which was not discussed , is that of non uniform filling of the radar beam. At a mean range of 128 km, this warrants investigation.

Examination of error estimates at the other three stations during the July 19th storm, and for all stations during several other events, suggest that spatial averaging and wind are two major sources of error. For light rainfall, the frequent occurrence of RER=0 appears to be related to the inability of the radar to detect a signal of less than 20 dBZ. The general tendency toward underestimation of precipitation by radar is also believed to be related to an inappropriate radar calibration equation.

3.6 Utilization of Radar Data for Spatial Estimates of Precipitation

The potential for radar estimates of precipitation to contribute information on precipitation receipt is highest in spatial precipitation studies. The Atmospheric Division of the Alberta Research Council have portrayed the usefulness of spatial estimates of precipitation in hydrologic forecasting in Alberta (Barge and Humphries, 1978; Folliot and Ramsden, 1979).

In view of the good correlations between RER and GER for Calgary on July 19, 1978, it would appear logical to utilize the radar data to generate spatial estimates of precipitation totals in Calgary for the same time period. Comparisons with gauge derived estimates could then be made.

By extracting and synthesizing reflectivity values over the city at a constant altitude of 2100 m a.g.l., radar estimates of precipitation were obtained for some 150 locations in Calgary (Fig. 3.6.1). This represents a much denser network than was provided with rain gauges

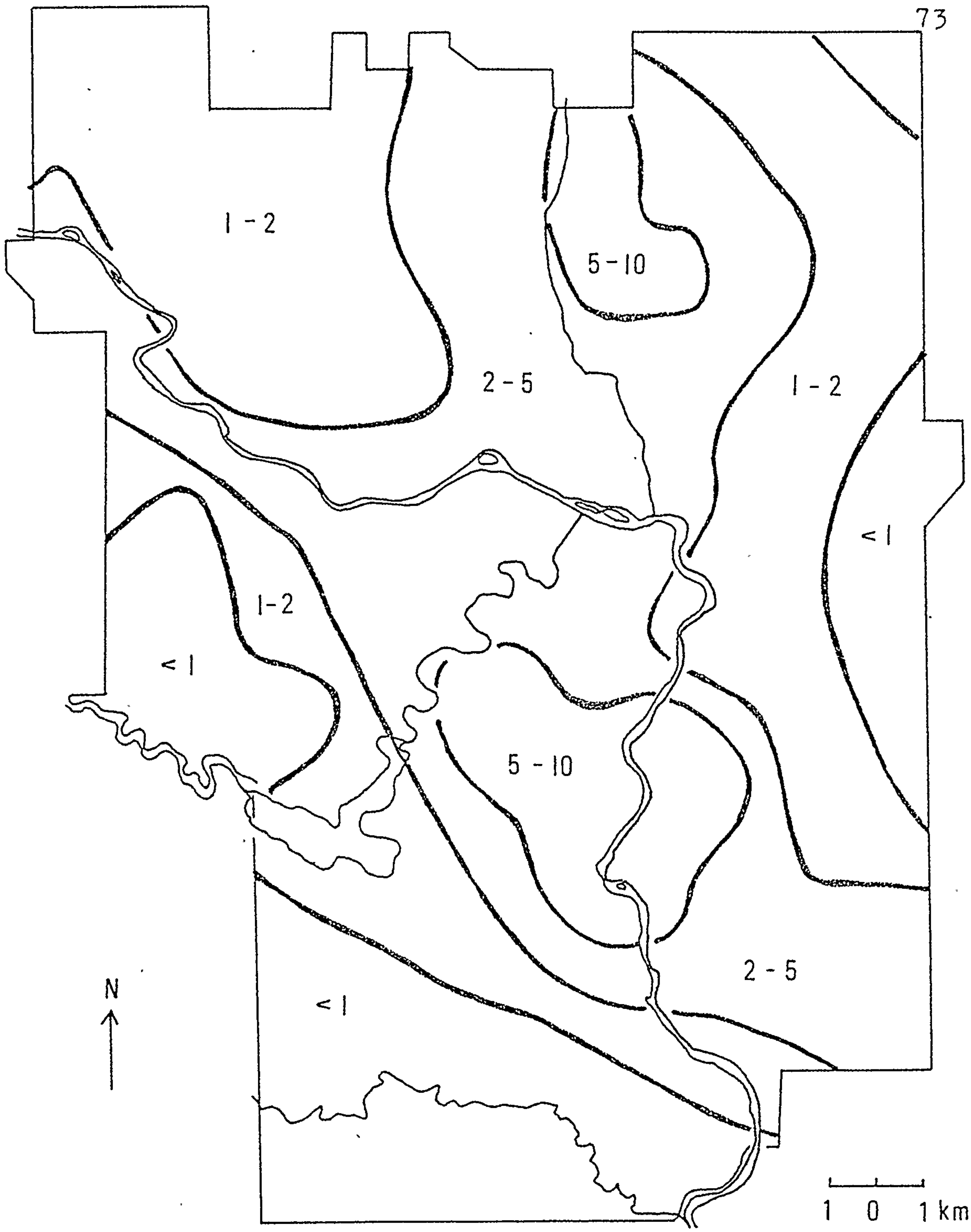


FIGURE 3.6.1
RADAR ESTIMATED RAINFALL (mm)
JULY 19, 1615 - 1815 MDT

alone. A comparable pattern was found by linear interpolation between rain gauge values (Fig. 3.6.2). The zones of gradient are positioned similarly in both cases. Note, however, that adjustments for wind speed and direction are necessary. In addition, a refinement of the Marshall-Palmer radar calibration appears necessary because of the consistency with which radar underestimated precipitation.

In summary, radar data has the potential to provide spatial precipitation estimates with a reasonable degree of accuracy, even at a mean range of 128 km. Interpretation of the radar estimates must be made with caution, however, due to the problems inherent in comparing RER and GER at this distance.

3.7 Summary

When radar and gauge estimates of precipitation were compared for 22 rain periods in Calgary, it was found that a substantial underestimation of precipitation by radar occurred. The discrepancy between the radar and gauge estimates was less for localized convective storms than for all storms combined.

Detailed examination of the July 19 multicell storm revealed that the tendency toward low radar estimates of precipitation was partially explained by problems of

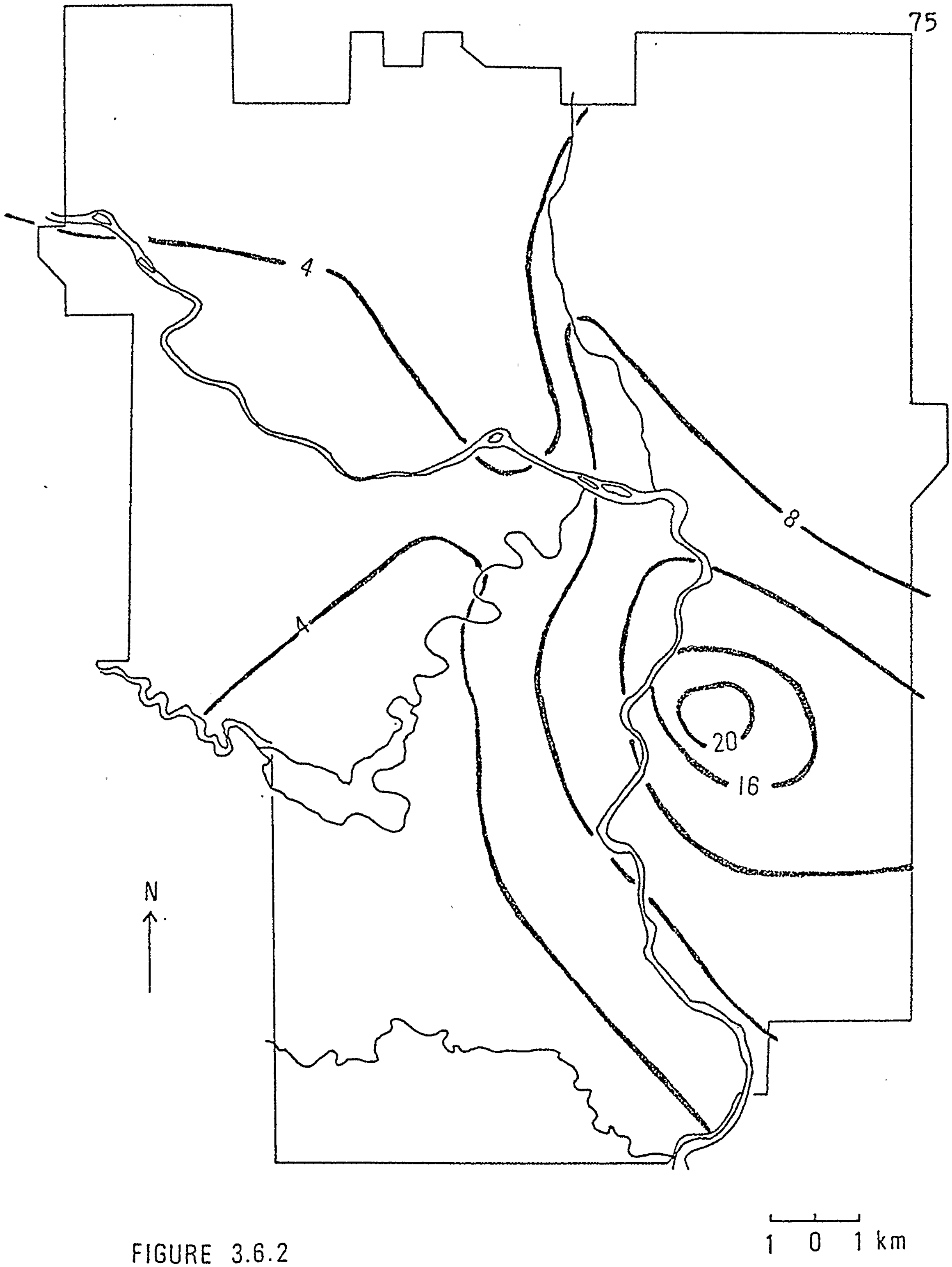


FIGURE 3.6.2

GAUGE ESTIMATED RAINFALL (mm)

JULY 19, 1615 - 1815 MDT

spatial averaging, wind, and an inappropriate radar calibration equation.

In order to correct for the underestimation of radar, it is suggested that a calibration period be set up for the concurrent acquisition of radar and gauge data. The regression equations provided by comparisons of RER and GER by storm type could then be used to adjust the radar calibration for use outside the calibration period.

Spatial estimates of precipitation afforded by radar for the July 19th storm were encouraging. It appears that for complex storms, radar data is capable of facilitating spatial interpolations of precipitation totals, even at a mean range of 128 km.

In addition, radar echoes were found to provide detailed knowledge of storm structure and movement. This provides a basis for defining storm tracks within the study area.

CHAPTER FOUR : TEMPORAL ASPECTS OF RAINFALL IN CALGARY

4.1 Introduction

Chapter 4 deals with temporal aspects of precipitation in Calgary. It is intended to give the reader insight into Calgary's precipitation history and to reveal some of the characteristics of the precipitation that occurred during the study period.

Section 4.2 is an historical approach to precipitation in Calgary and the surrounding area. Section 4.3 examines the distribution of precipitation that occurred during the study period by synoptic type, month, day of the week, and hour of the day. In Section 4.4 one facet of precipitation, that of storm duration, is examined as it relates to rainfall intensity.

4.2 Precipitation Histories

Analysis of past precipitation records from several stations in and around Calgary was undertaken in order to:

1. Allow the study period to be placed in an historical context.
2. Verify if there has been a trend in city precipitation, which could have parallelled the geometric population growth and/or the enhanced heat island intensity observed in the course of the past decade.

3. To verify if Calgary's urban complex has had any significant effect on the rainfall regime downwind of the city.

Records for eight sites were obtained. Two were for locations within the city limits while six were peripheral to Calgary (Fig. 4.2.1). The eight sites were as follows:

Sites	Records Used
Calgary International Airport	1949-1978
University of Calgary	1962-1978
Cochrane	1962-1978
Crossfield	1962-1978
Gleichen	1949-1978
High River	1949-1978
Madden	1962-1978
Turner Valley	1949-1978

Both annual and May - September precipitation totals were examined for each of the eight sites.

To estimate the missing values, a long-term ratio of mean precipitation between two adjacent sites was calculated. This ratio was then applied to missing values in the annual and May - September records. Thus, for a specific year, where Station A's total was missing but its adjacent station, Station B's was not, an approximation for Station A was calculated as follows:

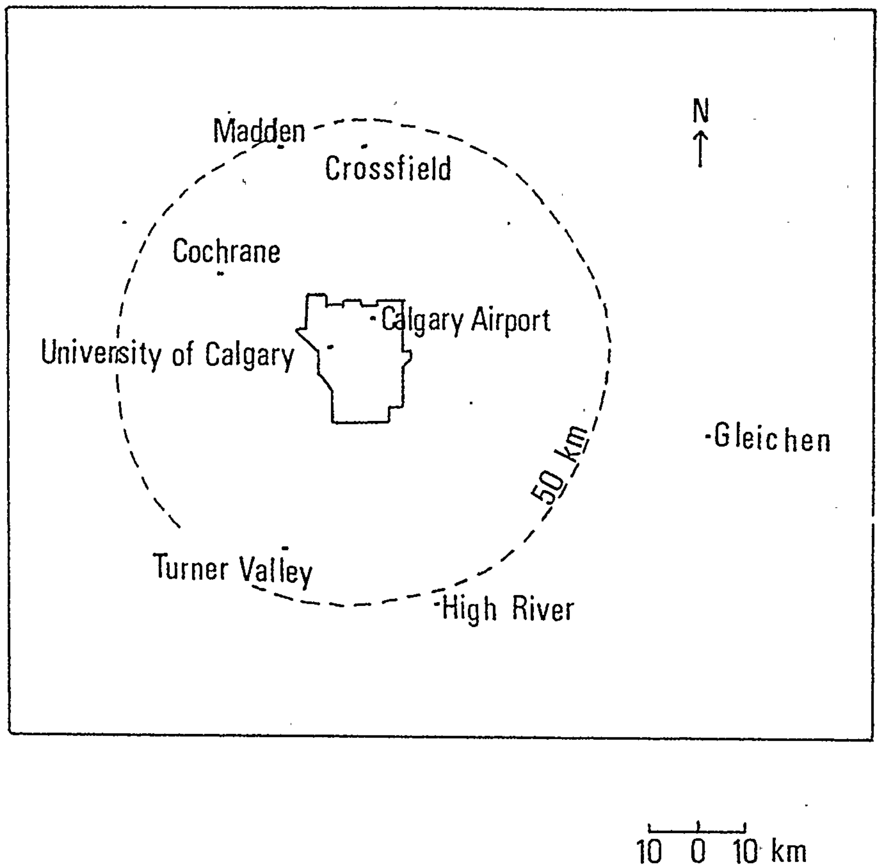


FIGURE 4.2.1

LOCATIONS OF SITES USED IN HISTORICAL ANALYSIS

$$\frac{\text{Amount at Station A}}{\text{Amount at Station B}} = \text{long term ratio of A to B}$$

This resulted in a complete sample for the years indicated.

The data were tested for trend with the use of linear regression analysis. None of the 8 station records showed significant linear trend (significance level = .05) in annual or in May-September totals (Fig. 4.2.2).

This suggests that the period under investigation was situated within a timeframe that appears to be relatively stable in terms of precipitation. Hence, there does not appear to be a correlation between population and precipitation or between heat island intensity and precipitation. In addition, despite Calgary's expanding urban complex, the area immediately downwind[1] of the city does not appear to have experienced any corresponding temporal change in precipitation receipt.

4.3 The Study Period - Temporal Characteristics

4.3.1 An Introduction

The remainder of this chapter summarizes the temporal aspects of the storms that occurred during the study period. The discussion is brief, as the study is spatially oriented. Nonetheless, its importance is twofold:

[1] Due to the prevailing northwesterly winds, unless otherwise specified, downwind refers to the region southeast of Calgary.

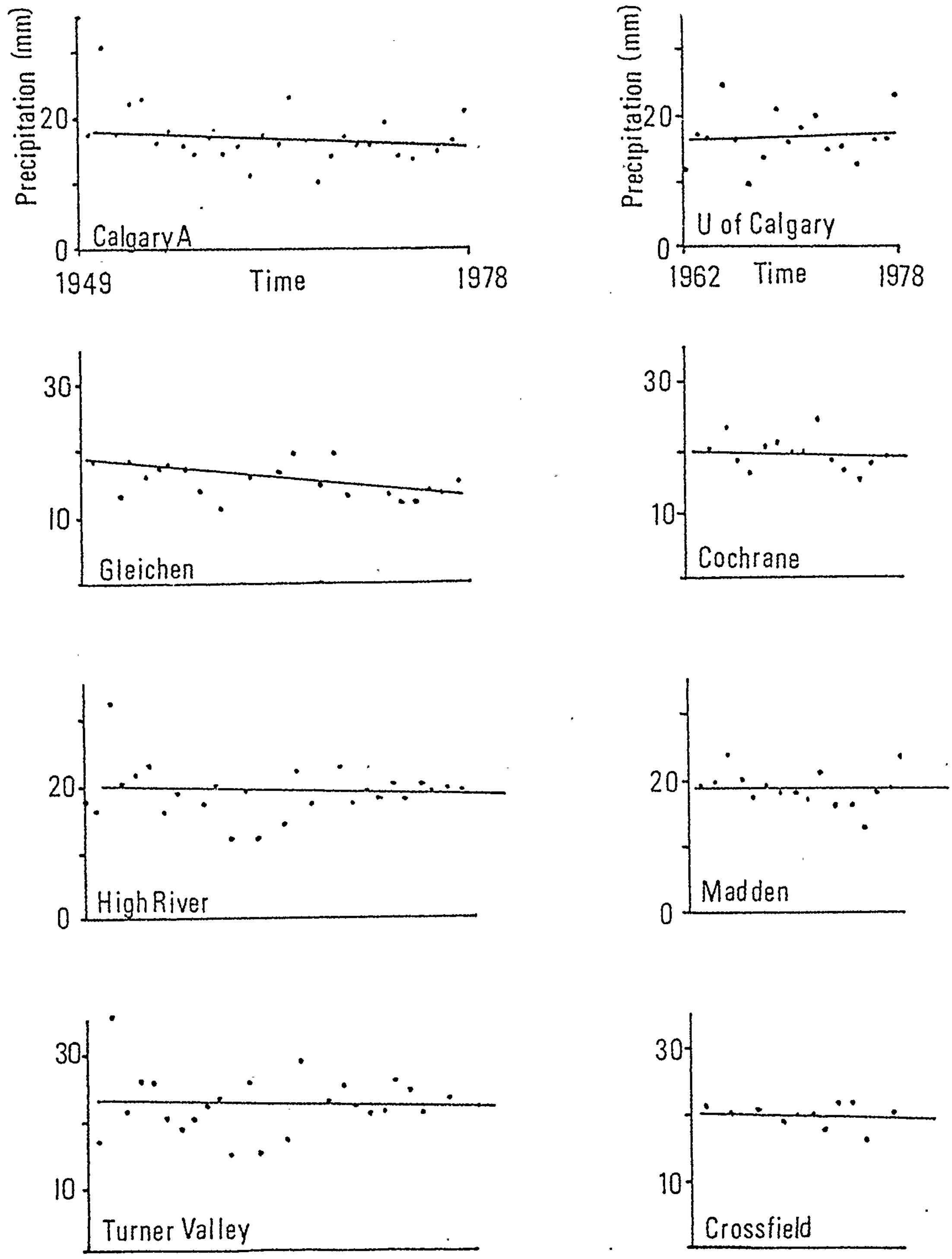


FIGURE 4.2.2

STATION HISTORIES - TRENDS EXAMINED, ANNUAL TOTALS

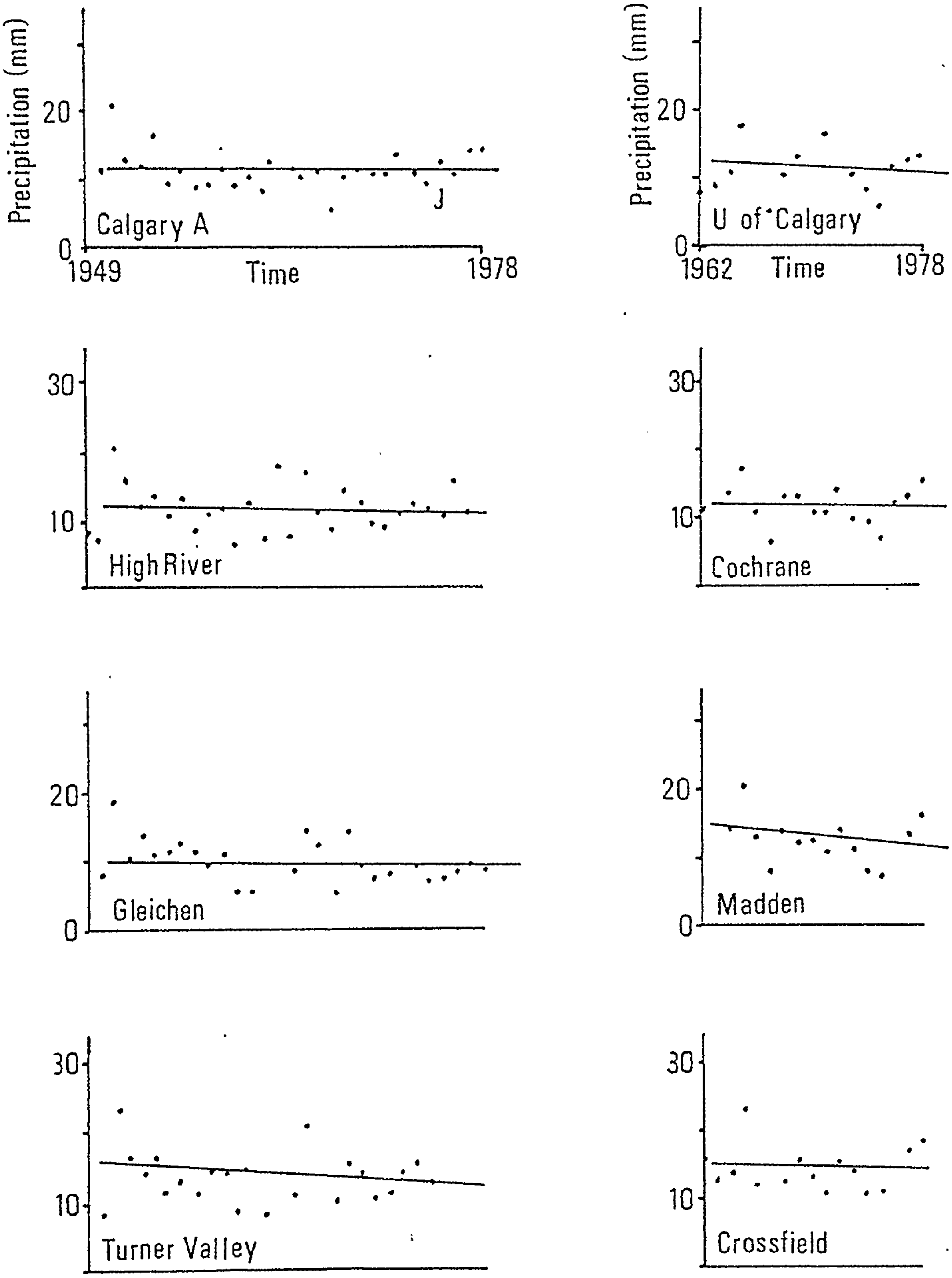


FIGURE 4.2.2. (Continued)

STATION HISTORIES - TRENDS EXAMINED, MAY TO SEPTEMBER TOTALS

First, by placing precipitation in the context of time, a fuller understanding of the storms themselves is obtained. This provides a better base from which to discuss the resultant spatial patterns. Secondly, an insight into the possible effects that the urban complex may have had on the precipitation process can be gained by examining certain temporal aspects of the data.

The time period under investigation is that of May 16 to September 30, 1978. During that time, 51 storms, spanning 74 days, occurred. Fourteen were cyclonically related, 17 were frontally associated, and 20 were localized convective storms. The mean total precipitation for the city was 338.26 mm.

The total precipitation at Station 4 (Calgary's International Airport) was 360.0 mm. This represents approximately 25 % more rain than the long term average, which is approximately 290 mm.

4.3.2 A Synoptic Classification of Storms

Upper air charts, teletype printouts, and synoptic summaries were used in classifying the 51 storms by synoptic type. The following traditional classes were used: cyclonic, frontal, and localized convective storms (Table 4.3.1).

Cyclonic events occurred least frequently, yet

TABLE 4.3.1

A BREAKDOWN OF PRECIPITATION BY SYNOPTIC TYPE *

	Synoptic Types			
	Cyclonic	Frontal	Localized Convective	All Types
Number of Storms	14	17	20	51
Per Cent of Storms	27.5	33.3	39.2	100.0
Total Mean Precipitation (mm)	190.6	90.2	55.5	336.3
Total Mean Precipitation (% of all storms)	56.7	26.8	16.5	100.0

* Table is based on records from all twenty gauges in the city network.

contributed greater than 56 % of all the precipitation received. Frontal events comprised one-third of all storms, but accounted for only 26.8 % of all precipitation. Localized convective storms, which occurred most frequently, were responsible for only 16.5 % of the total mean precipitation. Thus, a large variation in mean storm total exists among the different synoptic types. The effect of these different processes on the spatial distribution of precipitation is discussed in Chapter 5.

4.3.3 The Distribution of Precipitation by Month

An examination of precipitation by month enabled the time period under investigation to be studied as it proceded from spring, through summer, and into autumn.

In Calgary, spring is normally a period of heavy precipitation due to the occurrence of extensive cyclonic conditions. The latter half of May, 1978 was the wettest period observed, with an abnormally high mean daily precipitation total of 4.34 mm (Table 4.3.2). This was the result of frequent and intense cyclonic and frontal disturbances.

June is normally the heaviest rainfall month of the year with a long term average of 91.7 mm total precipitation. June, 1978 was the driest month observed with

TABLE 4.3.2

DISTRIBUTION OF PRECIPITATION BY MONTH *

	May (16-31)	June	July	Aug.	Sept.	Study Period
Number of Days with Rain	7	17	21	15	14	74
Per Cent of Days with Rain	43.8	56.7	67.7	48.8	46.7	53.6
Mean Total Precipitation (mm)	69.5	53.1	55.6	87.6	70.5	336.3
Mean Daily Precipitation (mm)	4.34	1.77	1.79	2.83	2.35	2.44

* Table is based on records from all twenty gauges in the city network.

40 % less precipitation than normal. The frequency with which rain occurred was high (17 out of 30 days). However, the mean precipitation per event was just over 4 mm (Table 4.3.3).

July was characterized as the most convectively active month. This is reflected by its relatively high frequency of days with hail (Deibert, 1979). The number of rain days in July, 1978 was 21, the highest of any month studied. This occurred mainly as a result of frequent localized convective showers, which on average dropped 3.9 mm of precipitation. Estimated cloud heights often extended beyond 10 km a.s.l. and occasionally beyond 13 km a.s.l..

August, 1978 was unusually wet, receiving 57 % more precipitation than the long term average. This is partially explained by the August 15-17 cyclonic disturbance that resulted in precipitation totals varying from 31 to 71 mm throughout the city [1]. The impact of this storm on August total precipitation was substantial (Fig. 4.3.1). The exclusion or special treatment of this event occurs in further discussions because of the large quantity of precipitation and high wind speeds associated with it.

September, 1978 was also wetter than normal due to

[1] See Appendix 7 for storm totals.

TABLE 4.3.3

DISTRIBUTION OF PRECIPITATION BY MONTH AND SYNOPTIC TYPE

		May	June	July	Aug.	Sept.
Mean Total Precipitation,* per cent of all storms	Cyclonic	74.8	34.4	5.7	93.0	40.2
	Frontal	25.2	46.2	10.5	2.2	59.8
	Convective	0.0	19.4	83.9	4.8	0.0
Number of Storms	Cyclonic	3	3	3	4	2
	Frontal	2	5	3	3	4
	Convective	0	5	12	3	0
	Total	5	13	17	10	6

* Based on tipping bucket gauge records.

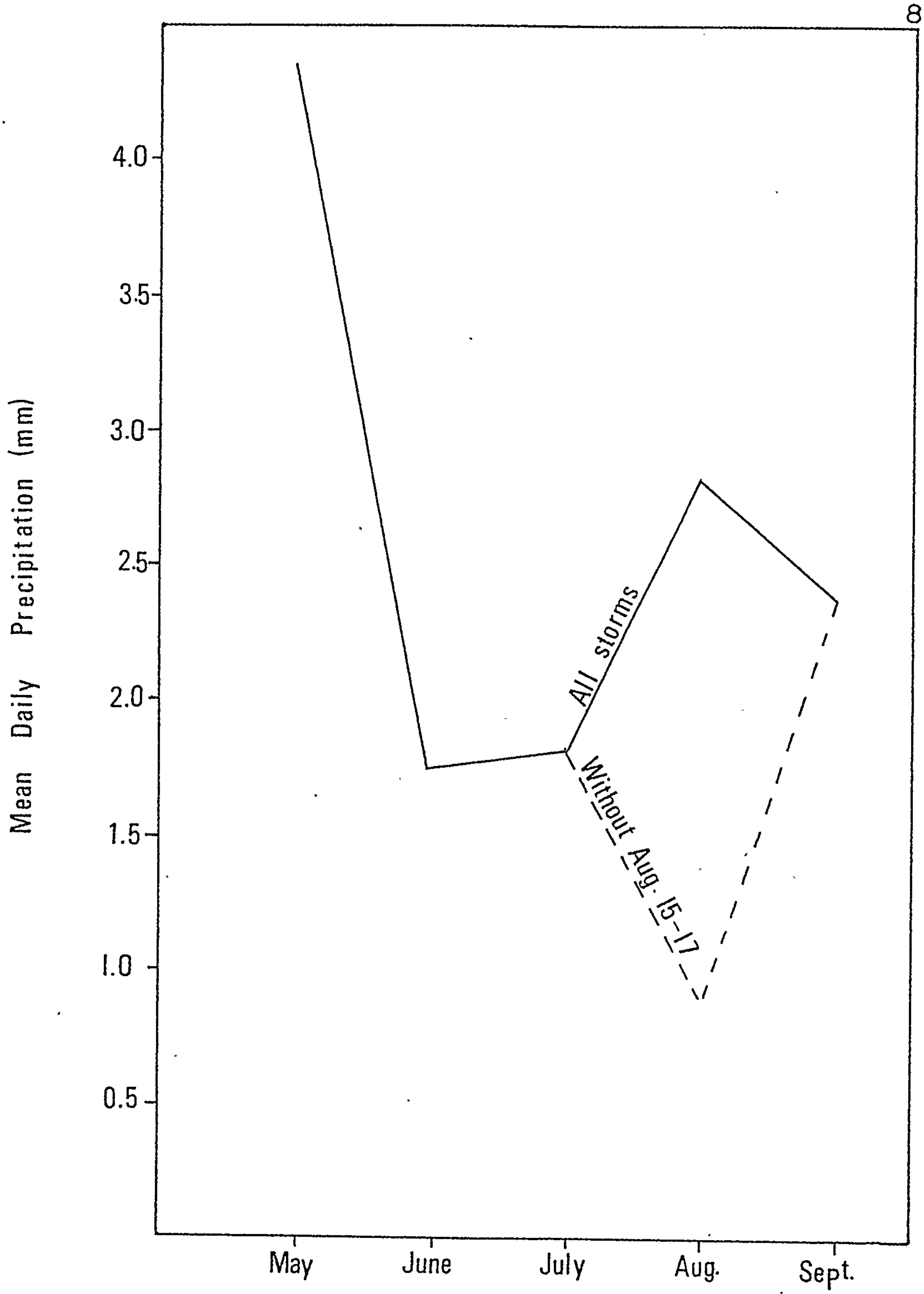


FIGURE 4.3.1

MEAN DAILY PRECIPITATION BY MONTH

several large-scale, slow moving disturbances that crossed southern Alberta in the early part of the month. Thirteen of the first 19 days of the month experienced rainfall.

4.3.4 The Distribution of Precipitation by Day of the Week

A breakdown of precipitation by day of the week revealed a peak in mid-week (Tues.-Wed.) for both total rainfall and number of rain days (Tables 4.3.4 and 4.3.5, Fig. 4.3.2, 4.3.3, and 4.3.4). Wednesday's relatively high rainfall value is partially explained by the fact that August 16, on which almost one-half of August's rainfall occurred, was a Wednesday (Fig. 4.3.3). The other peaks have no obvious explanation. No synoptic type showed a preference for any given part of the week.

The records for all four tipping bucket gauges showed similar weekday patterns (Fig. 4.3.2 and 4.3.4). The only apparent anomaly occurred on Saturday at Station 6. A convective storm, characterized by extreme spatial variability[1] occurred on Saturday, July 22. Station 6 received considerably more precipitation than other localities, resulting in a relatively high Saturday total. In terms of the number of rain days, the higher frequency of rain days for the total network over any of the four

[1] The coefficient of variation was 103 %, which is 51 % higher than the mean of all storms with greater than 1 mm mean precipitation.

TABLE 4.3.4

DISTRIBUTION OF PRECIPITATION BY DAY OF THE WEEK *

Day of the Week	Per Cent Total Precipitation			
	Cyclonic	Frontal	Localized Convective	All Events
Sunday	4.50	1.14	3.30	8.94
Monday	.43	7.25	3.63	11.32
Tuesday	9.49	13.22	2.58	25.29
Wednesday	27.24	.34	2.23	29.79
Thursday	4.75	2.76	1.77	9.29
Friday	4.58	2.67	.74	7.98
Saturday	2.80	1.19	3.39	7.39
ALL DAYS	53.79	28.57	17.64	100.00

* Table is based on records from the tipping bucket gauges.

TABLE 4.3.5

NUMBER OF DAYS WITH RAIN VERSUS DAY OF THE WEEK *

Day of the Week	Total Number of Days with Rain: Cyclonic	Frontal	Localized Convective	All Events
Sunday	4	2	4	10
Monday	3	6	1	10
Tuesday	5	5	5	15
Wednesday	4	4	5	13
Thursday	4	1	4	9
Friday	4	3	2	9
Saturday	3	2	3	8
ALL DAYS	27	23	24	74

* Table is based on records from the tipping bucket gauges.

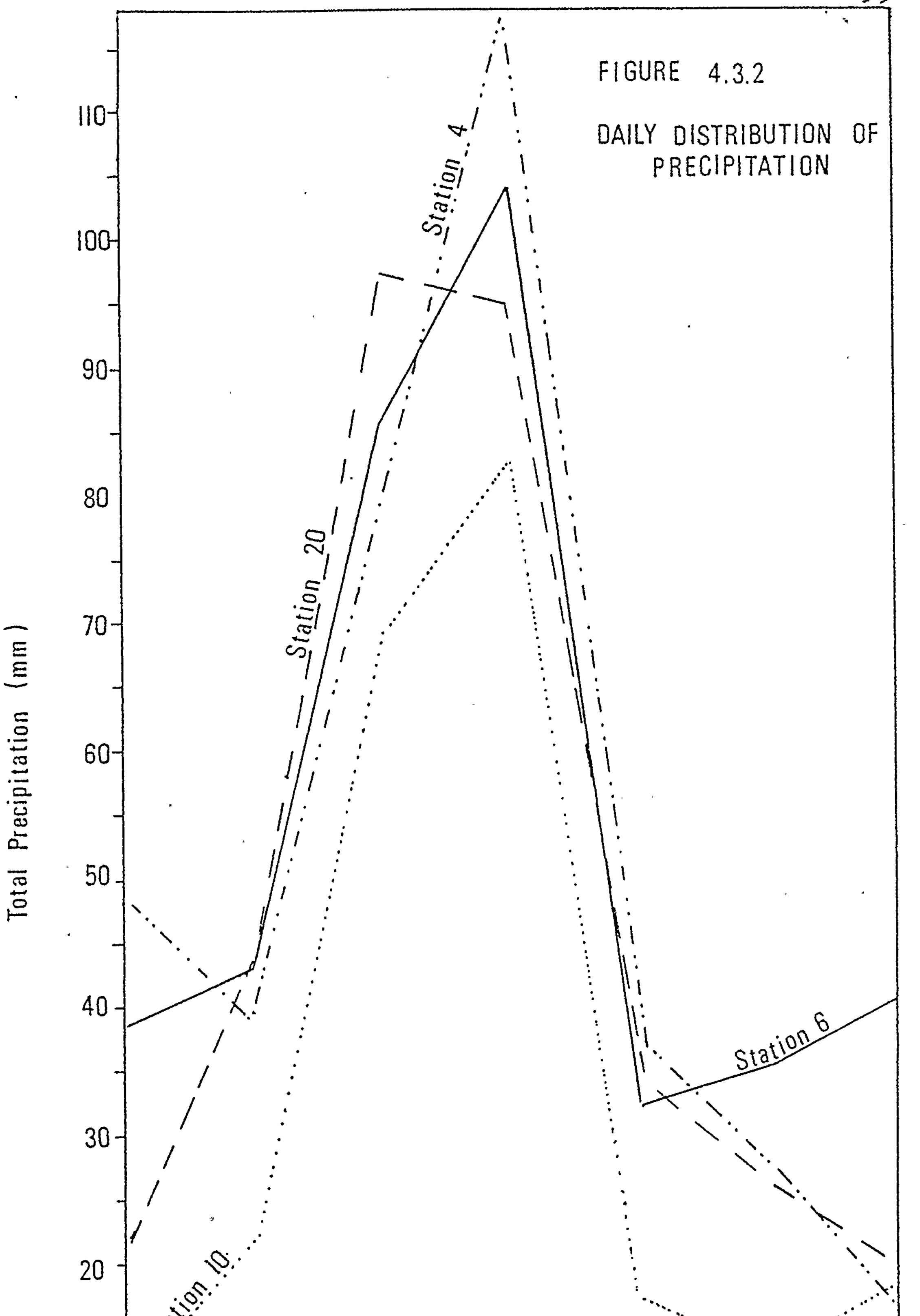


FIGURE 4.3.2
DAILY DISTRIBUTION OF PRECIPITATION
Total Precipitation (mm)
110
100
90
80
70
60
50
40
30
20
10
Station 4
Station 20
Station 6
Station 10
Sun.
Mon.
Tues.
Wed.
Thurs.
Fri.
Sat.

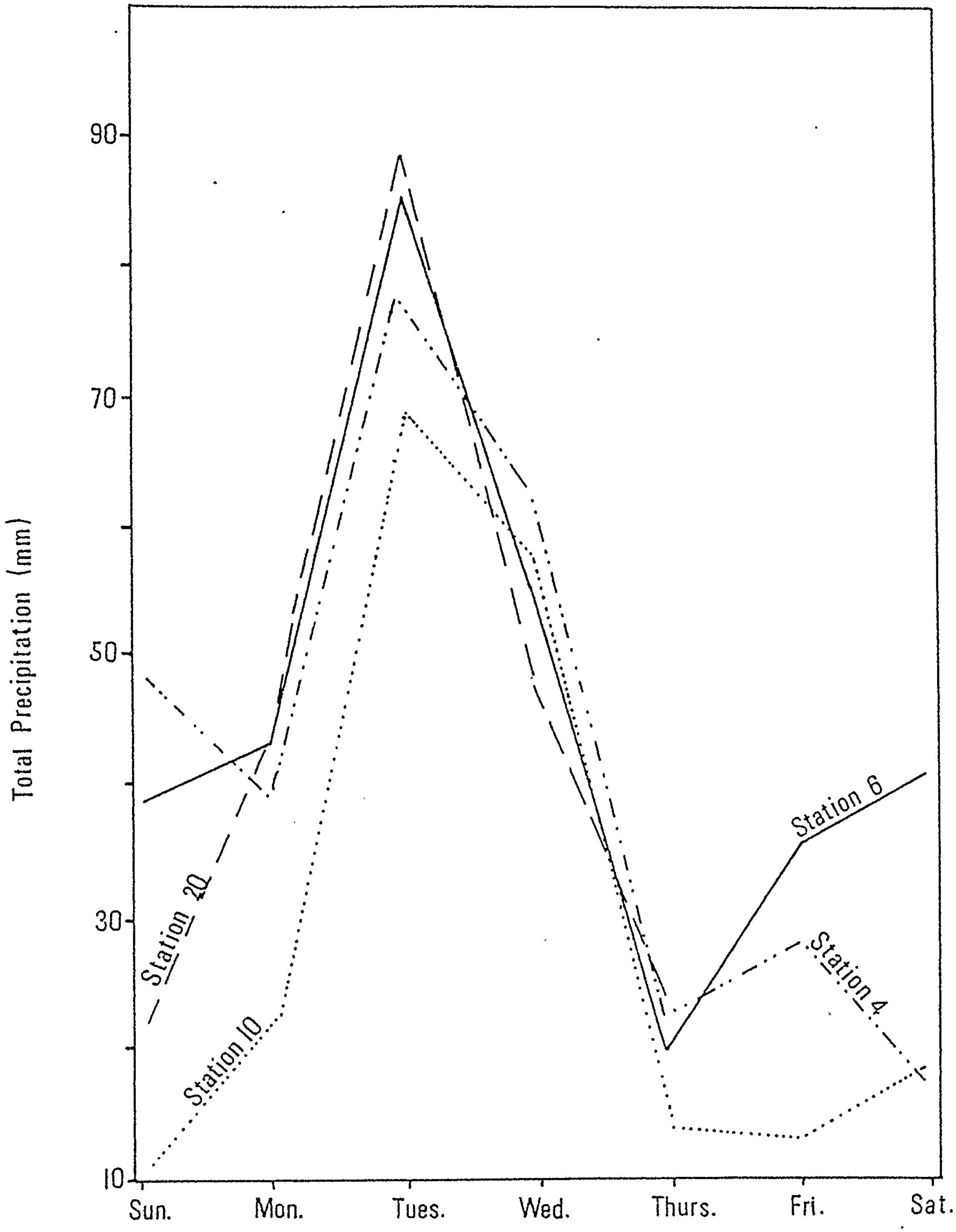


FIGURE 4.3.3

DAILY DISTRIBUTION OF PRECIPITATION, AUG. 15-17 STORM REMOVED

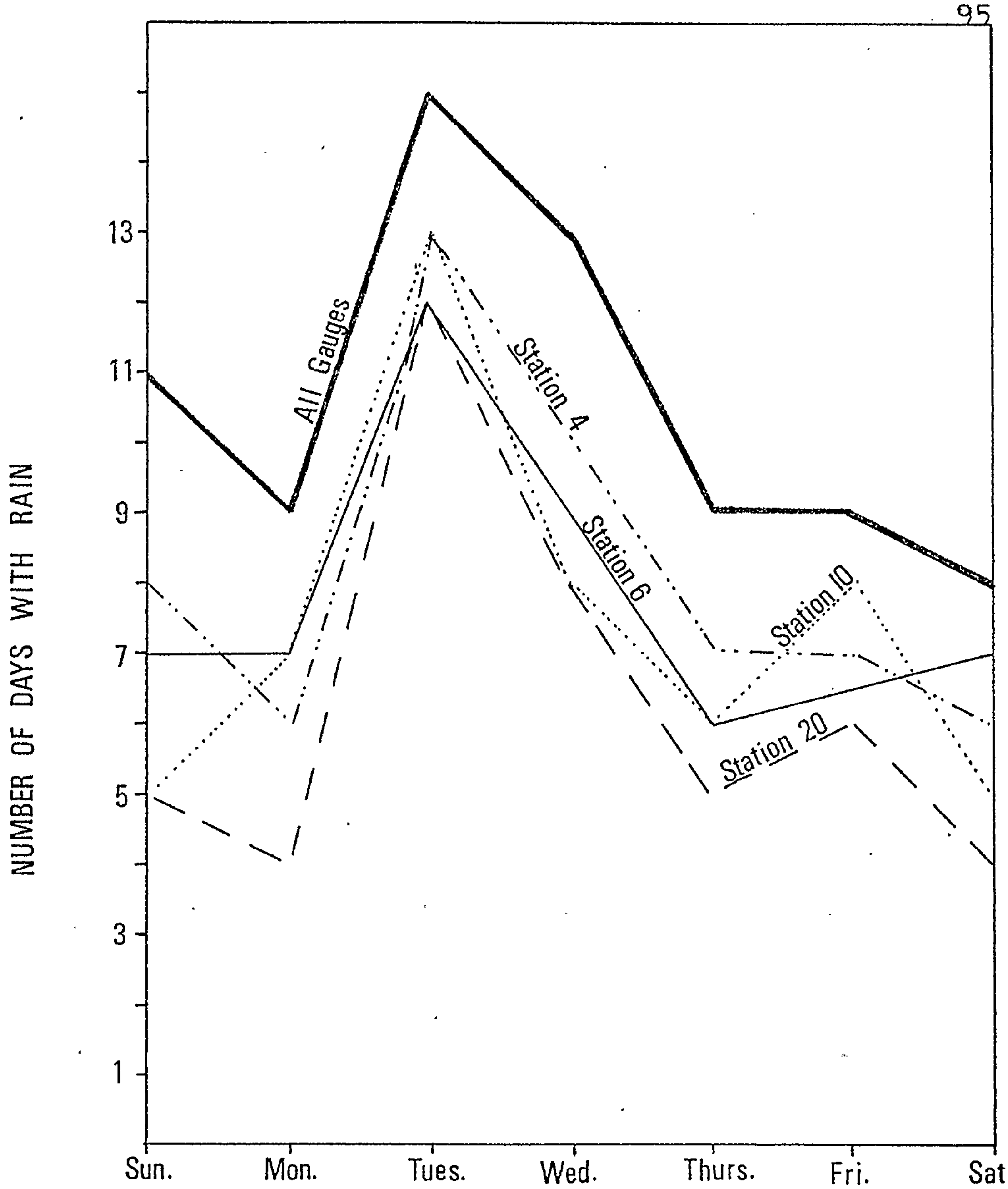


FIGURE 4.3.4

NUMBER OF DAYS WITH RAIN BY DAY OF THE WEEK individual tipping bucket sites is explained merely by areal probability.

The observed trend toward decreased precipitation in the latter part of the week and over the weekend has questionable interpretation in terms of urban effects. Ashworth (1929) documented a minimum in total precipitation on Sunday in the manufacturing town of Rochdale, England. Since at Stoneyhut, England, where factories did not predominate, all days of the week were more nearly alike, Ashworth suggested a possible causal relationship between increased precipitation and industrial outputs of nuclei and hot gases.

In the case of Calgary, the weekend/weekday daily precipitation ratio for the four tipping bucket gauge records and all events combined was .488. With the August 15-17 storm removed, the ratio was .610. This may be interpreted as indicating the possible existence of urban effects but further investigation is necessary.

4.3.5 The Distribution of Precipitation by Time of Day

For all storms combined, hourly precipitation totals were calculated (Fig. 4.3.5). A small peak in total precipitation was found to have occurred between 1600 and 1800 MDT. According to Huff (1975), late afternoon (1600-1900 Local Daylight Time) is the period when the

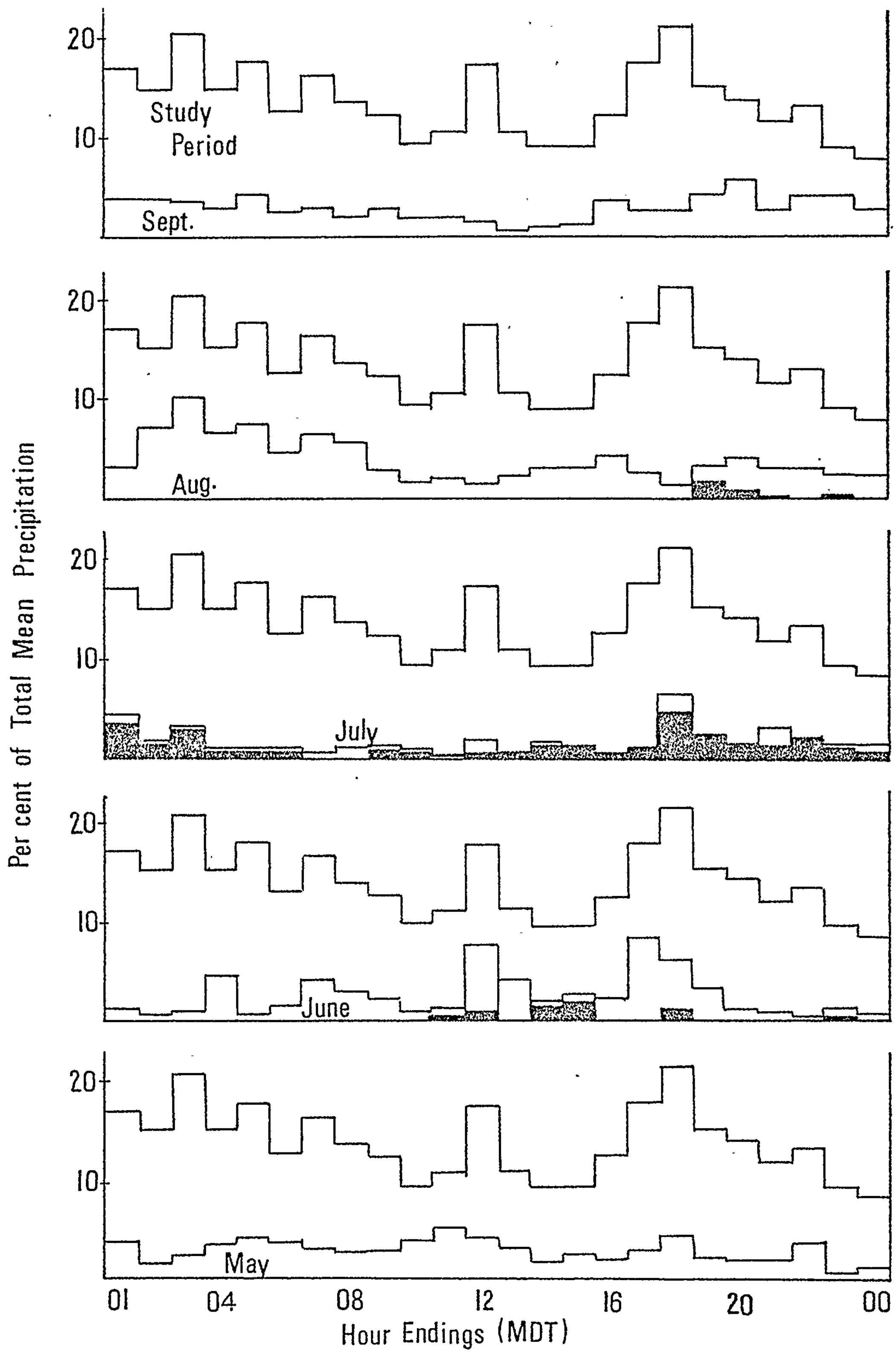


FIGURE 4.3.5

HOURLY DISTRIBUTION OF PRECIPITATION

thermal contribution to the initiation and intensification of convection would normally maximize, when the output of urban heat is superimposed on the natural diurnal heating pattern. This appears to explain the observed precipitation peak.

There appears to be a phase lag of approximately one hour between the times of maximum available heat and maximum precipitation from localized convective storms. No phase lag is evident for all storms combined, however.

The late afternoon peak in precipitation is coincident with the time of day when the urban/rural heat differential is smallest. This is an effect - effect relationship. Daytime heating enhances convective development but retards the development of a strong heat island formation.

An examination of the hourly breakdown of precipitation for individual months reveals four interesting facts. May and September do not exhibit any prominent troughs or peaks. Large scale storms, whose instabiity is less controlled by local daytime heating, predominated during these two months.

For June, two peaks are evident, a well developed one between 1700 and 1800 MDT, and a secondary one at midday. The influence of localized convective showers, as a result of daytime heating, can be noted.

July exhibits a precipitation minimum during the early hours of the day (0400-1100 MDT) and a peak at 1800 with continuing high values until approximately 0300. Daytime heating appears to be a major cause for the development of this precipitation peak. A small lag exists between the times of maximum available heat and maximum precipitation.

August experienced large amounts of precipitation during all hours, especially between 0200 and 0900. The effect of the August 15-17 storm is evident. For all three days of this storm, the heaviest rainfall occurred between 0200 and 0900 MDT.

4.4 A Study of the Relationship between Rainfall Duration and Rainfall Intensity

Despite the fact that a variety of synoptic and wind conditions prevailed during rain storms, a general observation of decreased storm duration with increased rainfall intensity was noted. In order to gain insight into expected storm duration with various storm intensities, the two variables were examined simultaneously for all rain periods.

The two variables were found to be logarithmically related, as was expected (Butler, 1957). The equation defining the relationship is:

$$\ln (Y) = 4.89 - 0.89 \ln (X)$$

where Y is the estimated storm duration (minutes) and X is the mean rainfall intensity (mm/hr) (Fig. 4.4.1). The relationship was significant at a .05 alpha level. The correlation coefficient was -.62. The standard error of the estimate was 1.16 minutes.

For any given intensity, a wide range of durations may be expected. While 'cloudbursts' characterized by mean intensities of greater than 10 mm/hr are generally short lived, expected durations vary between 2 and 180 minutes at a 95 % confidence level. On the other hand, for rain periods whose mean intensities are less than .5 mm/hr, durations exceed one-half hour 95 % of the time. Either extreme in intensity occurs relatively infrequently, however, approximately 15 % and 25 % of the time respectively.

4.5 Summary

Chapter four has examined the temporal aspects of precipitation in Calgary. An historical evaluation of precipitation in and around the city of Calgary revealed no precipitation trends through time. Thus, it can be inferred that no correlation between population and total

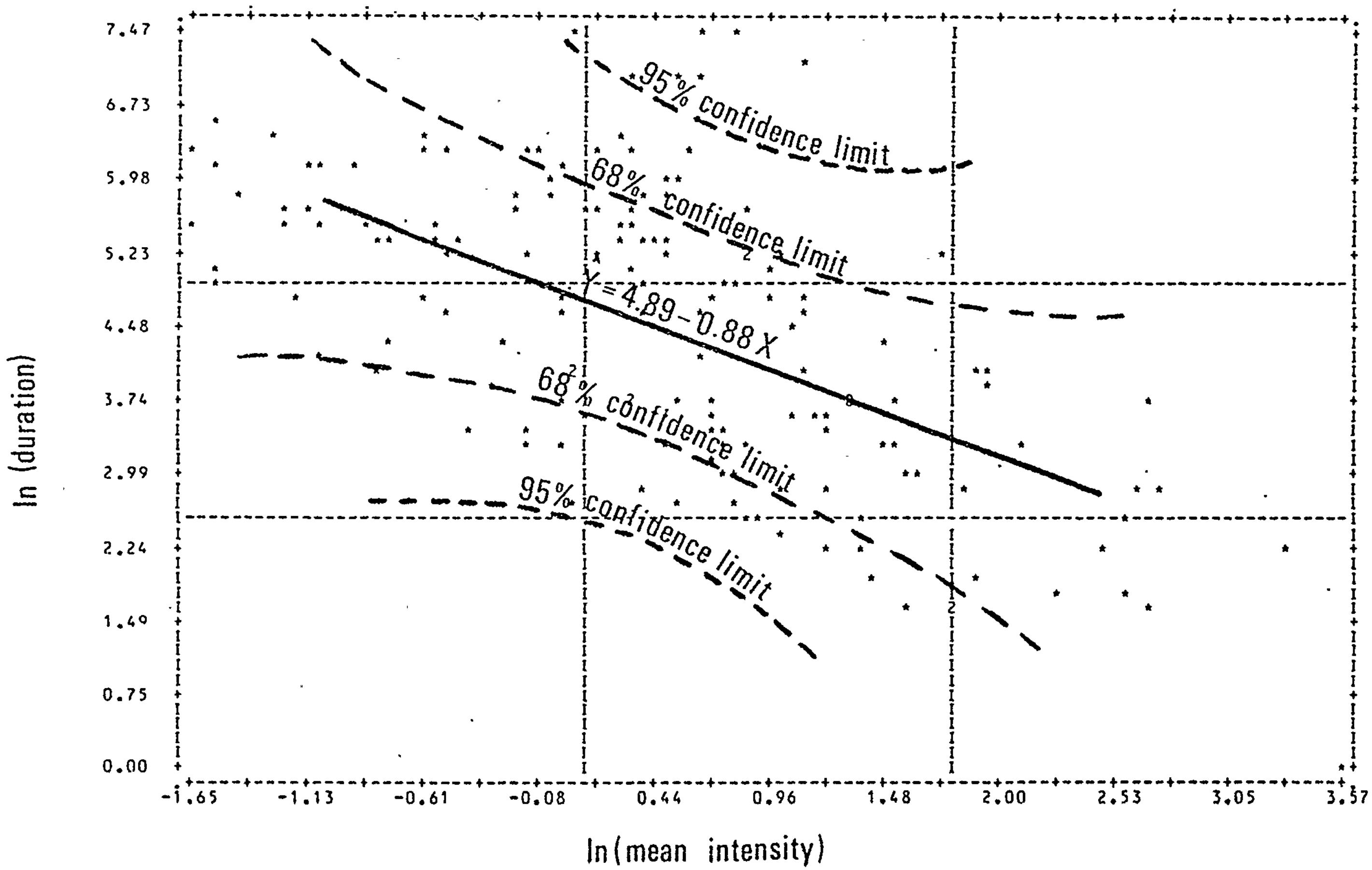


FIGURE 4.4.1
RAINFALL DURATION VERSUS INTENSITY

precipitation or between heat island intensity and total precipitation exists. Also, despite Calgary's expanding urban complex, the area downwind of the city does not appear to have experienced any corresponding change in precipitation.

During the study period, 51 storms occurred resulting in a mean precipitation of 338.26 mm. Localized convective storms occurred most frequently, but in absolute terms, cyclonically related storms were responsible for the most rainfall. According to data from Calgary's International Airport, the study period was approximately 25 % wetter than was normal. May, August, and September were unusually wet months, while June and to a lesser extent July were drier than normal. For all storms combined, a weekday peak in precipitation occurred during the Tuesday-Wednesday period. A weekend minimum was observed. This pattern may be related to urban industrial activity. Late afternoon (1700-1800 MDT) was the time of day that received the largest amount of precipitation. This is believed to be the result of daytime heating.

Storm duration was examined as it related to mean rainfall intensity. A logarithmic function relating the two variables was defined, with a correlation coefficient of -.62.

CHAPTER FIVE: THE SPATIAL DISTRIBUTION OF RAINFALL IN CALGARY

5.1 Introduction

Chapter 5 discusses the spatial distribution of precipitation in Calgary for the study period involved. Firstly, the study area is placed in a larger areal context with respect to precipitation receipt. Then, the spatial patterns of precipitation within the city are examined. The effects of various physical and man created phenomena on the observed spatial patterns are discussed.

5.2 The Study Area - Is It Unique?

Prior to a discussion of the observed spatial distributions of precipitation within Calgary, the relationship between the study area and its environs is examined with respect to precipitation. The purpose for this is to establish whether or not Calgary is unique to its environment. This will provide a focus for the study. If Calgary can be identified as being separate from its environs, then this study describes the precipitation regime of a local, unique, urban entity. If the city of Calgary is not unique with respect to precipitation, then the study takes on a different focus. It becomes a study of the spatial variability of precipitation in a small area of southern Alberta.

To allow Calgary to be examined within a large spatial context, 26 gauge sites peripheral to Calgary, but within a range of 165 km from the city centre, were examined. The intent was to determine whether or not Calgary fits into the general spatial pattern of precipitation on a relatively large scale for the study period as a whole. To represent Calgary, the precipitation records from the International Airport were used. This site is near the edge of the city and is therefore a good choice for comparison with other rural stations.

Since the effect of elevation on the spatial distribution of precipitation can be substantial (Duckstein et al., 1973; Reid, 1973; Longley, 1975), regression analysis was employed to remove this effect. A linear relationship between elevation and precipitation was defined. Precipitation was found to decrease with increasing elevation. The association between the two variables was weak (insignificant at a .05 alpha level) with only 4 % of the variation in precipitation being explained by elevation. The removal of elevation from further analysis was accomplished by bringing all gauge sites to the common elevation of 905 m a.s.l.[1]

The resultant spatial pattern of precipitation indicates that Calgary was situated within a band of relatively low precipitation running east-west (Fig. 5.2.1).

[1]Of the 26 sites examined, Gleichen and Acme were located at the lowest elevation, that of 905 m a.s.l.

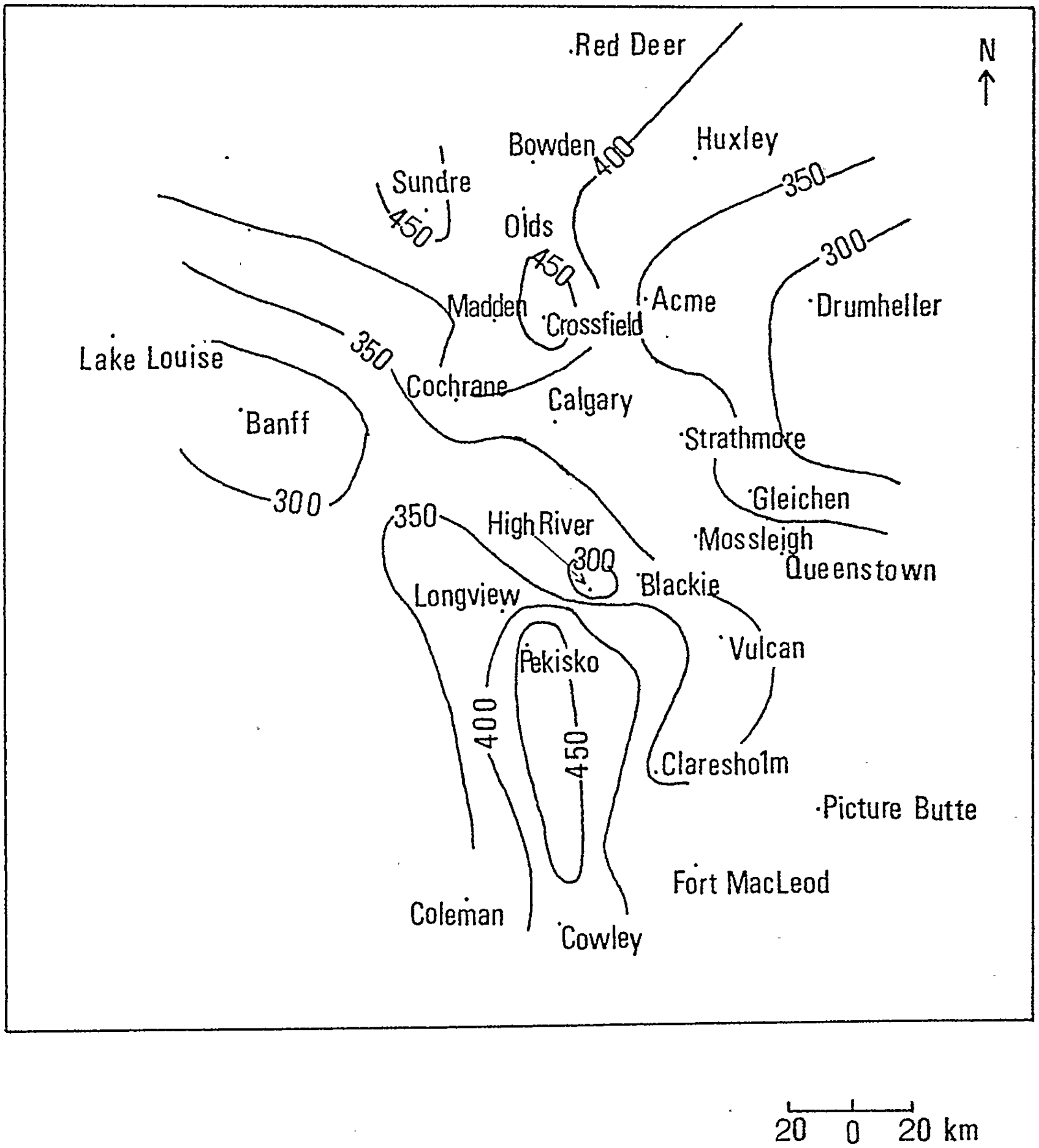


FIGURE 5.2.1

DISTRIBUTION OF PRECIPITATION OUTSIDE CALGARY - ELEVATION REMOVED

Two nodes of higher precipitation were located directly north and south of the Calgary area. In terms of gradient, no unusual zones can be identified. Of particular interest is the fact that the rate of change directly outside the city limits was no greater than for the area as a whole. Therefore, Calgary appears to fit into the regional pattern of precipitation.

The second task was to determine whether or not the city, in its entirety, was significantly different from its environs in terms of precipitation totals. The 20 gauge network was compared to the nearest 20 gauges outside the city limits. A two-tailed t-test was employed. At a significance level of .05, there was a significant difference between city precipitation and rural precipitation. The city was found to receive less rainfall than the surrounding countryside. This is in direct opposition to findings in other urban areas. Calgary's valley location offers one possible explanation for this deviation. Longley (1975) concluded that for four Canadian prairie valleys examined, the valley locations received 10 - 20 % less rainfall than did the level land situated on either side of the valleys.

A problem with gauge density exists in the analysis, however, with the city's network being approximately 100 times more dense than its rural counterpart. No solution to this problem is available. If other localities were densely gauged it is possible that their precipitation regimes might also display qualities of spatial complexity and significant variation from regimes of the surrounding countryside.

In conclusion, the precipitation received at Calgary's International Airport suggests that Calgary fits into the spatial trends that exist over a large area surrounding Calgary. However, the precipitation records from the dense network within the city suggest that the city as a whole forms a separate precipitation regime that is unique from the surrounding country. This decision is compl mented by the complexity of Calgary's rainfall pattern.

5.3 The Spatial Distribution of Precipitation in Calgary- The Study Period

For the study period involved, Calgary was found to exhibit a high degree of spatial variability in precipitation. Mean total precipitation was 338.26 mm, but total accumulated precipitation ranged from 227.5 mm to 367.5 mm within the city, a difference of 62 % between the highest and lowest values. The standard deviation was 31.27 mm.

In addition, the spatial pattern of precipitation totals was found to be complex (Fig. 5.3.1). The pattern was particularly involved in the western half

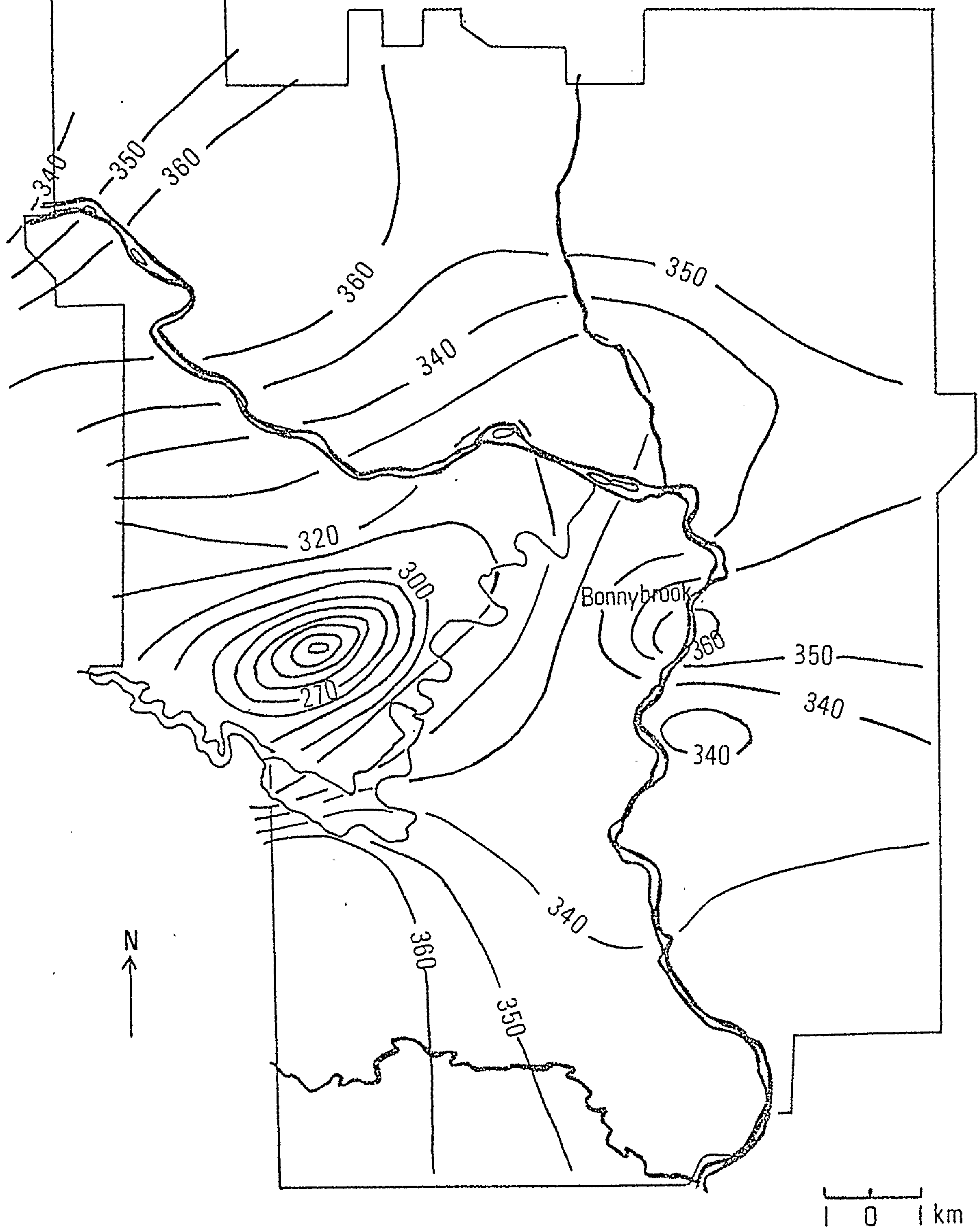


FIGURE 5.3.1

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)

MAY 16 - SEPTEMBER 30, 1978

of the city. Two zones of relatively high precipitation were identified. The largest was a band extending from northwest Calgary to industrial Bonnybrook. The 'high' was most pronounced in the residential areas to the northwest of the University of Calgary (Brentwood, Dalhousie, and Varsity Acres) and more locally in Bonnybrook. A second region of high precipitation existed in deep southwest Calgary, between Glenmore Reservoir and the southern city limits. Precipitation decreased to the east and northeast of these two zones.

A district of relatively low precipitation was noted in west Calgary, just north of Glenmore Reservoir, between the Bow and Elbow Rivers. This 'low' was well defined. It appeared consistently in 8 out of 10 storms with greater than 10 mm mean precipitation and was apparent under all synoptic conditions.

All of the main features of this pattern remained when the contribution of the August 15-17 storm was removed from the precipitation totals. Therefore, none of the above mentioned features appear to be attributable to this single large event.

In examining Calgary's city core, it was found that the Central Business District (CBD) received 6.6 % less precipitation than the mean. The zone of high precipitation in the southwest (Woodlands) received 16.4 % more precipitation than did the CBD. The 'low' situated north of Glenmore Reservoir received 28 % less. Precipitation increased to the northwest (1.6 % per km), southwest (1.4 % per km), and southeast (3.4 % per km) of the CBD. The gradient of change in rainfall receipt from the CBD to the 'low' north of the reservoir was a decrease of 4.5 % per km.

The International Airport in northeast Calgary was found to receive 6.4 % more precipitation than the mean, when all storms were combined. For some individual storms, this deviation from the mean increased to greater than 20 %. The zone of highest rainfall in Calgary received 2.1 % more precipitation than the airport and the zone of lowest precipitation, 36.8 % less. It would therefore appear that this single station does not fully represent Calgary's precipitation regime (Fig. 5.3.2).

5.4 The Spatial Distribution of Precipitation in Calgary, A Breakdown by Synoptic Type

Synoptic conditions are known to affect the degree of spatial variability in precipitation. Typically, cyclonic disturbances cover relatively large areas with a relatively uniform distribution of precipitation. In Calgary, substantial spatial variation did occur under cyclonic conditions, however (Fig. 5.4.1). The pattern closely resembled that for all synoptic conditions

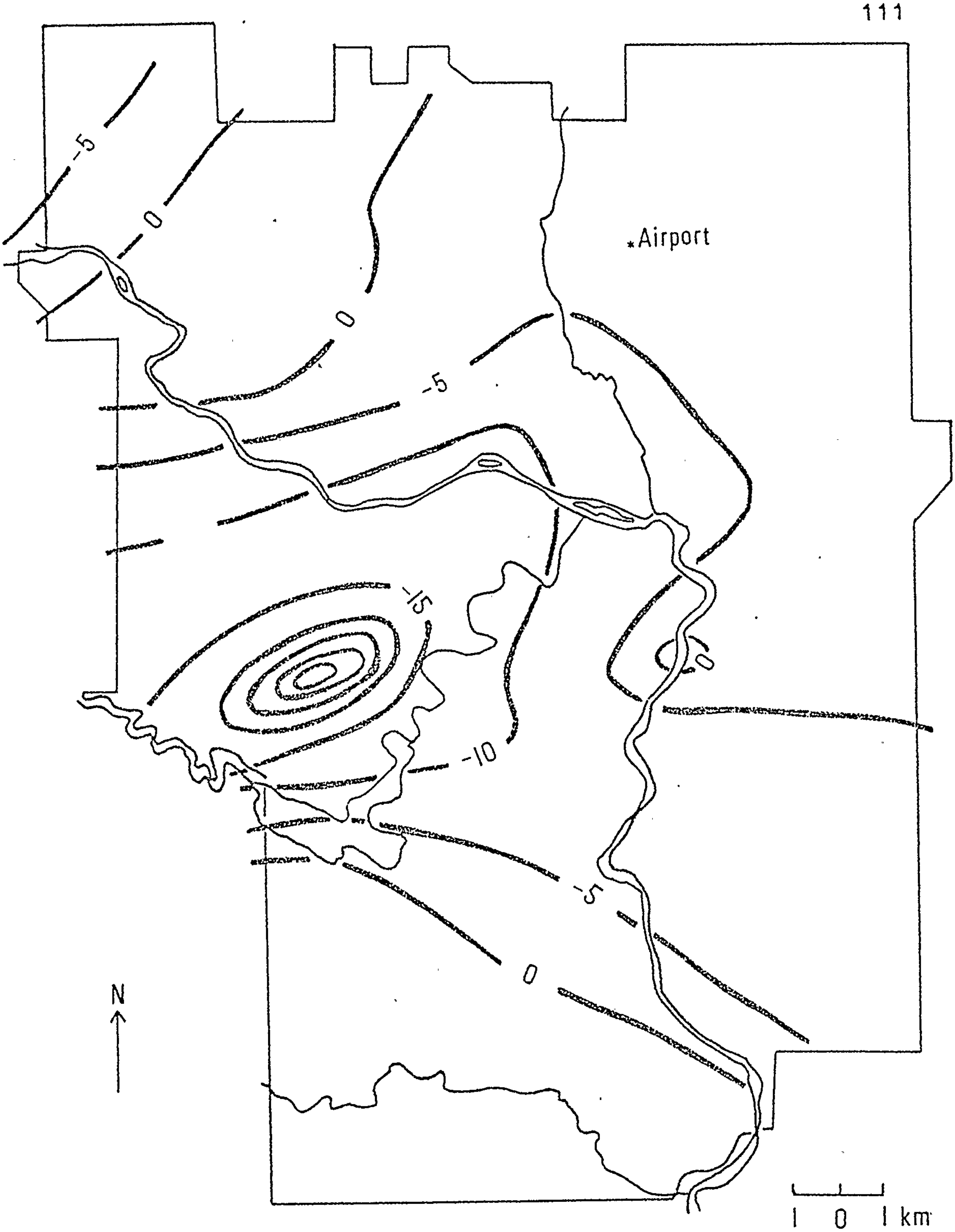


FIGURE 5.3.2

PER CENT DEVIATION FROM AIRPORT RAINFALL TOTAL - MAY 16 - SEPTEMBER 30, 1978

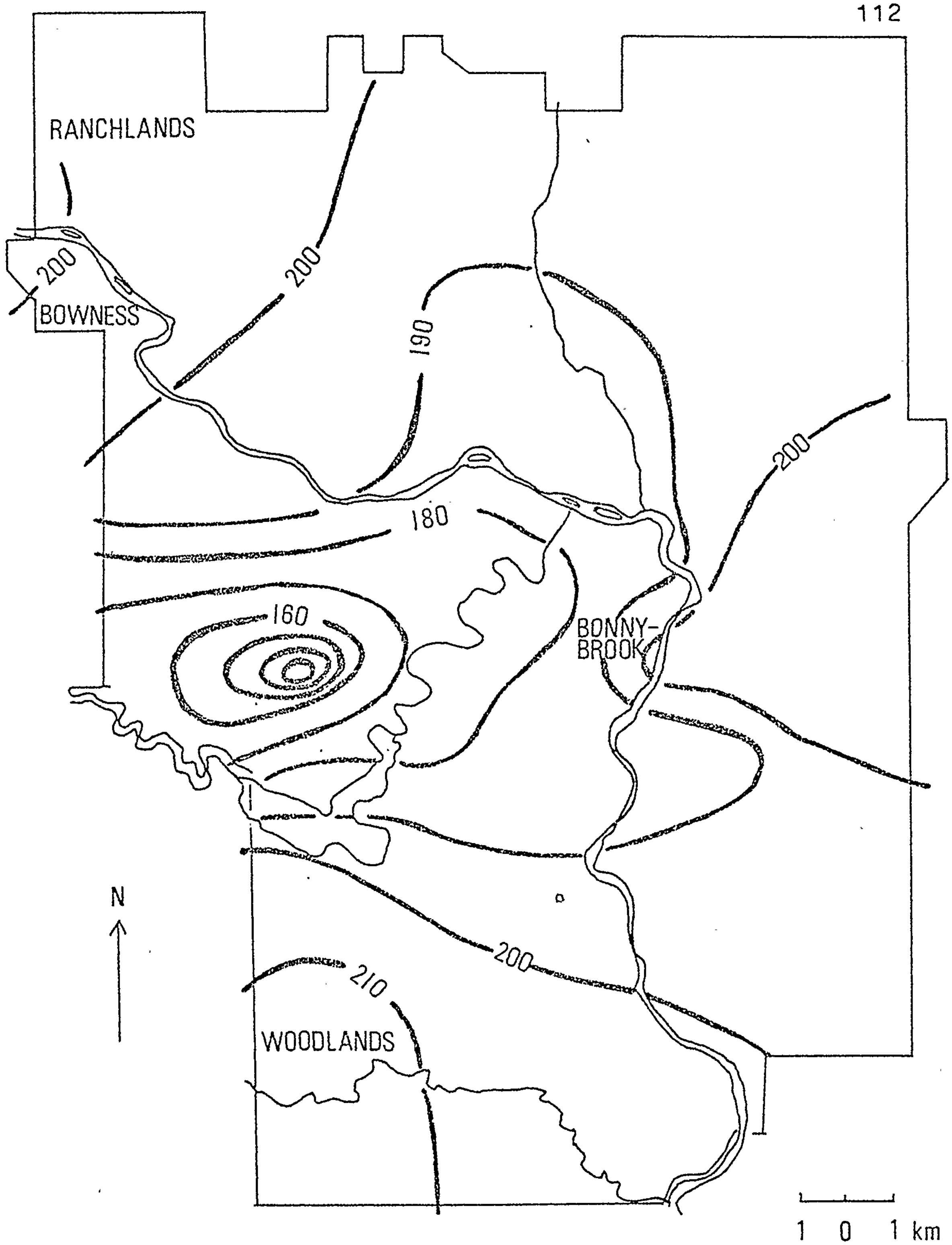


FIGURE 5.4.1

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)

CYCLONIC STORMS

combined. Pronounced 'highs' occurred in Calgary's northwest (from Bowness to Ranchlands) and southwest (in and south of Woodlands). The deep low, situated north of Glenmore Reservoir, was well expressed and extended further northeastward.

The CBD received less precipitation than the mean. Going outward from the CBD, precipitation decreased rapidly southwestward (toward Station 10), but increased to the northwest, deep southwest and southeast (Table 5.4.1).

When the August 15-17 storm was removed (Fig. 5.4.2), the only change that occurred in the pattern was in southeast Calgary. Bonnybrook, identified in Fig. 5.4.1 as an area of relatively high precipitation, no longer appeared as such. Its existence was apparently attributable to the August 15-17 storm.

During frontal conditions, less spatial variability existed (Fig. 5.4.3). Once again, the southwest was an area of high precipitation. The formerly identified region of high precipitation in northwest Calgary increased in size and was displaced eastward (centred over Dalhousie). Bonnybrook represented a local weak positive anomaly. Two areas of low precipitation were found, a large zone extending from just north of the reservoir northeastward through the city core, and a less prominent one southeast of the industrial zone of

TABLE 5.4.1

THE GRADIENTS OF CHANGE IN RAINFALL RECEIPT FROM THE CBD TO OTHER AREAS

	All Storms	Cyclonic	Frontal	Convective
Northwest (Station 2)	↑1.6% per km	↑1.6% per km	↑3.7% per km	↓2.1% per km
Southwest (Station 18)	↑1.4% per km	↑1.5% per km	↑3.0% per km	↓1.4% per km
Ogden (Station 13)	↑3.4% per km	↑2.1% per km	↑4.2% per km	↑4.3% per km
'Low' in West (Station 10)	↓4.5% per km	↓5.4% per km	↓2.1% per km	↓6.0% per km

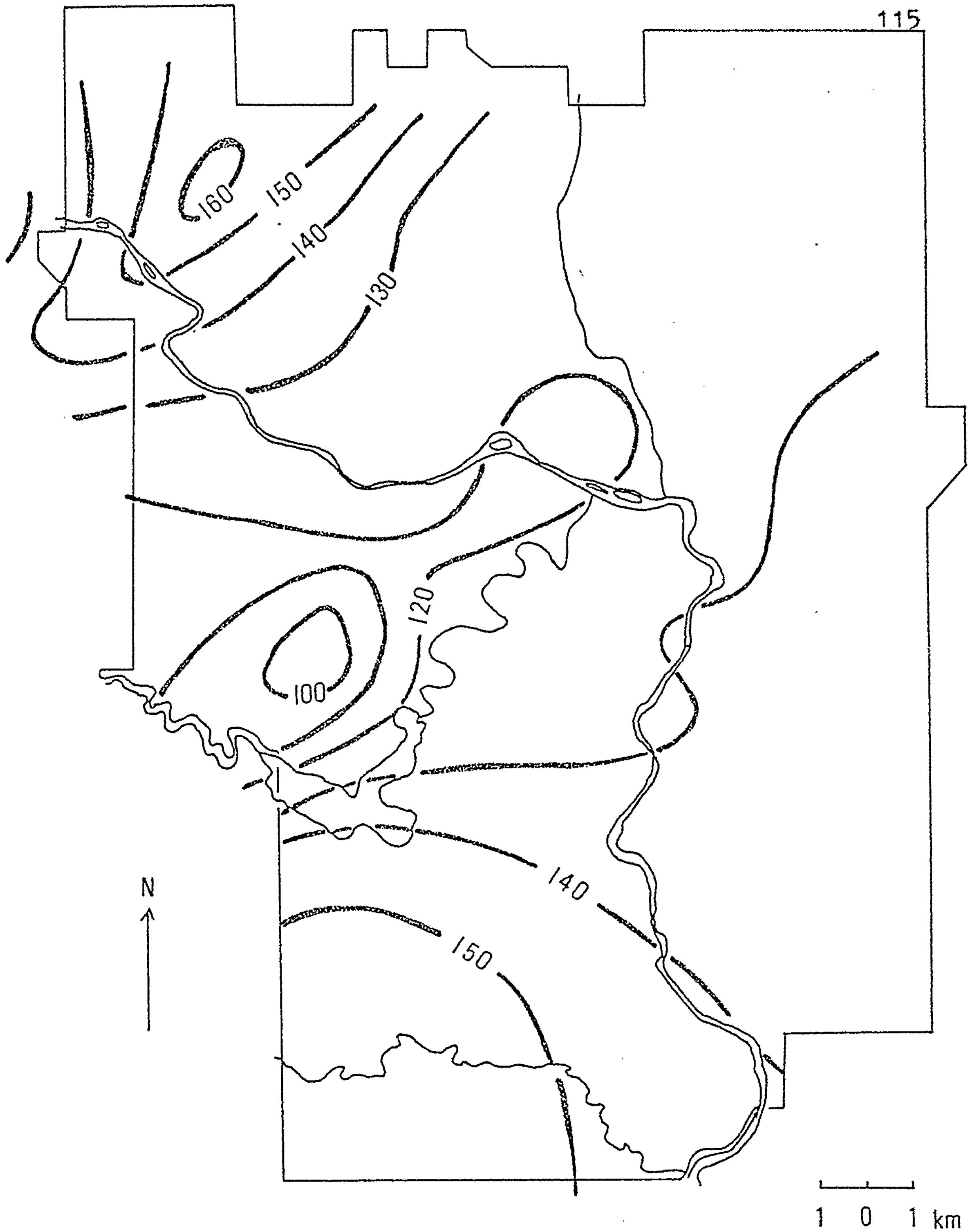


FIGURE 5.4.2

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)

ALL CYCLONIC STORMS EXCEPT THE AUGUST 15 - 17 EVENT

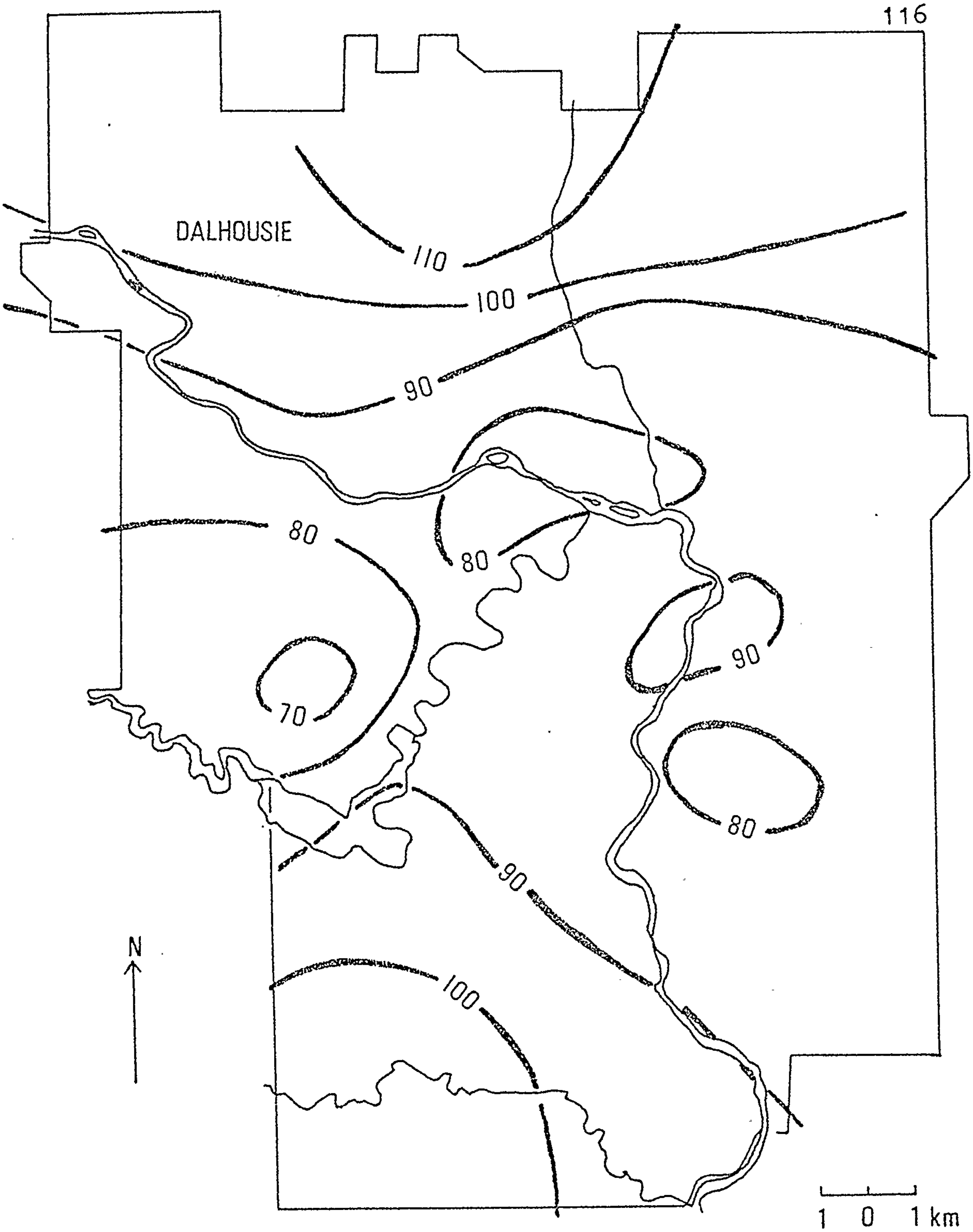


FIGURE 5.4.3

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)

FRONTAL STORMS

Ogden in southeast Calgary.

The area of greatest precipitation receipt during all frontal storms combined received 68.3 % more rainfall than did the area of lowest receipt. The CBD received 12.4 % less rainfall than the mean. A sharp positive precipitation gradient existed to the north of the CBD (Table 5.4.1). The precipitation value at the airport was 15 % greater than the mean.

Localized convective showers produced a somewhat different pattern (Fig. 5.4.4). Southwest and northwest Calgary were considerably drier. Two precipitation maxima occurred, one in Bonnybrook and a secondary one south of Bowness in the vicinity of Paskapoo and Broadcast Hills. Once again, the low situated north of Glenmore Reservoir was well defined.

The degree of spatial variability was higher for convective type precipitation than for other synoptic types. The area of highest precipitation received 90.5 % more than the lowest. The gradient of change in precipitation receipt from the CBD to the 'low' north of the reservoir was 6.0 % per km.

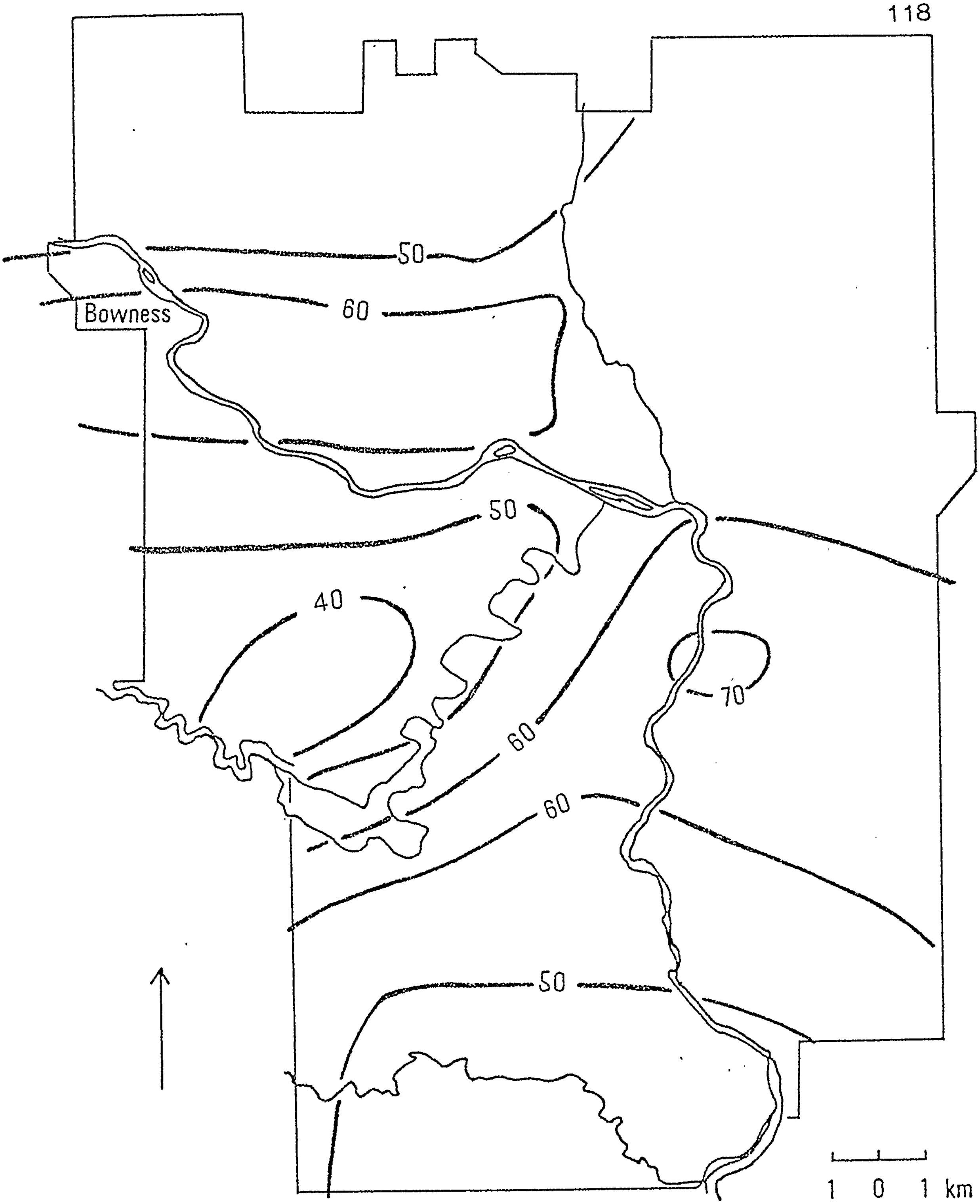


FIGURE 5.4.4

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)

LOCALIZED CONVECTIVE STORMS

5.5 The Spatial Distribution of Precipitation in Calgary, The Effect of Topography

5.5.1 Elevation

Topography is recognized as a major control over the distribution of precipitation at a local scale. The effects of elevation, in particular, have been documented. Most work, however, has been concentrated in extremely diverse topographic regions. In this thesis, elevation is examined as it affects the distribution of precipitation in Calgary, an area characterized by gently rolling topography.

Linear regression analysis was used to determine the effects of elevation on the receipt of precipitation. For the study period as a whole, it was found that elevation did not significantly affect precipitation receipt at a significance level of .05. A weak positive relationship, in which less than 5 % of the variation in precipitation was explained by elevation, was defined.

When all storms were examined individually, it was found that elevation played a significant role in only 12 of the 37 cases[1]. No tendency toward decreased

[1] Only those storms where 11 or more stations received measurable amounts of precipitation were used.

or increased precipitation with increased elevation was found, even after stratification by synoptic type and by mean precipitation totals. A higher proportion of localized convective showers displayed significance than either frontal or cyclonic rainfall.

Both wind speed and direction were found to be important parameters in explaining the effect of elevation on precipitation receipt under certain circumstances. During 8 or the 12 events in which elevation was found to play a significant role in defining precipitation receipt, the wind prevailed from the southeast or the northeast. For the study period as a whole, less than one-half of all precipitation events had such wind conditions (Table 5.5.1). Since Calgary's elevation rises from southeast to northwest, it is believed that a topographic upslope effect, created only under easterly wind conditions, explains the fact that elevation was significantly correlated with precipitation more frequently under easterly wind conditions than under any other wind condition. No tendency toward decreased or increased precipitation with increased elevation was found for these eight cases, even when the events were subclassified as having predominantly southeast or predominantly northeast winds.

It would therefore appear that wind direction is a major control over when elevation plays an important

TABLE 5.5.1

WIND DIRECTION FREQUENCIES DURING STORMS

	NW	W	SW	S	SE	E	NE	N
Per Cent Storms with Given Direction as a Dominant Component	45.9	37.8	9.5	12.2	10.8	21.6	14.9	58.1
Per Cent Storms with Given Direction as a Dominant Component and a Significant Linear Relationship between Precipitation and Elevation	25.0	8.3	8.3	16.6	50.0	0.0	50.0	25.0

role in defining Calgary's spatial precipitation patterns. No insights as to how the spatial pattern is affected by elevation was gained, however.

In addition, the occurrence of a significant relationship between elevation and precipitation receipt was found to be related somewhat to wind speed. All 12 cases in which a significant linear relationship was defined had wind speeds of between 3 and 7.8 m sec^{-1}. For all rain events, the same class of wind speed accounted for only 64.7 % of all storms. Although further investigation is needed, it would appear that elevation affects precipitation receipts most under moderate wind speed conditions.

The effects of slope angle, orientation, and exposure are implicitly described in Section 5.5.2.

5.5.2 The Spatial Distribution of Precipitation in Calgary, A Comment on Storm Tracks

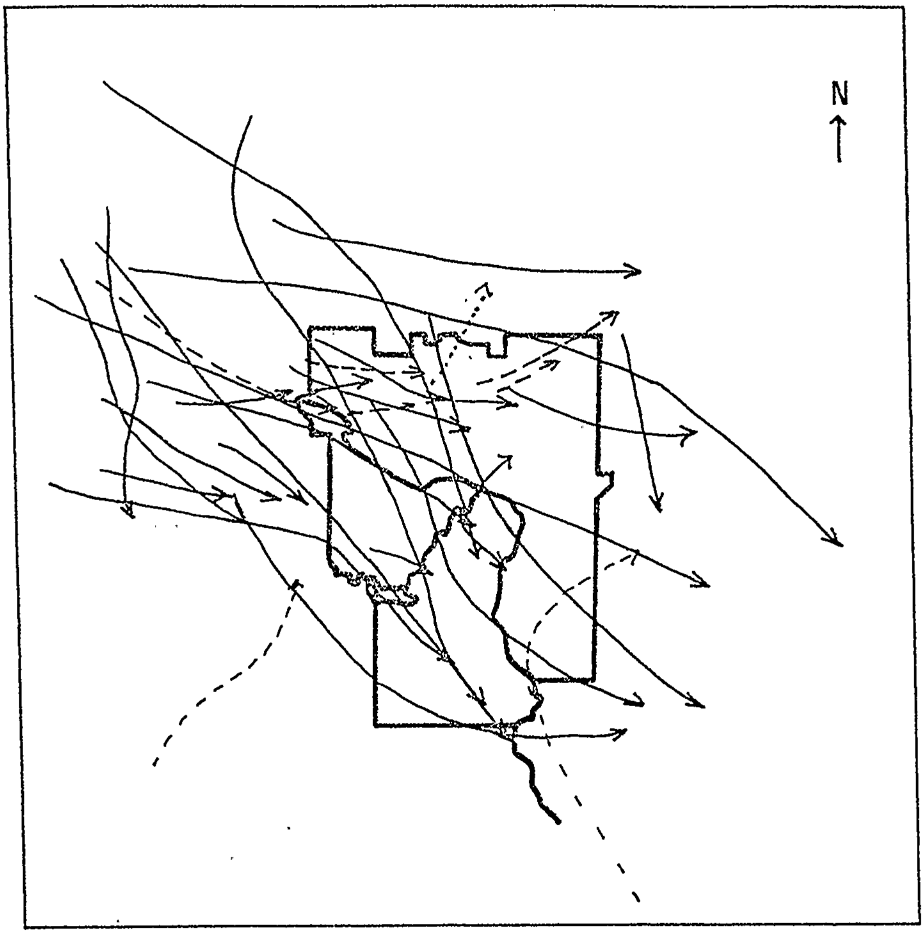
An insight into why the spatial distribution of precipitation in Calgary is as observed would be gained if the clouds themselves could be examined throughout their passage over the city. This would allow cloud paths or storm tracks to be defined.

In order to accomplish the above, radar data from the S-band system in Penhold, Alberta were obtained.

Static pictures of cloud images, taken at approximately 10 minute intervals and an antenna elevation of 0.6 allowed storm tracks to be defined for each case studied. Unfortunately, time and data restraints allowed only 11 storms to be examined in detail. Seven were convective storms, three were frontal and one was cyclonic. The storm tracks for the individual events were traced (Fig. 5.5.1). On closer examination, three general paths emerged. These have been identified for discussion purposes as tracks one, two and three (Fig. 5.5.2).

Storm cells travelling west to east through north Calgary, over the Nose Hill area, define track one. These cells enter the city at its northwest corner, traverse the Nose Hill ridge area, and procede eastward over relatively low lying land. The path branches into two just east of the International Airport, where elevation rises slightly. The cells appear to be steered due eastward by the protrusion of Nose Hill. The forking that occurs in east Calgary similarly appears to be related to topography.

Track two is much broader, extending from northwest Calgary through the city core and into the industrial southeastern zone. Cells travelling this path tend to enter Calgary at one of two locations. The Bow River valley is one entry zone, with a secondary route extending from north central Calgary southward over the eastern



LEGEND

Cyclonic ·····   Frontal – –   Localized Convective ——

FIGURE 5.5.1

STORM TRACKS OF INDIVIDUAL CELLS

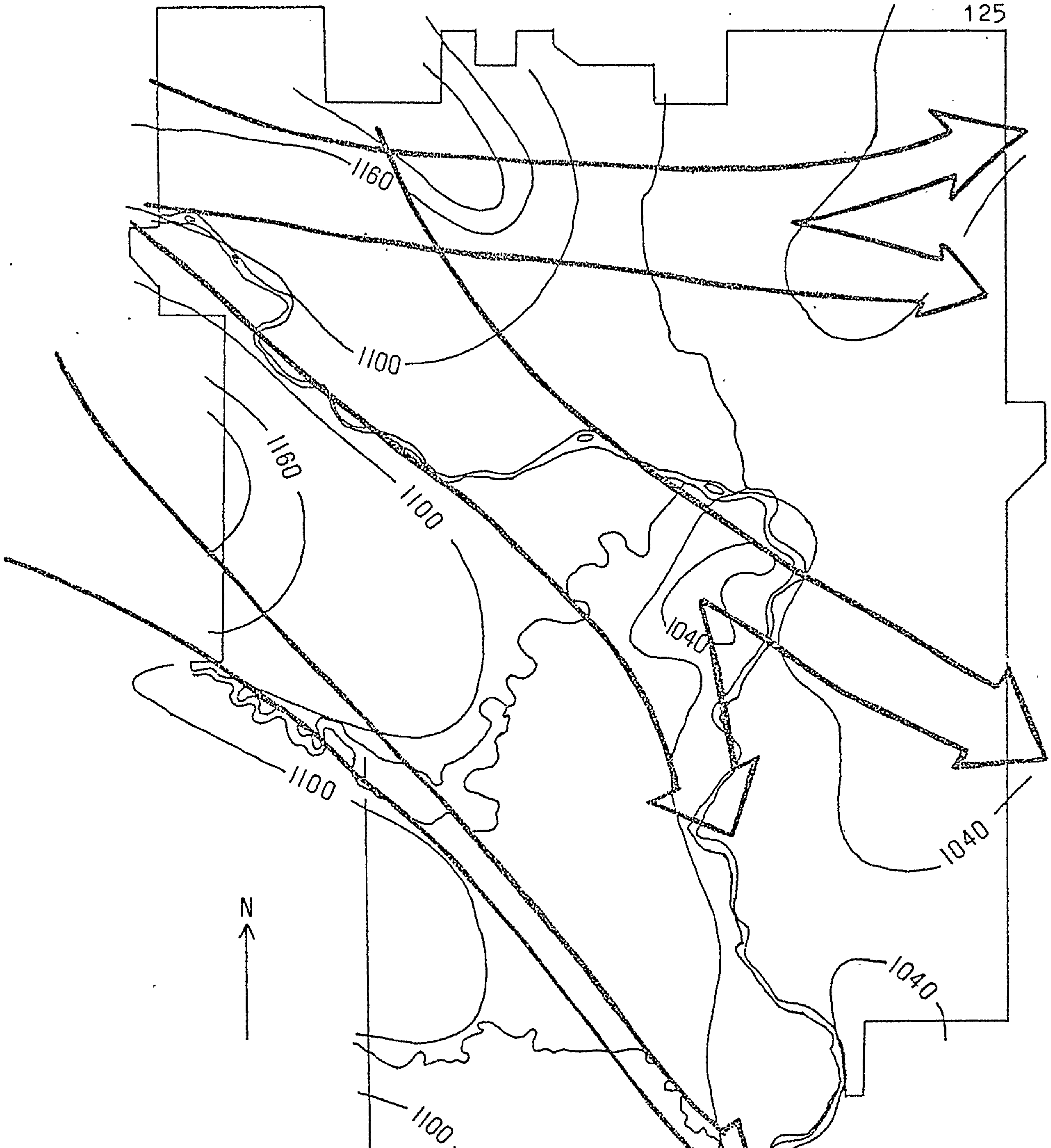


FIGURE 5.5.2

STORM TRACKS

edge of Nose Hill. From this point on, cells travel southeastward through the low areas of central Calgary. A fork in the path occurs just southeast of the junction of the Bow and Elbow Rivers, where a small increase in elevation is observed. Again, topography appears to act as a steering mechanism for cells travelling this path.

Track three is a relatively narrow path extending from just north of the Elbow River at the western city limits, southeastward over Glenmore Reservoir and into southwest Calgary. The initial 7 km of the path is defined by the Elbow River valley. Cells tend to follow the low lying area wedged between Broadcast Hill to the north and an area of moderately high elevation (1100-1150 m a.s.l.) to the south. Cells then pass over the reservoir, continue southwestward over the low lying areas of southern Calgary, and exit from the city through the Bow River valley at the southern city limits. Here, as in the case of track two, cells follow low lying areas. Topographic steering appears to be a major influence.

Thus, although elevation, as such, did not contribute significantly to the spatial pattern of precipitation in Calgary, it appears that steering effects due to topographic barriers are an important consideration when defining the areal distribution of rainfall in Calgary.

The storm tracks manifest themselves in the spatial patterns of precipitation in the following ways. The band of relatively high precipitation that covers the Nose Hill area of Calgary appears to be a reflection of track one. For convective storms, in particular, the influence of track two is apparent in the precipitation pattern. The extension of high precipitation that begins in Bowness and extends to Bonnybrook industrial zone is coincident with storm track two. The region of relatively high precipitation in southwest Calgary is partially explained by the fact that storm cells following track threc pass directly over the reservoir and continue southwestward through the city.

The rainfall minimum observed north of Glenmore Reservoir, between the Bow and Elbow River valleys, is explained by the lack of storms passing directly overhead this area. In general, radar data revealed that large, intense storm cells tended to pass on either the north or south flank of the area but not directly overhead. This appears to be due to a topographic blocking effect set up by the position of Broadcast Hill to the northwest. As storms enter the city from the northwest, they tend to follow either the Bow or Elbow River valleys, avoiding the highlands between the two valleys. As a result, a well defined negative precipitation anomaly exists downwind of Broadcast Hill,in the region just north of Glenmore Reservoir.

In conclusion, a small data base has allowed three storm tracks to be identified. Each contributes to the explanation of the spatial distribution of precipitation in Calgary. The zones of relatively high precipitation in northwest Calgary and in Bonnybrook appear to be the result of two storm tracks,which pass over the Nose Hill area and through the Bow River valley into southeast Calgary. Both tracks appear to be topographically defined. Similarly, the relatively high precipitation receipt in southwest Calgary (Woodlands area) appears to be related to a storm track found to pass southeastward over Glenmore Reservoir. The rainfall minimum north of Glenmore Reservoir appears to be the result of a topographic blocking effect set up by Broadcast Hill. Thus, the effects of valley orientation, slope angle, and exposure are observed to be important in defining storm tracks in Calgary.

5.6 The Spatial Distribution of Precipitation in Calgary under Various Wind Conditions

5.6.1 The Role of Wind Direction

The 51 storms were stratified according to wind direction in order to discover any spatial consistencies that may have existed in the precipitation patterns under given wind conditions. Eighteen storms were classified as having predominantly north or northwesterly flow, eleven as having a dominant easterly component (E, SE, or NE) and four as having south or southwesterly winds. For eighteen storms, wind direction was variable.

For those storms characterized by north or northwesterly winds, two zones of relatively high precipitation have been identified. The most pronounced of the two was in northwest Calgary (Silversprings) and a secondary one existed in the deep southwest (Woodlands) (Fig. 5.6.1). A high degree of pattern consistency existed for individual storms. An area of low precipitation receipt was observed near Station 10, just north of the reservoir.

When the August 15-17 storm was removed, the general pattern, as described above, remained. However, the low near Station 10 was extended northeastward.

It appears that the pattern was defined essentially by the location of the storm tracks identified in Section 5.4.3. All three tracks require a basic northwesterly flow.

When winds were essentially from the east, northeast or southeast, a low degree of consistency in the spatial patterns existed for individual cases. Generally, a fan-shaped region of high precipitation was observed extending from the north Bow River valley outward to

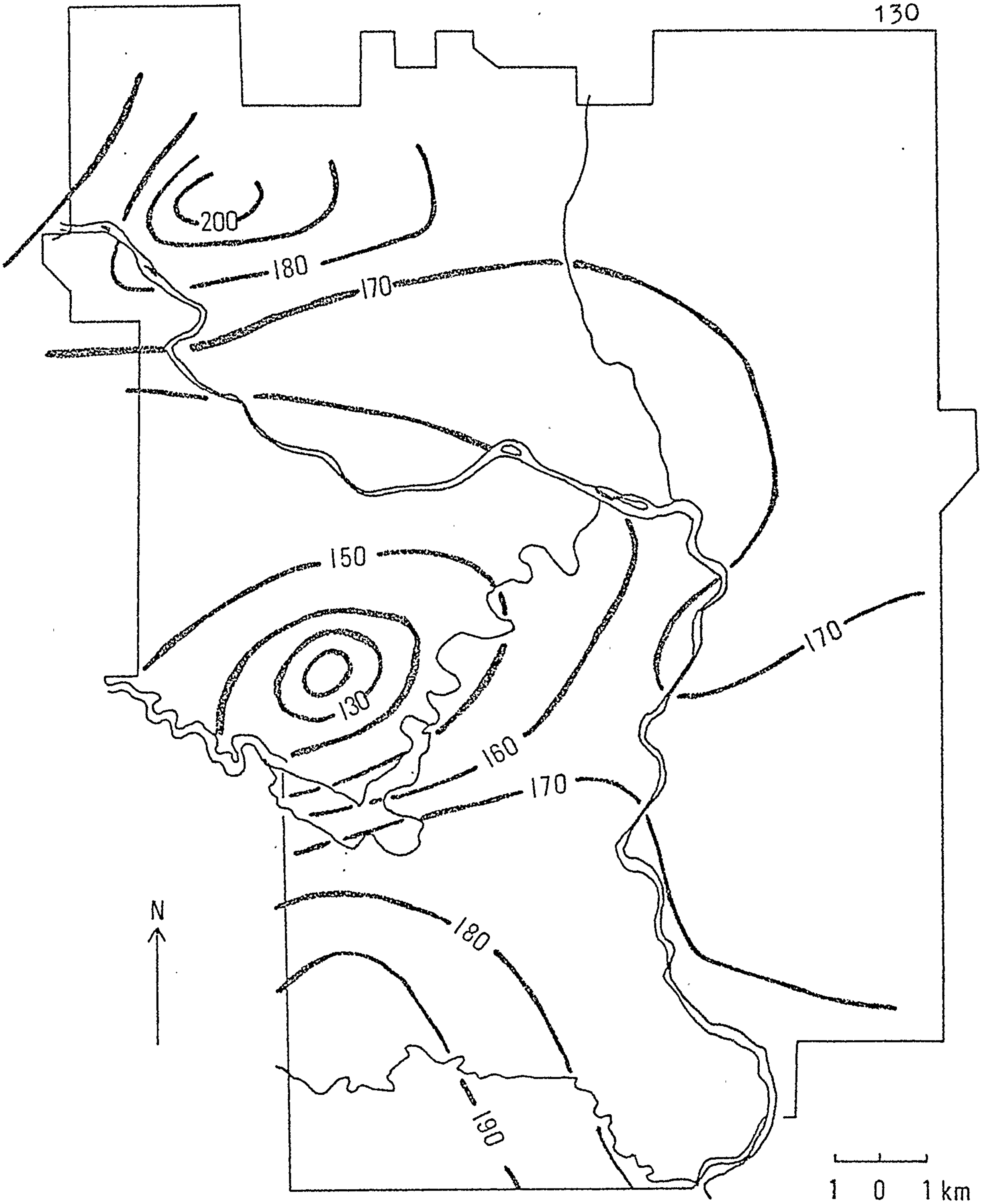


FIGURE 5.6.1

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)

NORTH AND NORTHWESTERLY WIND CONDITIONS

southeast Calgary (Fig. 5.6.2). This zone of high precipitation was restricted to the low lying areas of Calgary. Storms entering the city from the east or southeast appear to have been funnelled northwestward, through the Bow River valley corridor. This is a reverse procedure from what happened under northwesterly flow conditions.

Only four brief showers could be classified as having essentially south or southwesterly flow. This provides an inadequate base from which to draw conclusions.

The 18 storms characterized by variable wind conditions produced a variety of spatial precipitation patterns. No obvious consistencies were noted.

5.6.2 The Role of Wind Speed

Wind speed appears to have played a dual role in defining Calgary's precipitation patterns. Firstly, a significant linear relationship (at a significance level of .05) between mean wind speed and the degree of spatial variability was found to exist. Eight per cent of the variation in precipitation variability was explained by mean wind speed. The slope of the relationship was negative. Storms characterized by a high degree of spatial variability in precipitation tended to be

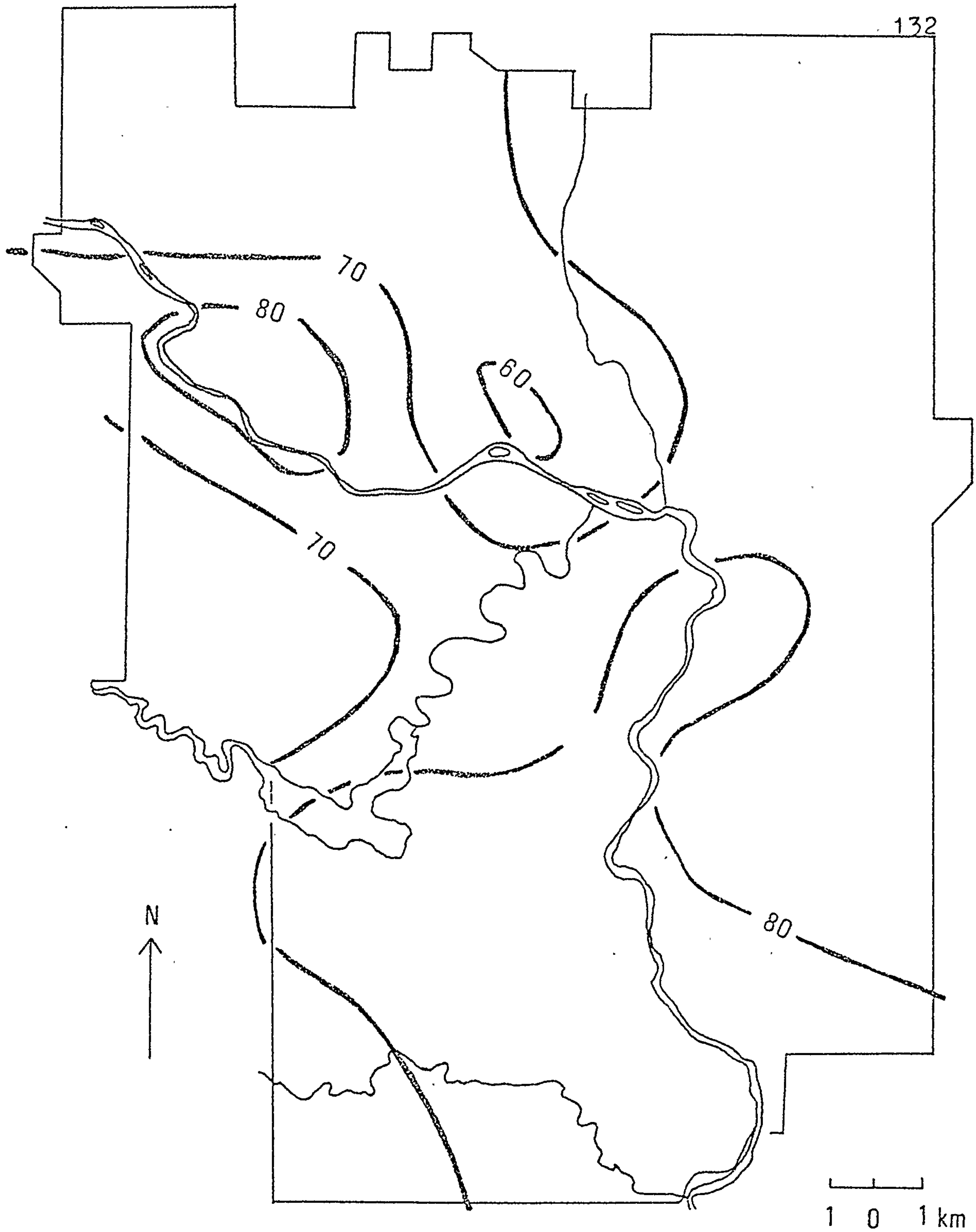


FIGURE 5.6.2
DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)
EASTERLY WIND CONDITIONS

associated with low wind speeds.

Secondly, different wind speed categories appear to be associated with different precipitation patterns. One possible reason for this finding is discussed.

If the urban structure of Calgary does actively modify the precipitation processes in a measurable way, this effect should be maximized under low wind speed conditions. It is then that Calgary's heat island is best defined (Yudcovitch,1967) and low-level air flow is most perturbed by the existence of a city (Principle Investigators of Project Metromex, 1976).

The totals for all events with a mean precipitation total of greater than 1 mm and a mean wind speed at Station 4 of less than 5 m sec^{-1} were combined and the resultant pattern examined (Fig. 5.6.3). Two zones of maximum precipitation were revealed, one in northwest Calgary (community of Bowness) and a second in the industrial zones of Bonnybrook and Ogden. A local positive temperature anomaly has been identified in the industrial zone of Ogden, both at street level and to a considerable distance above ground level (Nkemdirim, 1976). In addition, Bonnybrook-Ogden is located downwind (southeast) of Calgary's CBD, where considerable vertical development has occurred in recent years and where the heat island is extremely well defined.

When wind speeds were high (greater than 8 m sec^{-1}),

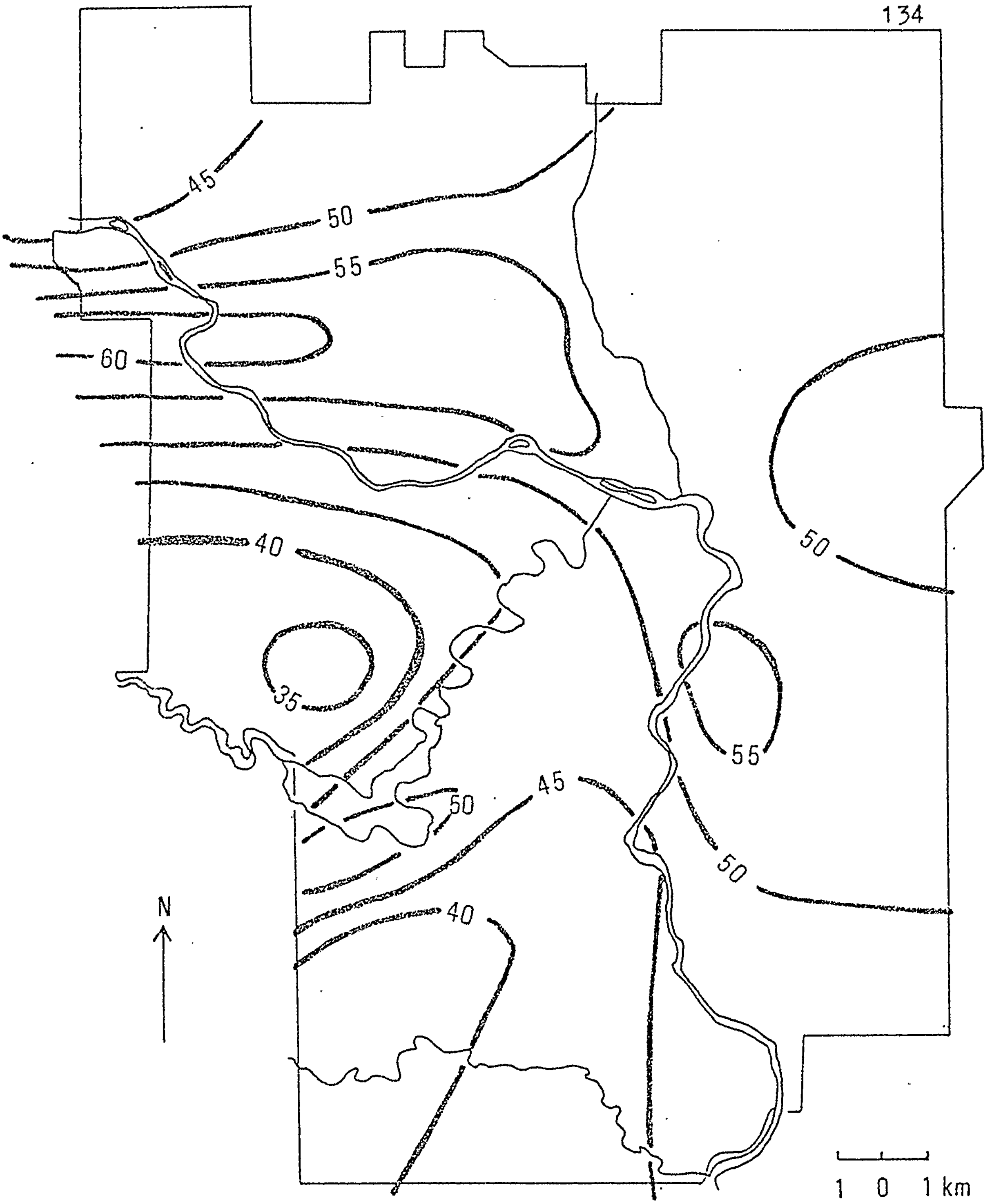


FIGURE 5.6.3

DISTRIBUTION OF PRECIPITATION IN CALGARY (mm) WHEN MEAN WIND SPEEDS WERE <5 m sec^{-1}

the zone of high precipitation receipt in the northwest remained but was displaced northeastward. The Bonnybrook-Ogden pocket was characterized by low precipitation receipt, however (Fig. 5.6.4).

This reversal from high precipitation receipt to relatively low receipt under increased wind conditions does indicate a possible urban effect under low wind speed conditions. Further discussion of possible urban effects is included in Section 5.8.

5.7 The Spatial Distribution of Precipitation in Calgary, The Effect of Glenmore Reservoir

An anomalous zone of high precipitation receipt has been identified in the southwest quadrant of the city. It is suspiciously located downwind of the only major water body in the city, the Glenmore Reservoir, which covers approximately 4 km^2.

In order to identify any possible effects that the reservoir may have had on the precipitation processes, the spatial precipitation patterns were examined in detail for areas in close proximity to the reservoir. Fourteen events were identified as being characterized by both consistency in wind direction and precipitation totals of greater than 1 mm in the vicinity of the reservoir. For 13 of the 14 cases, it was observed that precipitation

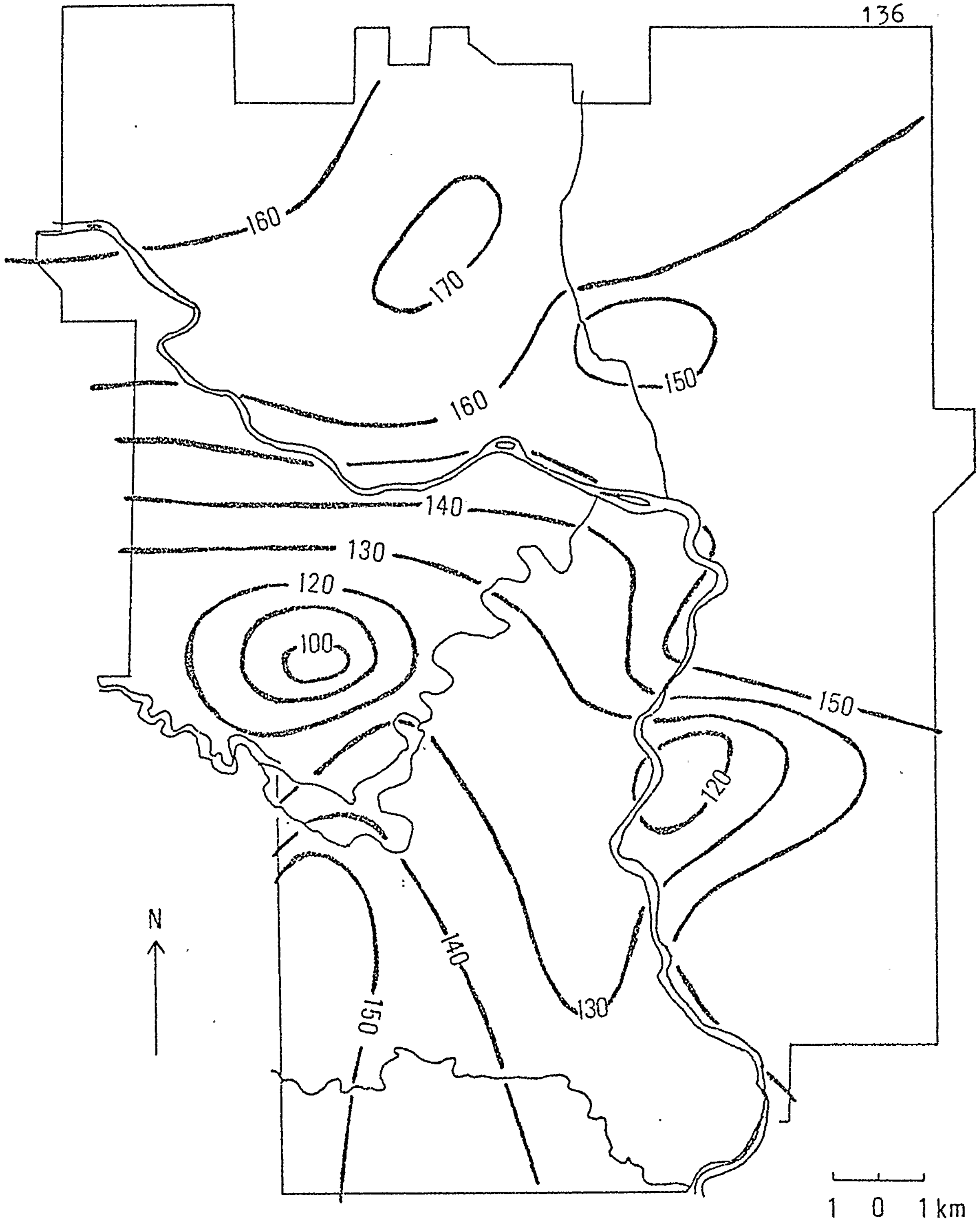


FIGURE 5.6.4
DISTRIBUTION OF PRECIPITATION IN CALGARY (mm)
WHEN MEAN WIND SPEEDS EXCEEDED 8 m sec^{-1}

increased downwind of the reservoir by 7 to 200 %.

The distance downwind at which the point of maximum increase in precipitation was observed was found to be related to mean wind speed. As wind speed increased the distance downwind at whch the maximum occurred also increased. The relationship was not significant at a .05 significance level, however.

In addition, a tendency toward increased differentials between precipitation at and downwind of the reservoir was found to be associated with increased wind speed. Once again, however, the relationship was not significant at a .05 significance level.

Since greater than 70%of all precipitation events were accompanied by a dominant north or northwesterly wind component, and since precipitation was found to increase downwind of the reservoir, the author suggests that the relatively high precipitation receipt observed in SW Calgary, formerly attributed to the passage of a storm track overhead, is enhanced by the downwind effect of the reservoir.

5.8 The Effect of the Urban Complex on the Distribution of Precipitation in Calgary

5.8.1 A Study of the Bonnybrook-Ogden Area

Scientific findings by Project Metromex and numerous others indicate that an urban complex has the potential to modify precipitation processes in and downwind of a city. In general, a positive precipitation feature can be identified, the location and intensity of which vary with the prevailing character of the summer weather (Huff and Schickedanz, 1974).

In Calgary, during the study period as a whole, the city received significantly less precipitation than did the surrounding countryside. This would appear to be in opposition to findings in other urban areas. Closer examination of the precipitation patterns in the city reveals that this is not necessarily so, however. An active precipitation modifying effect appears to exist very locally in the industrial area of Bonnybrook.

Discussions thus far have explained the parameters that appear to have accounted for the various features observed in the spatial precipitation patterns for Calgary. The zone of relatively high precipitation in northwest Calgary (extending from Bowness northward to Ranchlands and eastward to Dalhousie) was attributed to the position of two storm tracks that passed through northwest Calgary. The area of high precipitation in southwest Calgary was largely explained by a combination of storm track position and the downwind effects of the reservoir. The area of relatively low precipitation receipt north of Glenmore Reservoir is believed to exist due to a topographic blocking effect set up by Broadcast Hill to the northwest.

The local positive precipitation feature identified in industrial Bonnybrook was partially explained by the passage of a well defined storm track down the Bow River valley and into the industrial southeast of Calgary. However, no other zone along the storm track existed so distinctly as a positive feature as did Bonnybrook. Therefore, storm track position alone does not appear to explain this feature.

Further explanation may be related to the effects of urban industrial phenomena on the rainmaking process. The causes of positive precipitation anomalies in urban areas are related to:

1. destabilization of the lower atmosphere as a result of heat island formations
2. increased low-level mechanical turbulence from urban created obstructions to air flow
3. modifications of low-level moisture content

4. the addition of cloud condensation and ice nuclei from industrial atmospheric effluent releases.

In Calgary, extensive documentation of the formation of the heat island at street level and at considerable distances above ground level have been carried out (Nkemdirim, 1976; Truch, 1977; Leggat, 1978). A high thermal zone extending from downtown to the industrial park of Ogden was identified, with maximum intensities at the city centre and Ogden. The locations of peak heat emissions from man-made sources and peak heat island intensity corresponded. As a result, it is likely that destabilization of the lower atmosphere would occur in the vicinity of Bonnybrook-Ogden and the city core due to the increased low-level temperatures.

In addition, the CBD was documented as being an area of enhanced surface roughness. This is the "result of intensive land use, high rise buildings, complex street geometry, and the urban fabric of slablike surfaces" (Nkemdirim et al., 1977, p. 20). High heat emissions, maximum heat island intensity, and increased mechanical turbulence in the CBD would produce impetus for cloud development. An increase in cloud development in the CBD would be likely to create a positive precipitation anomaly downwind of the city centre. The location of the

Bonnybrook precipitation feature in question is located approximately 5 km downwind (southeast) of Calgary's CBD.

Also, Bonnybrook and Ogden's zoning classification is 'heavy industrial'. The levels of particulate pollution are high (greater than 50 tons per year) (Alberta Environment, 1973). Considerable emission of water vapour also typifies a heavy industrial zone. The combined effects of increased low-level moisture and added condensation and ice nuclei provide essential ingredients for the formation of an urban related precipitation enhancement effect.

As a result of the above mentioned facts, the positive precipitation feature, located in Bonnybrook, is believed to be related to urban industrial effects.

Examination of the weekday distribution of rainfall at Station 20 (located approximately 6 km SSE of Bonnybrook), also in industrial southeast Calgary, adds evidence for this conclusion. The weekend/weekday daily precipitation ratio at Station 20 was .344, 36 % less than at the other three tipping bucket gauge sites (Fig.5.8.1). This is consistent with findings by Braham and Dungey (1978), which show that in the greater St. Louis area, urban precipitation enhancement tended to occur mainly on weekdays.

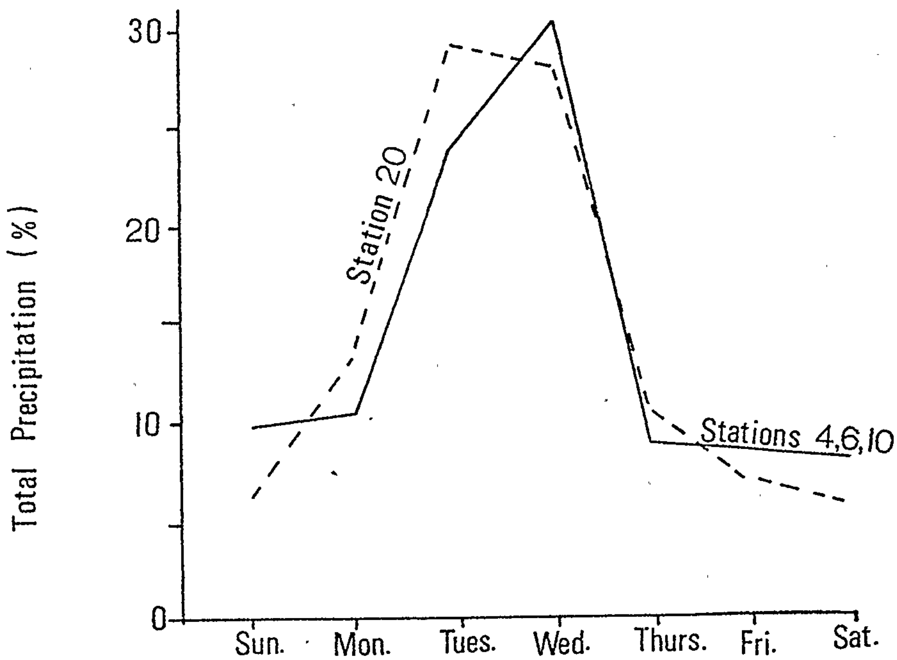


FIGURE 5.8.1

WEEKDAY DISTRIBUTION OF PRECIPITATION

STATION TWENTY VERSUS THE MEAN OF STATIONS FOUR, SIX & TEN

5.8.2 An Examination of Cloud Development Over the City of Calgary

Investigations by Metromex indicate a high incidence of echo formation and echo merging over the urban area of St. Louis, resulting in a positive precipitation feature in and downwind of the city (Changnon, 1976; Braham and Dungey, 1978). Radar images for 11 storms that occurred in Calgary were examined in order to comment on the formation, merging and dissipation of echoes in this somewhat smaller city, whose precipitation was found to be less than in the surrounding country for the study period involved.

For the 11 cases examined, it was found that most storm cells causing rainfall to occur in Calgary originated outside the city limits. Isolated cases of echo formation within the urban area were observed in the downwind core area, over Nose Hill area, and in the industrial southeast.

Only three cases of echo merging were observed. One occurred in deep southwest Calgary (Woodlands area), another in the northwest in the vicinity of the university, and a third over Broadcast Hill.

Several cells were observed to have dissipated during passage over the city. This occurred in two areas in particular, in the downtown core and the Nose Hill areas. Isolated cases of echo dissipation were also observed at various points in southern Calgary.

Since no rural control was employed, no comment on the relative frequency of the above can be made. However, the fact that more cells were observed to dissipate than to be generated, and the rarity with which echo merging occurred would seem to indicate that findings are not in keeping with those by Metromex. Further investigation is necessary.

5.9 The Spatial Distribution of Precipitation in Calgary, The Effects of Cloud Seeding

A cloud seeding program conducted by the Alberta Hail Project was operational from late June to early September, 1978. The operations centre was Penhold, Alberta. Seeding occurred within a range of approximately 130 km from Penhold. Calgary is situated within the zone of possible influence.

The cloud seeding program concentrated on shelf cloud or 'new growth' zones. Cloud top and base flares of AgI particles, producing 10^{13} nuclei per gram at -10 ^{c} were used (Deibert, 1979).

Careful evaluation of all storms that occurred in Calgary throughout the study period were carried out in order to isolate and comment on those cases where cloud seeding affected the study area. Detailed information on seeding tracks, storm trajectories, and radar echoes suggest that cloud seeding affected the spatial distribution of Calgary's precipitation during only three storms, those of June 22, July 22 and July 29. For these cases, seeding occurred either over or upwind of the city. The effect of the seeding activity was limited to parts of the June 22 and July 29 storms, and all of the July 22 event.

In general, the effect of the seeding during the above mentioned events was to cause cloud decay at and downwind of the seeding location, resulting in low precipitation receipts (Fig. 5.9.1). Since most of the seeding occurred northwest of the city, the result was that precipitation maxima occurred slightly further west than was normal (Fig. 5.9.2). When all storms were considered, however, the effect of the seeding on the spatial distribution of precipitation in Calgary was negligible.

Although seeding did occur in the Calgary region more frequently than suggested above, for all other cases the effect did not extend into the city. This was due to premature seeding, cells originating in zones unaffected by the seeds, or total dissipation of seeded clouds prior to passage over the city.

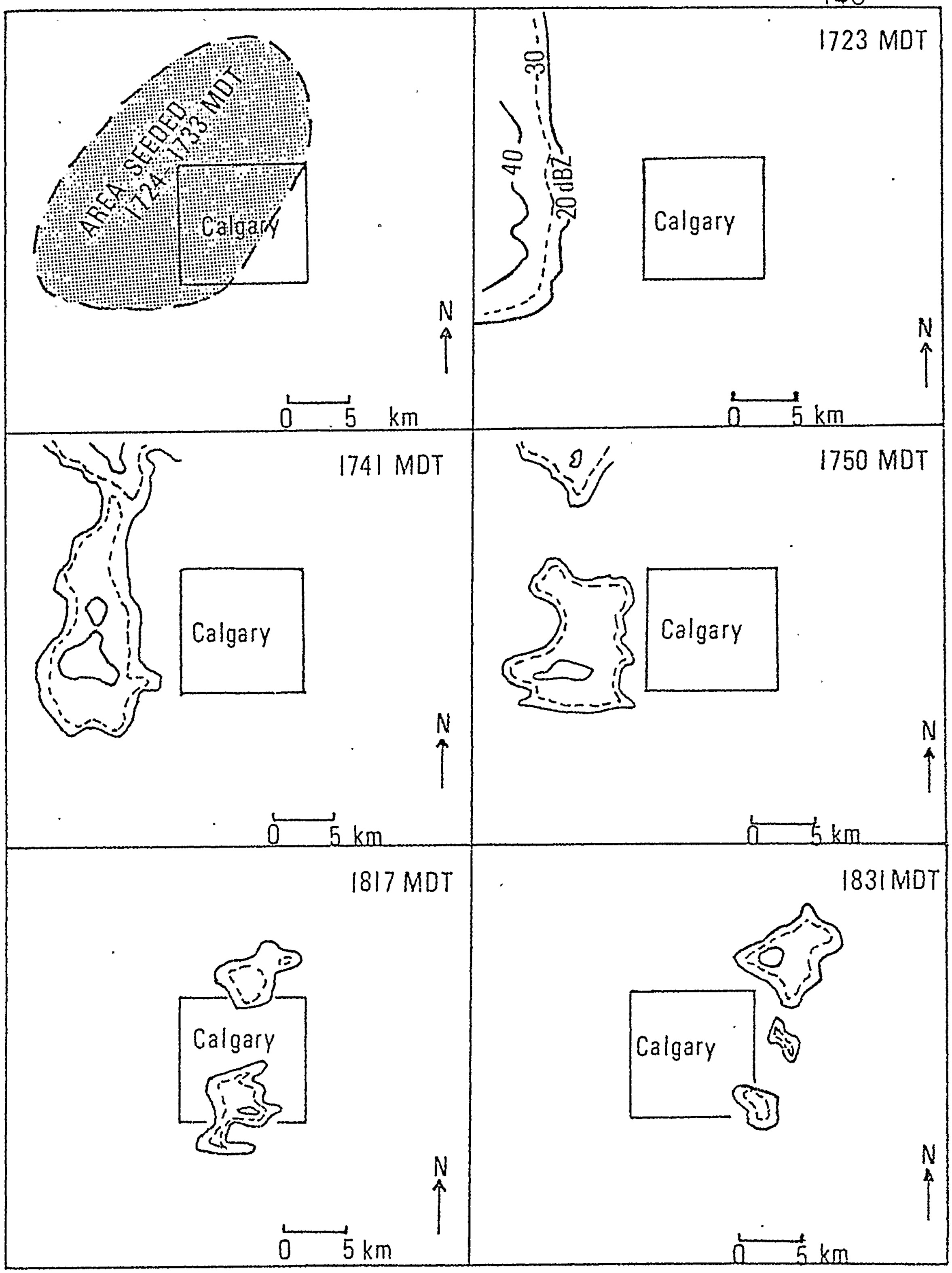


FIGURE 5.9.1.
AN EXAMPLE OF STORM DECAY WITH CLOUD SEEDING - JULY 22

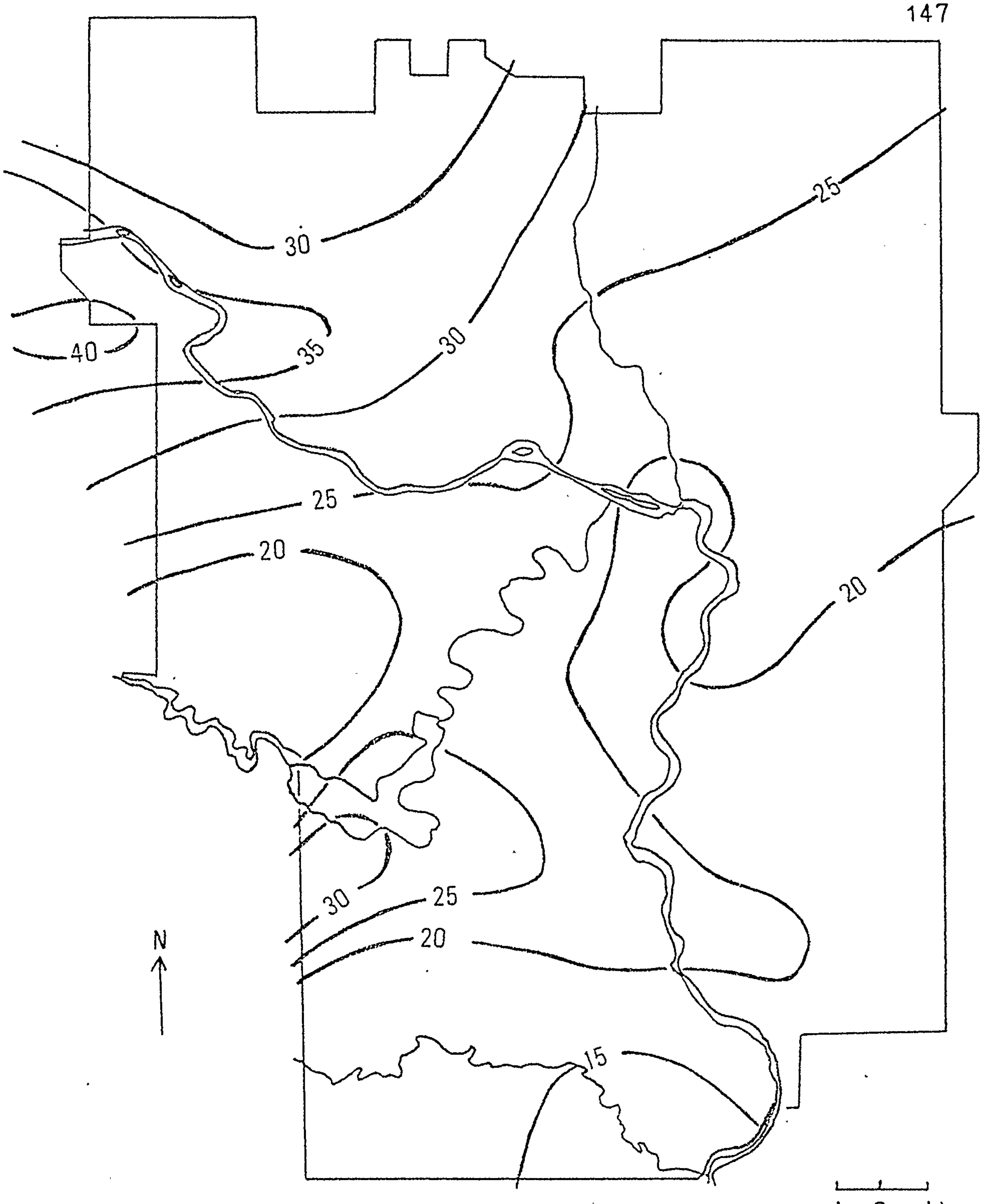


FIGURE 5.9.2

THE SPATIAL DISTRIBUTION OF PRECIPITATION IN CALGARY - SEEDED STORMS

5.10 Summary

The precipitation regime of Calgary comprises a local unique entity. The spatial distribution of rainfall within Calgary was found to be affected by synoptic conditions, topography, wind speed and direction, the position of Glenmore Reservoir, the urban structure, and during isolated cases by cloud seeding.

The most important controls appear to be related to steering and blocking effects. The Bonnybrook feature appears to be in part a function of urban industrial effects.

CHAPTER SIX : CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Conclusions

The purpose of the thesis was to document and explain the spatial distribution of precipitation within the city of Calgary, Alberta. Precipitation data from a network of twenty gauges located within the city were collected from May 16 to September 30, 1978. During this time, 51 storms occurred. Analysis of the data from these storms allows the following conclusions to be made:

For the study period involved, precipitation totals indicated that Calgary comprised a precipitation regime, which was unique from the surrounding rural areas.

For all storms combined, two areas of relatively high precipitation receipt were noted in the city:

1. A local but well defined region in deep southwest Calgary, and
2. A wide band extending from northwest Calgary to industrial Bonnybrook, with peaks over the residential area northwest of the University of Calgary and in Bonnybrook.

A negative precipitation feature was identified in west Calgary, just north of Glenmore Reservoir. The zone of highest precipitation receipt in southwest Calgary recorded

62 % more rainfall than the area north of the reservoir.

On average, the city core area was found to receive approximately 7 % less rainfall than the mean. Rainfall receipt increased rapidly to the northwest, southwest, and southeast of the CBD at rates of 1.6 % per km, 1.4 % per km, and 3.4 % per km respectively. The International Airport, situated in northeast Calgary, received 6.4 % more precipitation than the mean.

The observed precipitation features do not appear to be the result of any one synoptic condition. A relatively high degree of spatial consistency existed among different synoptic type storms. However, the degree of spatial variability did vary by storm type. Convective storms were characterized by the highest degree of spatial variation and cyclonic disturbances by the lowest. In addition, the zone of high precipitation, located in Bonnybrook, was more poorly defined for cyclonic and frontal storms than for localized convective storms. In general, both southwest and northwest Calgary were least 'wet' during convective storms.

North or northwesterly wind conditions occurred most frequently. The positive features in both northwest and southwest Calgary, as well as the negative feature near Glenmore Reservoir, were all well expressed under these wind conditions. During easterly wind conditions, less spatial consistency was observed. In general, a fan-shaped region of high precipitation was observed, extending from the north Bow River valley outward into southeast Calgary. This zone appears to be topographically defined.

In general, low wind speed conditions were associated with a higher degree of spatial variation in precipitation. Bonnybrook area was best defined as an area of high precipitation under low wind speed conditions, and existed as a negative feature under high wind speed conditions. A possible urban industrial effect exists here.

For the study period as a whole, elevation did not significantly affect the distribution of precipitation in Calgary. However, elevation did appear important under easterly wind conditions.

The affects of valley orientation, slope angle, and exposure on precipitation receipt appear to be expressed in storm track position. Three storm tracks were defined within the city. Each contributes substantially to the explanation of the spatial patterns of precipitation in Calgary. All three tracks appear to be topographically defined.

The location of Glenmore Reservoir appears important in explaining the positive precipitation feature in southwest Calgary. For 13 of 14 cases studied, precipitation was found to increase downwind of the reservoir. The position downwind at which this increase is maximized appears to be a function of wind speed.

The pocket of relatively high precipitation in Bonnybrook could not be totally explained by storm track position. A combination of urban industrial effects are maximized in this area and are believed to be partially responsible for the observed phenomenon of increased precipitation.

Cloud seeding was found to affect the spatial distribution of precipitation during only three events. In general, the effect of the seeding was to cause cloud decay, resulting in lower precipitation receipts.

The rain gauge data collected during the study period are believed to be of high quality. The main source of measurement error is believed to have been related to variable gauge exposure. The amount of spatial variation observed in Calgary's precipitation is believed to be approximately 75 % accurate after random and exposure related errors were removed.

S-band radar data were found to contribute knowledge on storm structure and movement. In order to use this radar data to give spatial estimates of precipitation at the necessary distance range, considerable adjustments to the calibration equation and further research into error sources would be required.

The study period was temporally positioned within a timeframe characterized by relative stability in precipitation receipt. No significant temporal trends in precipitation could be identified in Calgary or at any of eight rural sites studied. Hence, at this large scale, there does not appear to be a correlation between population and precipitation or between heat island intensity and precipitation.

Fifty-one storms occurred during the study period. Localized convective storms occurred most frequently, but in absolute terms, cyclonic events were responsible for the most rain. According to data from the Airport, the study period was approximately 25 % wetter than was normal.

For all storms combined, a weekday peak in precipitation occurred in midweek. A weekend minimum was observed. This was particularly evident in southeast Calgary and may be related to urban industrial effects. Late afternoon was the wettest time of day. This is believed to be the result of convective instability caused by daytime heating.

In summary, the observed temporal and spatial patterns of precipitation in Calgary are believed to be accurate. Topography appears to be the most important element in defining the spatial distribution of precipitation in Calgary. Of secondary importance are explanations afforded by wind, urban industrial effects, the location of Glenmore Reservoir, synoptic conditions and cloud seeding tracks.

These finds provide a basis for future studies to evaluate the effect of city growth on the spatial distribution of rainfall in Calgary.

6.2 Recommendations for Further Research

Additional field seasons are recommended in order that the observed patterns may be substantiated. Further storm track definition with the use of radar images is also suggested. Information of this nature would provide a more accurate picture of storm cell and precipitation distribution in Calgary and would thus provide a basis for modelling these phenomenon.

In order to accurately detect the affect of the city on the receipt of precipitation in Calgary, three measures should be taken. These include:

1. the use of rural control gauge sites in conjunction with specified urban study zones,
2. gaining additional information on the generation, development, and dissipation of clouds over various parts of the city, and
3. performing a series of precipitation studies, designed to determine the effects of city growth on the receipt of rainfall in Calgary.

SELECTED BIBLIOGRAPHY

Alberta Environment. 1973. Inventory of Air Pollution Sources and Emissions in the City of Calgary, 1971. Prepared by Western Research and Development Ltd.

______. 1976. An Application of an Urban Air Pollution Model to the City of Calgary. A summary report prepared by Western Research and Development Ltd.

Andrey, J. and V. Drakeford. 1979. A Case Study of a Multicell Storm to Determine the Contribution of Radar to a Microprecipitation study, when the Study Area is located 128 km from the Radar Site. Occasional Papers, Western Division of C.A.G.

Ashworth, J. R. 1929. The influence of smoke and hot gases from factory chimneys on rainfall. Royal Met. Soc. Quart. J., 55:341-350.

Atkinson, B.W. 1971. The Effect of an Urban Area on the Precipitation from a Moving Thunderstorm. J. Appl. Meteor., 10:47-55.

______. 1975. The mechanical Effect of an Urban Area on Convective Precipitation. Occasional Papers No. 3, Dept. of Geography, Queen Mary College, U. of London.

______. 1977. Urban Effects on Precipitation:An Investigation of London's Influence on the Severe Storm in August, 1975. Occasional Papers No.8, Dept. of Geography, Queen Mary College, U. of London.

Atmospheric Sciences Section, Illinois State Water Survey. 1974. METROMEX:An overview of Illinois State Water Survey Projects. Bull. Amer. Meteor. Soc., 55:89-90.

Auer, A. H. Jr. and R. Dirks. 1974. Contributions to an urban meteorological study: METROMEX. Bull. Amer. Meteor. Soc., 55:106-110.

Barge, B. L and R. Humphries. 1978. Precipitation Measurement by weather radar, A Review. Alberta Research Council, Atmospheric Sciences Report 78-1.

Barge, B. L., R. Humphries, S. Mah and W. Kuhnke. 1978. Weather radar rainfall measurements - Applications to operational hydrology in Alberta. Alberta Research Council, Atmospheric Sciences Report 78-2.

Borchert, J. R. 1950. The climate of the central North American grassland. Ann. Assoc. Amer. Geog., 4:1-39.

Braham, R. R. Jr. 1974. Cloud physics of urban weather modification - A preliminary report. Bull. Amer. Meteor. Soc., 55:100-106.

Braham, R. R. Jr. and M. Dungey. 1978. A study of urban effects on radar first echoes. J. Appl. Meteor., 17:644-654.

Braham, R. R. Jr. and D. Wilson. 1978. Effects of St. Louis on convective cloud heights. J. Appl. Meteor., 17:589-592.

Buishand, T. A. 1979. Urbanization and changes in precipitation - A statistical approach. J. Hydrology, 40:365-375.

Butler, S. S. 1957. Engineering Hydrology, Prentice-Hall Inc., Englewood Cliffs, N.J.

Canada. Department of Transport, Meteorological Branch. 1967. Storm rainfall in Canada, Toronto.

Canada. Department of Transport, Meteorological Branch. 1968. Climatic Normals, Sunshine, Cloud, Pressure and Thunderstorms, Downsview.

Changnon, S. A. Jr. 1968. The LaPorte weather anomaly - fact or fiction? Bull. Amer. Meteor. Soc., 49:4-11.

Changnon, S. A. Jr. 1976. Effects of urban areas and echo merging on radar echo behavior. J. Appl. Meteor., 15:561-570.

________. 1978. Urban effects on severe local storms at St. Louis. J. Appl. Meteor., 17:578-586.

________. 1979. What to do about urban-generated weather and climate changes. J. Amer. Planning Assoc., 45:36-47.

Changnon S. A. Jr., F. Huff and R. Semonin. 1971. METROMEX: an investigation of inadvertent weather modification. Bull. Amer. Meteor. Soc., 52: 958-967.

Changnon S. A. Jr., R. Semonin and F. Huff. 1976. A Hypothesis for urban rainfall anomalies. J. Appl. Meteor., 15:544-560.

City of Calgary, Public Information Department. 1977. Municipal Handbook, Calgary.

Collier, C. G. 1975. Rainfall Measurement by Radar. Proceedings, Symposium on weather radar and water management, Water Research Centre, Medmenham, England, 1975.

Craddock, J. M. and B. Wales-Smith. 1977. Monthly rainfall totals representing the East Midlands for the years 1726-1975. Meteor. Mag., 106:97-111.

Danielwicz, Z. W. 1977. Some Characteristics of Large Scale Winter Chinooks in Southern Alberta. Unpublished M. Sc. thesis, University of Calgary.

Deibert, J. 1979. Alberta Hail Project Field Program 1978. Alberta Weather Modification Board Report No. 7, Alberta Agriculture, Three Hills, Alberta.

Donley, D. E. and R. Mitchell. 1939. The relation of rainfall to elevation in the Southern Appalachian Region. Amer. Geophysical Union Trans., 20:711-721.

Duckstein, L., M. Fogel and J. Thames. 1973. Elevation effects on rainfall: A stochastic model. J. Hydrology, 18:21-35.

Environment Canada. 1975, a. Canadian Normals, Temperature, 1941-1970, Downsview.

________. 1975, b. Canadian Normals, Precipitation, 1941-1970, Downsview.

________. 1975, c. Canadian Normals, Wind, 1941-1970, Downsview.

Folliott, B. W. and J. Ramsden. 1979. Extraction of CAPPI's from Logged Radar Data - Simultaneous Precipitation Measurement. Alberta Research Council, Atmospheric Sciences Division.

Gatz, D. F. 1974. METROMEX: Air and rain chemical analyses. Bull. Amer. Meteor. Soc., 55:92-93.

Gilman, C. S. 1964. Rainfall. In Handbook of Applied Hydrology. Editor in chief - Ven Te Chow, McGraw-Hill Book Co., New York.

Harnack, R. P and H. Landsberg. 1975. Selected Cases of Convective Precipitation Caused by the Metropolitan Area of Washington, D. C. J. Appl. Meteor., 14:1050-1060.

Huff, F. A. 1975. Urban effects on the distribution of heavy convective rainfall. Water Resources Research, 11:889-896.

Huff, F. A. and S. A. Changnon Jr. 1972. Climatological assessment of urban effects on precipitation at St. Louis. J. Appl. Meteor., 11:823-842.

________. 1973. Precipitation modification by major urban areas. Bull. Amer. Meteor. Soc., 54:1220-1232.

Huff, F. A. and P. Schickedanz. 1974. METROMEX: Rainfall Analyses. Bull. Amer. Meteor. Soc., 55:90-92.

Huff, F. A. and G. Stout. 1952. Area-Depth studies for thunderstorm rainfall in Illinois. Amer. Geophysical Union Trans., 33:495-498.

Huff, F. A. and J. Vogel. 1978. Urban, Topographic, and Diurnal Effects on Rainfall in the St. Louis Region. J. Appl. Meteor., 17:565-577.

Keers, J. F. 1977. Rainfall criteria for urban drainage design. Meteor. Mag., 106:117-126.

Khemani, L. T. and B. Murty. 1973. Rainfall variations in an urban industrial region. J. Appl. Meteor., 12:187-194.

Landsberg, H. E. 1956. The Climate of Towns. In Man's Role in Changing the Face of the Earth. Edited by W. L. Thomas, Jr. et al., University of Chicago Press, Chicago, Illinois.

Larson, L. W. and E. Peck. 1974. Accuracy of Precipitation measurement for hydrologic modelling. Water Resources Research, 10:857-863.

Lawrence, E. N. 1973. High values of daily areal rainfall over England and Wales and Synoptic patterns. Meteor. Mag., 102:361-366.

Leggat, K. R. 1978. Vertical Temperature Structure of Calgary's Urban Heat Island. Unpublished M. Sc. thesis, University of Calgary.

Leung, S. K. 1977. The Alberta Hail Project Radar Systems, Alberta Research Council, Atmospheric Sciences Report 77-4, Edmonton.

Linsley, R. K. and M. Kohler. 1951. Variations in Storm Rainfall over Small Areas. Amer. Geophysical Union Trans., 32:245-250.

Longley, R. W. 1975. Precipitation in Valleys. Weather, 30:294-300.

Lowry, W. P. 1974. Project METROMEX: Its History, Status, and Future. Bull. Amer. Meteor. Soc., 55:87-88.

Lowry, W. P. and F. Probáld. 1978. An attempt to detect the effects of a steelworks on precipitation amounts in Central Hungary. J. Appl. Meteor., 17:964-975.

Lunn, G. and L. Wojtiw. 1977. Climatologically related hail research at the Alberta Hail Project. In Applications of climatology: Proceedings of the workshop and annual meeting sponsored by the Alberta Climatological Committee. Edited by J. M. Powell.

Maidens, A. L. 1965. New meteorological office rain gauges. Meteor. Mag., 94:142-144.

Maisel, T. N. 1971. Early Micrometeorological changes caused by Urbanization. Unpublished M. Sc. thesis, University of Maryland.

Marshall, J. S. 1948. The distribution of raindrops with size. J. Meteor., 5:165-166.

Nkemdirim, L. C. 1976. Dynamics of an Urban Temperature Field - A Case Study. J. Appl. Meteor., 15:818-828.

Nkemdirim, L. C. and P. Truch. 1977. Variability of temperature fields in Calgary, Canada. Atmos. Envir., Nkemdirim, L. C., P. Truch and K. Leggat. 1977. Calgary's Urban Heat Island 1975 - Surface Features. Weather Research Monograph No. 1, final report to AERT under award No. 143.

Ogden, T. L. 1969. The Effect of rainfall on a large steelworks. J. Appl. Meteor., 8:585-587.

Principal Investigators of Project METROMEX. 1976. METROMEX update. Bull. Amer. Meteor. Soc.,57:304-308.

Reid, I. 1973. The influence of slope aspect on precipitation receipt. Weather, 28:490-494.

Reynolds, G. 1965. A History of Rain gauges. Weather, 20:106-114.

________. 1971. Ground-level rain gauges in Scotland. Weather, 26:379-381.

Robinson, A. C. and J. Rodda. 1969. Rain, wind and the aerodynamic characteristics of Rain gauges. Meteor. Mag., 98:113-120.

Sanderson, M. and R. Gorski. 1978. The effect of metropolitan Detroit-Windsor on precipitation. J. Appl. Meteor., 17:423-427.

Sanderson, M., I. Kumanan, T. Tanguay and W. Schertzer. 1973. Three aspects of the urban climate of Detroit-Windsor. J. Appl. Meteor., 12:629-638.

Schermerhorn, V. P. 1967. Relations between topography and annual precipitation in Western Oregon and Washington. Water Resources Research, 3:707-711.

Schickedanz, P. T. 1974. Inadvertent Rain Modifications as Indicated by Surface Raincells. J. Appl. Meteor., 13:891-900.

Semonin, R. G. and S. A. Changnon, Jr. 1974. METROMEX: Summary of 1971-1972 Results. Bull. Amer. Meteor. 55:95-100.

Smithson, P. A. 1974. Heavy rainfall over Central Northern England. Weather, 29:17-24.

Spreen, W. C. 1947. A Determination of the effect of Topography upon precipitation. Amer. Geophysical Union Trans., 28:285-290.

Stanhill, G. 1958. Rainfall Measurements at Ground Level. Weather, 13:33-34.

Truch, P. 1977. Spatial and Temporal Variations of Calgary's Surficial Temperature Field. Unpublished M. Sc. thesis, University of Calgary.

Vasanji, Z. and I. Gartshore. 1978. An analysis of six simultaneous wind records taken near Vancouver. Atmosphere-Ocean, 16:145-156.

Vogel, J. L. and F. A. Huff. 1978. Relation between the St. Louis urban precipitation anomaly and synoptic weather factors. J. Appl. Meteor., 17:1141-1152.

Williams, P. Jr. and E. L. Peck. 1962. Terrain influences on precipitation in the Intermountain West as related to synoptic situations. J. Appl. Meteor., 1:343-347.

Wilson, W. T. 1954. Analysis of winter precipitation observations in the Cooperative Snow Investigation. Monthly Weather Review, 82:183-195.

World Meteorological Organization. 1971. Guide to Hydrometeorological Practices. 4th Edition. Geneva, Switzerland.

Yudcovitch, N. T. 1967. Some aspects of temperature conditions in Calgary. Unpublished M. Sc. thesis, University of Calgary.

Zobel, R. F. 1965. Wind strength and rainfall - Are they related? Weather, 20:13-16.

APPENDIX ONE

ABBREVIATIONS AND SYMBOLS

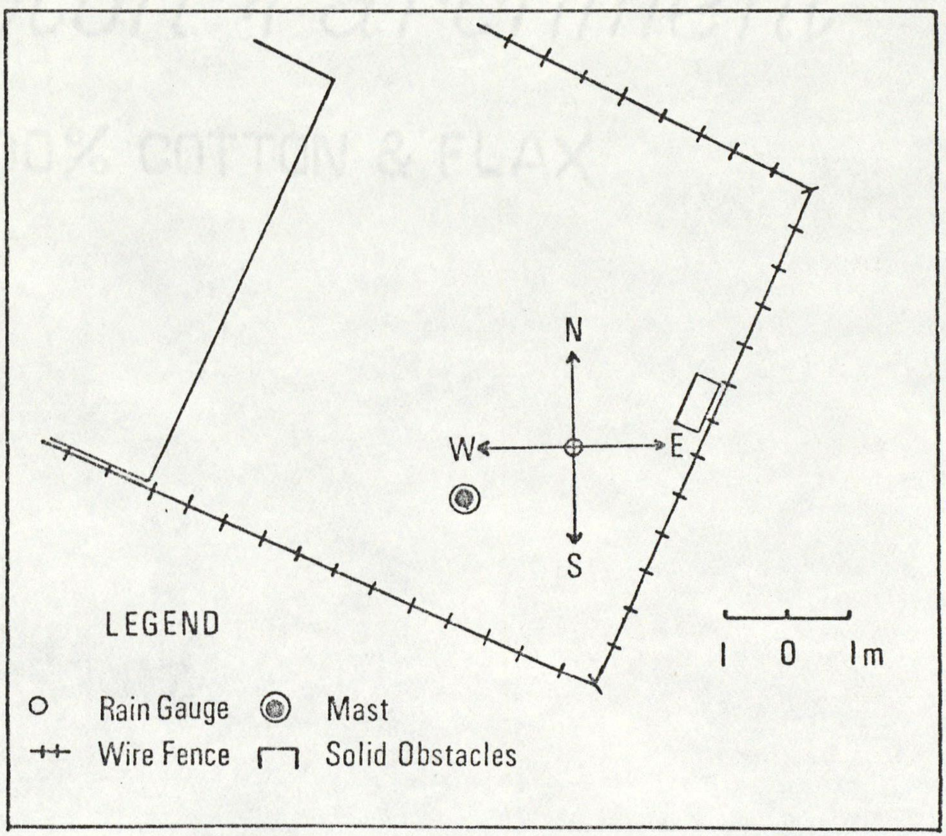
a.g.l.	above ground level
a.s.l.	above sea level
cm	centimetre
dB	decibel
GER	gauge estimated rainfall
GHz	gegahertz = 10^9 cycles per second
km	kilometre
m	metre
MDT	Mountain Daylight Time
min	minute
MJ	megajoule
mm	millimetre
RER	radar estimated rainfall
RPM	revolutions per minute
sec	second
$S.E._{\overline{X}}$	standard error of the mean
TR	trace of precipitation
Z	reflectivity
°C	degrees Celcius
$\overline{X}$	mean
μs	microsecond
σ	standard deviation

APPENDIX TWO

LOCATIONS OF RAIN GAUGES IN CITY NETWORK

Station Number	Address
1	Bearspaw Dam Control Station
2	5620 Buckboard Road
3	5144 Nesbitt Road
4	Calgary International Airport
5	Paskapoo Ski Resort
6	University of Calgary Weather Research Station
7	Fire Alarm Station, 7th Ave. and Centre St. N.E.
8	Elks Golf Course, 24 Ave. and 6 St. N.E.
9	Firehall No. 12, 123 - 44 St. S.E.
10	Mount Royal College Weather Instrument Site
11	Firehall No. 5, 3129 - 14 St. S.W
12	Firehall No. 3, 2308 - 17 St. S.E.
13	Bonnybrook Tower, Ogden Road S.E.
14	Engineered Homes, 3130 Palliser Dr.
15	Glenmore Dam Control Station
16	Canadian Western Natural Gas Control Station, 58 Ave. and Blackfoot Tr. S.E.
17	Firehall No. 9, 6805 Ogden Rd S.E.
18	2223 Anderson Rd S.W.
19	115 Parkland Place S.E.
20	C.I.L. Explosives Plant, 24 St. S.E.

SITE CHARACTERISTICS OF STATION 13



APPENDIX FOUR

THE DEGREE OF VARIATION IN PRECIPITATION TOTALS WITHIN THREE RAIN GAUGE NETWORKS

Coefficients of Variation

Date	City Network	Dense Network, Control Gauges	Dense Network, Barrier Gauges
Aug 07	87.40	25.00	43.14
11	171.79	5.52	4.43
12-13	26.17	0.58	4.78
15-17	14.82	1.67	8.91
19-20	37.69	2.42	2.41
22-23	24.49	1.60	1.85
Sep 05-08	29.10	1.17	1.85
11-13	16.58	3.18	9.10
14-16	56.11	6.05	36.29
17-18	83.75	8.41	24.94
27	43.89	4.82	2.92
$\bar{X}$	53.80	5.49	12.78

APPENDIX FIVE

STANDARD ERRORS OF THE MEAN (%)

DATE	$\bar{X}$ PRECIPITATION	$S.E._{\bar{X}}$
May 16 - Sep 30	338.26	2.12
May 16-31	69.94	6.01
June	53.44	5.21
July	55.88	4.11
August	88.08	3.05
September	70.92	3.24
<u>Convective Storms</u>		
June 11	.19	33.10
13	.15	105.40
15-16	6.80	5.63
20	.11	73.15
25-26	.55	16.95
July 2	1.07	28.00
3	.03	100.18
4	1.57	29.47
11-12	1.75	7.28
17	11.07	7.78
17-18	2.35	8.49
18-19	3.33	21.77
19	6.61	20.39
21	.28	34.28
22	2.86	22.66
28-29	2.46	19.36
29-30	14.16	8.82
Aug 7	.89	19.40

Appendix Five
cont'd

DATE		$\bar{X}$ PRECIPITATION	S.E.$_{\bar{X}}$
Aug	9	.14	56.69
	21	.07	100.02
<u>Cyclonic Storms</u>			
May	23-24	29.98	3.69
	28	.13	44.26
	30-31	23.33	8.04
June	9-10	20.62	8.11
	28	.10	24.39
	29	.38	33.04
July	9-10	1.04	15.63
	20	.43	24.48
Aug	12-13	12.07	6.07
	15-17	59.87	3.40
	19-20	4.72	8.97
	22-23	8.60	5.58
Sep	5- 8	20.09	6.58
	27	8.66	10.49
<u>Frontal Storms</u>			
May	16	16.10	6.01
	17	TR	-
June	5- 6	11.72	4.35
	18	3.74	7.92
	21	.17	46.18
	22	7.39	9.88
	23	1.34	32.10
July	1	.18	62.13
	5- 6	2.96	15.51

Appendix Five
cont'd

DATE	$\bar{X}$ PRECIPITATION	S.E.$_{\bar{X}}$
July 7- 8	3.98	6.06
Aug 1	.55	9.63
11	.56	39.52
31	.03	72.95
Sep 11-13	38.53	3.26
14-16	2.02	11.82
17-18	1.12	19.27
19	10.09	73.40

Summary - Mean S.E.$_{\bar{X}}$

All localized convective storms - 35.94
All localized convective storms having a mean precipitation total of greater than 1 mm - 16.33
All localized convective storms having a mean precipitation total of greater than 5 mm - 10.66

All cyclonic storms - 14.48
All cyclonic storms having a mean precipitation total of greater than 1 mm - 11.62
All cyclonic storms having a mean precipitation total of greater than 5 mm - 5.88

All frontal storms - 26.25
All frontal storms having a mean precipitation total of greater than 1 mm - 11.62
All frontal storms having a mean precipitation total of greater than 5 mm - 5.88

APPENDIX SIX

DATES AND TIMES(MDT) USED IN RADAR ANALYSIS

Localized Convective

Jun 15	1400 - 1500; 1645 - 1730
16	1545 - 1630
25	2211 - 2238
Jul 11	1600 - 1815
17	1745 - 2045
18	1945 - 2145
19	1330 - 1430; 1615 - 1815
22*	1715 - 1845
29*	1900 - 2230
30	1325 - 1915

Cyclonic

Jun 09	1705 - 1815
10	1530 - 1803; 1803 - 2000
Jul 10	1015 - 1135
20	1701 - 1802
Aug 12	1500 - 1615
15	1825 - 1945
16	0230 - 0815; 1145 - 1315
19	1730 - 1849
23	0620 - 0900
Sep 05	1100 - 1245
08	0930 - 1428

Frontal

Jun 18	1950 - 2045
21	1811 - 1820
22*	1511 - 1750
23	1715 - 1900
Jul 05	1945 - 2100
07	2000 - 2115
08	1014 - 1120

*indicates that cloud seeding by the Alberta Hail Project occurred in the Calgary area during the time peroid indicated.