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TIME SERIES ANALYSIS OF TWENTY YEAR HOURLY PRECIPITATION RECORD IN OSHTEMO, MICHIGAN

by

Robert James Ruhf

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
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Department of Geography

Western Michigan University
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In Loving Memory of Robbin Denise Markley
A Very Special Sister Who is Greatly Missed
(January 14, 1964 - August 23, 1998)

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Robert James Ruhf

TIME SERIES ANALYSIS OF TWENTY YEAR HOURLY PRECIPITATION RECORD IN OSHTEMO, MICHIGAN

Robert James Ruhf, M.A.

Western Michigan University, 2000

Hourly precipitation data from Oshtemo Township four miles (6.4 km) west of Kalamazoo, Michigan were examined for the period of July 18, 1979 through March 31, 2000.

Diurnal analysis of precipitation was performed on years, months, seasons, and the overall period of record. An overall maximum in the mean accumulation of precipitation was detected around 2000 LT, while a secondary maximum was detected during the morning hours. Elevated spring and fall accumulations were responsible for the evening maximum. Elevated summer and winter accumulations were responsible for the secondary morning maximum.

The pulse analysis of the time series of hourly precipitation showed that 91.5 % of the precipitation pulses lasted 5 hours or less, with 70 % lasting 1 to 2 hours. Precipitation yielding less than 1 inch (25.4 mm) accounted for 98 % of the total number of pulses. Approximately 97 % of the interludes were under 10 days long.

A storm event model was developed. The mean pulse duration was 2.44 hours. The mean interlude between pulses was 37.74 hours. The mean accumulation was 0.16 inches (4 mm). The mean rate was 0.06 inches per hour (2 mm h^{-1}).

Finally, inter-annual analysis was performed for the 19-year period of 1981 through 1999.

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CHAPTER I

INTRODUCTION

Precipitation climatology is essential for planning anthropogenic activities in both urban and rural settings. Oshtemo Township is experiencing rapid population growth accompanied by an intense urban development due to its close proximity to the city of Kalamazoo. This implies that changes are occurring on the surface cover. Farm and wooded area are being replaced by roads, residences, businesses, and parking lots which drastically disturb the local water cycle. With residential and commercial development, the permeability of the ground surface changes, infiltration of the available precipitation decreases, and the aquifer recharge area diminishes. Issues such as storm drainage control management and ground water supply become increasingly important. Accurate precipitation data for the township is therefore essential if these needs are to be adequately met. Understanding the precipitation cycles and the cycle of the rain / snow in Oshtemo will help city planners, civil and agricultural engineers, and farmers to better design and implement their activities.

Academic climatological researchers will also benefit greatly from this study. This thesis could serve as a base study for future climatic research in areas such as climate change. Researchers will be able to use the results of this study to help bring further understanding to issues such as global warming, increased urbanization, and natural climatic cycles. This thesis can also provide the means for achieving increased understanding of the influence of the Great Lakes. Oshtemo Township is located approximately 40 miles from the eastern shoreline of Lake Michigan, and therefore comes strongly under the lake's influence. Researchers could compare and contrast the results of this study with nearby regions not under the influence of the Great Lakes which could help detect many of the specific influences of the lake effect that as of yet are not fully understood.

For the past 20 years the geography department at Western Michigan University has funded the operation of a partial climatological station in Oshtemo Township near Kalamazoo, Michigan. Precipitation records from this station were processed and analyzed to provide a better understanding of the local precipitation regime and its structure. As far as can be determined from the literature review, no temporal analysis of year-round hourly precipitation is available for southwest lower Michigan. The site is located approximately 4 miles (6.4 km) west of the Kalamazoo city limit (7.5 miles west of Western Michigan University's campus). This is a valuable source of data because continuous precipitation data for the past several years in Kalamazoo is not available from official sources. A temporal precipitation analysis of recent years therefore cannot be performed for Kalamazoo using the official data. Data that were once collected at the Kalamazoo State Hospital ceased to be recorded in 1996, and an ASOS currently in operation at the Kalamazoo-Battle Creek International Airport has only been gathering data since 1998. The Oshtemo Township data therefore fills the gap produced by this problem.

This thesis aims to determine:

1. The diurnal cycle of the precipitation in Oshtemo Township.
2. The monthly, seasonal, and annual variability in the diurnal precipitation cycle.
3. A representative model to describe the structure of the precipitation amount, intensity, duration, and interlude.
4. The inter-annual variability of precipitation.

CHAPTER II

LITERATURE REVIEW

Analysis of time-series precipitation data is abundant in the literature (Belyi, 1990; Domroes, 1998; Garreaud, 1999; Onate, 1997; Rodriguez, 1999; Edgell, 1999). Researchers have used time-series analysis to detect possible trends in monthly precipitation over the Iberian Peninsula (Serrano, 1999), to study precipitation data recorded at five minute intervals (Bonacci, 1999), to estimate fecal coliform concentrations in Louisiana as a function of basin average precipitation (Barbe, 1999), to analyze extremes and increasing frequency of trace precipitation in northern Canada (Mekis, 1999), to analyze inter-annual variability of south-eastern African summer rainfall (Rocha, 1997), and to perform long-term trend analysis of daily precipitation in Switzerland (Widmann, 1997).

One notable study performed a plot analysis of hourly rainfall in central and eastern Brazilian Amazonia using a small network of autographic rain gages (Butzow, 1993; Cutrim, *et al,* 1999). This study attempted to determine whether or not storms on the coast of Brazil are similar to those in the interior with respect to timing, duration, and intensity, and whether storms of the floodplain were similar to those of the upland. Rain was measured at 1-hour intervals during the period of January 1, 1988 through December 31, 1990 at three stations, one in the coastal regime, one in the interior bottomland regime, and one in the interior upland regime. The results indicated that the storms on the coast were more showery than inland storms, and upland storms were more showery than interior lowland storms. Diurnal analysis was performed, and a rain event model was developed for each regime.

One of the most common uses of hourly precipitation is diurnal analysis. Diurnal analysis of hourly precipitation data has been a subject of intense scientific research in recent decades. Numerous researchers have analyzed diurnal variability of precipitation for many regions and individual locations since 1916, the year that the first comprehensive analysis of diurnal precipitation was performed for the entire United States using summertime data from 175 stations (Wallace, 1975). This sort of research has especially become widespread in recent decades since a 1975 study by J. M. Wallace that attempted to provide "comprehensive and consistent documentation" of diurnal variations of precipitation and thunderstorms at different levels of intensity over the United States during the summer and winter seasons (Wallace, 1975). Wallace collected data from hundreds of stations across the United States and set up intensity categories by which to analyze the data. He performed hourly and 3-hourly harmonic analysis on the data to obtain the amplitudes (the means subtracted from the daily maximums) and phases (the clock hours of maximum intensity rainfall) of both the diurnal and semidiurnal cycles. The amplitudes were normalized by dividing them by the 24-hour mean, and then multiplied by 100. The phases and normalized amplitudes were mapped in a vectorial format for the winter and summer seasons and for each category of intensity, and then were plotted in much the same manner that wind speeds are plotted. The orientation of the arrow was used to indicate the phase, and barbs on the tails of the vectors were used to indicate the normalized amplitudes. An arrow pointing from the south, for example, indicated a noon maximum. A short barb indicated a normalized amplitude of 0.05 (5%), a long barb indicated 0.10 (10%), and a triangle indicated 0.05 (50%). The results revealed a nocturnal maximum in regions east and south of the Ohio and Mississippi valleys, a morning maxima in Texas along the Gulf coast, a 6:00 A.M. LT (local time) maximum in the low plains, and a progressive transition toward a nocturnal maximum moving from west to east across the high plains. The results also showed that the greatest chance for precipitation in the lee of the Rockies was around 6:00 P.M. LT (local time). This study inspired numerous researchers to perform diurnal analysis on various regions. Climatologists have used, and even expanded upon, Wallace's method to analyze diurnal and semidiurnal variation of precipitation for the northeast United States during all four seasons (Landin, 1985), for the Canadian prairies during growing season (Chakravarti, 1993), for individual states such as Florida (Schwartz, 1979) and New Mexico (Tucker, 1993), for analysis of very heavy summertime precipitation in the eastern and central United States (Winkler, 1987), and for analysis of various categories of heavy hourly precipitation for all four seasons (Winkler, 1988).

There are many other researchers who have added to the available literature without necessarily using Wallace's method. These studies include an analysis of recent trends in diurnal variation at Valentia on the west coast of Ireland (Kiely, 1998) and an analysis of recent changes in the diurnal cycle over the United States (Dai, 1999). There has even been a diurnal analysis performed using hourly precipitation radar data (Walters, 1995).

Of special interest is a series of studies performed by Julie Winkler of Michigan State University. Winkler analyzed heavy precipitation across the United States making extensive use of Wallace's method. She analyzed very heavy summertime precipitation in the eastern and central United States (Winkler, 1987), and she analyzed various categories of heavy hourly precipitation for all four seasons across the entire United States (Winkler, 1988). A follow-up to Winkler's 1988 study attempted to clarify "…time and space dimensions of short-duration heavy precipitation by delineating, using cluster analysis, contiguous regions with similar diurnal properties and tracing the seasonal changes in the regional patterns" (Winkler, 1992). Southern Michigan was found to be in what was labeled "Region 1" during the winter months, which was characterized by nocturnal maximums and midday minimums. The entire state of Michigan was found to be in what was labeled "Region 14" and "Region 15" during the spring months, which was characterized by a broad nocturnal maximum and a late morning to midday minimum. Most of Michigan was found in what was labeled "Region 12" in the spring months, but a small part of the south-west corner of the Lower Peninsula was found in "Region 10." A broad nocturnal maximum and midday minimum were found in "Region 10," and nocturnal maximums with considerably less spatial variation were found in "Region 12." Finally, for the autumn season, most of the Lower Peninsula of Michigan was found in what was labeled "Region 10" where a nocturnal maximum was still characteristic.

CHAPTER III

THE LOCATION

Michigan is located within the Great Lakes region and is composed of two very large peninsulas. Oshtemo Township is located in the southwest portion of the southern peninsula (commonly referred to as the "Lower Peninsula") approximately 40 miles to the east of the western shoreline of Lake Michigan (Figure 1). This area receives uniformly distributed precipitation during all months of the year both because of its mid-latitude location and its close proximity to Lake Michigan.

The Köppen climate classification system places all of Michigan in a humid continental microthermal climate (Df). Cold winters, warm summers, and a fairly uniform distributed of precipitation during all months of the year are characteristic of this region. Michigan is found approximately halfway between the North Pole and the equator on the eastern half of the North American continent, and is influenced by continental polar and maritime tropical air masses, the sub-polar and sub-tropical jet streams, and numerous synoptic scale weather systems (Sousounis, 1995). Lake Michigan also has a dramatic influence on the climate of the region as it is a significantly sized body of water with a surface area of 22,300 square miles (35,680 km^2) (Hudson, 2000). It is interesting to note that Michigan has nearly 3,000 miles (4,800 km) of coastline which is more coastline than any other state in the United States except Alaska (Sousounis, 1995). The Great Lakes are five of the largest lakes in the world both in terms of volume of water and surface area (Sousounis, 1995).

Precipitation in the southwest portion of the southern peninsula is considered to be "moderate" when compared with other regions of the United States, but large

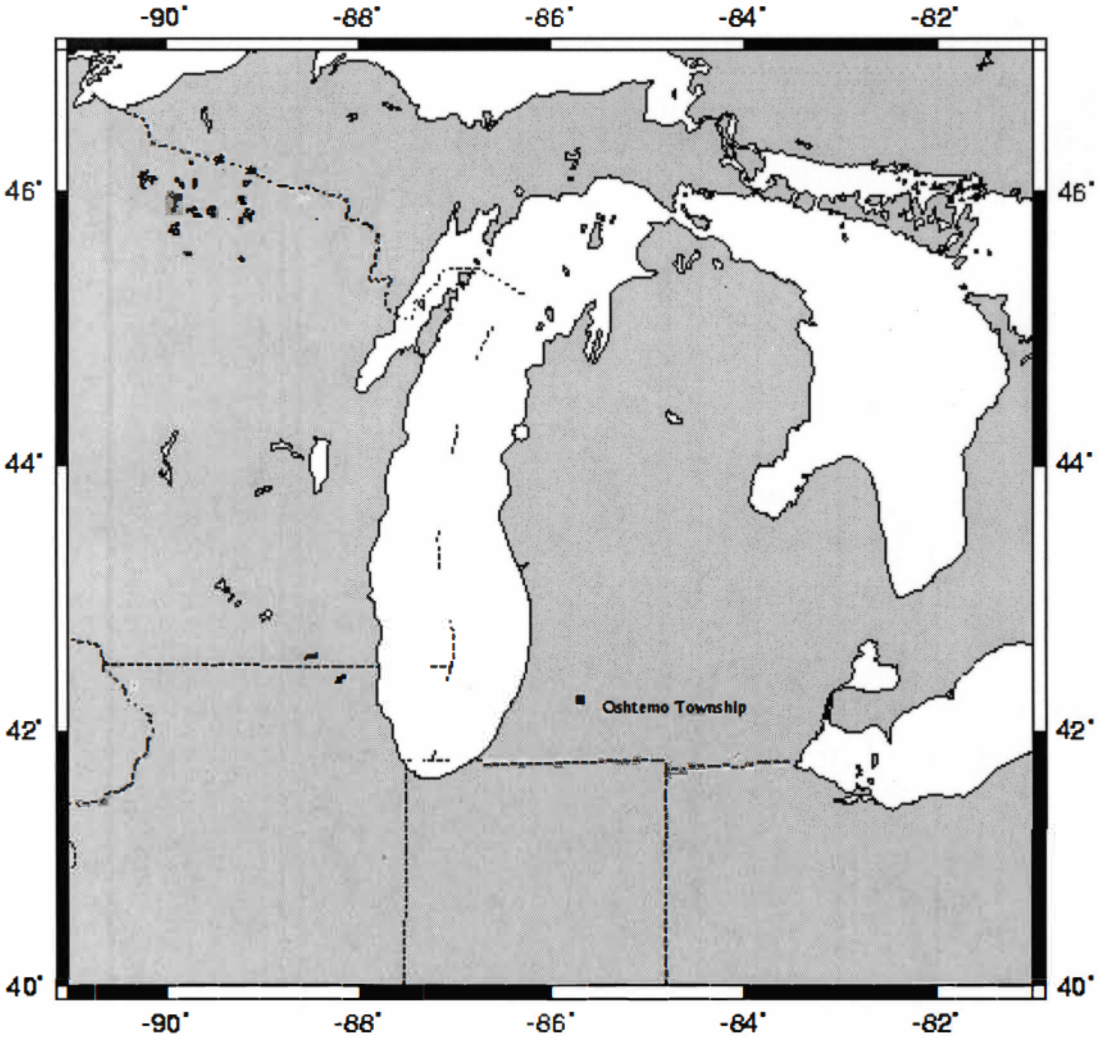

Figure 1. Site Location of Oshtemo, Michigan

when compared with other sections of Michigan (Eichenlaub, 1990). The influence of the jet stream allows for continuous synoptic scale activity at all times of the year. Winters are characterized by numerous lake-effect snowstorms resulting from rapid modifications of cold air masses moving over relatively warm lake waters (Kristovich, 2000), while summers are characterized by warm and humid conditions that allow for the common occurrence of convectional rain and thunderstorm activity

(Foltman, 1995).

The combination of all of the above mentioned factors make the western lower peninsula of Michigan an important center of commercial fruit production, a fascinating tourist area, and a significant climatic region to study.

CHAPTER IV

THE DATA

The Source of the Data

Precipitation data for Oshtemo, Michigan are available for the period of July 1979 through March 2000 in analog form. The recording precipitation gage, or pluviograph, registers the data on rectangular paper charts containing hours and dates along the x-axis and precipitation amounts along the y-axis. A 5-780 Series Universal Recording Rain Gage made by the Belfort Instrument Company of Baltimore, Maryland was used to collect the data. Most of the descriptive details of the rain gage are found in the instruction manual (Belfort Instrument Company, 1986). The gage sits 10 inches (25.4 cm) above the ground on a three-legged stand. A bucket contained in a circular horizontal opening 8 inches (20.3 cm) in diameter collects the precipitation as it falls. A mechanism sensitive to the weight of the bucket's contents, and calibrated to take the weight of the bucket into consideration, converts the weight of the precipitation into a readable paper format by means of a curvilinear and continuous pen trace on the paper chart. The chart, graduated in inches, is wrapped around a vertical cylinder that chronometrically rotates to the left. The pen trace moves up the chart as more weight is added to the bucket. If six inches (152 mm) of precipitation are recorded, the trace will reach the top of the chart and begin to move back down. Each chart contains seven days of data and is replaced every Monday. The station is installed on the property of Dr. George Vuicich, an emeritus geography professor from Western Michigan University, and is located in

Oshtemo Township four miles (6.4 km) west of the city of Kalamazoo at approximately 42° 16′ N Latitude, 85° 44′ W Longitude. The station is in a ridge at the southern edge of the Kalamazoo moraine. It sits at an elevation of approximately 965 feet (294 m) above mean sea level (United States Department of the Interior).

Images of the rain gage are found in the Appendix.

The Collection Period

The collection of data began on July 18, 1979 at 4:00 A.M. Eastern Daylight Time (EDT), and was still being gathered at the time this thesis was written. It should be pointed out that there were several periods of missing data. Except for the first two years of the series, the data set contained less than 11 % of missing recording hours per year. Less than 5 % missing hours occurred in 15 of the years. Four years had complete records. There were 983 hours of missing hours between July 18, 1979 and December 31, 1979, 478 of which were in the month of December. Instrument problems continued through the beginning of the following year resulting in nearly 3,200 hours of missing data in 1980, including the entire months of January and February, and most of the month of March. An account of missing data by year and month can be examined in Table 1.

The Potential Sources of Error

There were several sources of possible data error, the most significant of which involved the methods that were used to estimate precipitation amounts. The horizontal lines on charts indicating precipitation were 0.05 of an inch (1.3 mm) apart; however, precipitation amounts were estimated to the nearest 0.01 of an inch

Table 1

Hours of Missing Data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Percent
1979							411	39	21	34	0	478		
1980			728	82	43	39	242	0	116	0	79	410		
1981	26	0	0	90	50	223	0	21	6	6	0	95	517	5.9
1982	0	0	154	184	0	0	0	0	0	16	0	0	354	4.0
1983	451	0	0	0	0	17	0	0	0	0	0	229	697	8.0
1984	135	0	0	0	0	0	0	0	0	0	0	0	135	1.5
1985	425	11	0	0	0	0	0	0	0	0	0	447	883	10.1
1986	81	36	0	0	0	0	0	0	0	0	0	0	117	1.3
1987	0	0	54	113	0	0	0	73	0	0	65	80	385	4.4
1988	312	484	0	0	0	0	0	0	47	0	0	0	843	9.6
1989	0	0	0	0	0	0	0	0	0	0	0	101	101	1.2
1990	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1992	0	126	38	0	0	27	0	0	0	0	0	0	191	2.2
1993	0	0	0	16	0	0	0	0	34	0	0	0	50	0.6
1994	0	0	0	0	0	91	0	0	0	0	154	0	245	2.8
1995	0	0	0	161	59	18	0	0	0	0	0	0	238	2.7
1996	0	0	0	0	0	0	0	0	0	0	212	68	280	3.2
1997	0	0	0	0	0	0	0	0	0	0	33	0	33	0.4
1998	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
1999	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
2000	0	0	0											

A missing cell value indicates that data for that month either was not available or was not used in this study

(0.3 mm). There was sufficient distance between the lines to justify this estimation, but there was not enough space to eliminate the possibility of error entirely. Estimating to the nearest 0.01 of an inch (0.3 mm) was more accurate than rounding to the nearest 0.05 of an inch, and it allowed for the inclusion of numerous light precipitation occurrences (0.01-0.03 of an inch) that would be considered only a "trace" if rounded to the nearest 0.05 of an inch (1 mm).

A second potential source for error was the width of the ink trace on the charts. The typical width of the trace was approximately 0.02 of an inch (1 mm), although there were several occurrences of it being thinner as the pen ran low on ink, and much thicker immediately after the pen was refilled. This was somewhat problematic for estimating precipitation amounts because the trace was typically much thicker than the desired visual resolution of 0.01 of an inch (0.3 mm). The problem was at its worst during periods of one or two days following the pen being refilled, and there were even a couple of isolated episodes of the line being so thick that it became nearly impossible to make accurate estimations. This problem was tackled by basing the estimation on the middle of the line. For example, if the top of the line was estimated to be at 0.38 of an inch, and the bottom of the line was estimated to be at 0.32 of an inch, the amount would be recorded as 0.35 of an inch.

A third potential source of error was the collection of significant amounts of dew in the bucket on clear nights during the early morning hours. Dew was not considered to be precipitation, but it did often show up as measurable. It was sometimes difficult to know whether a small early morning reading was the result of dew or light precipitation. Two criteria were used to decide whether or not to ignore the reading as dew or to record it as precipitation. If the reading occurred on several successive mornings during periods that did not see precipitation during other times of the day (as was most often the case), then it was assumed that it was dew and it was not recorded. Secondly, if a small reading appeared on the chart during a period that was generally rainy at other times of the day, it was recorded as precipitation under the assumption that cloudy conditions would have prevented dew from forming during the morning. Using these criteria was not a guarantee, however, that dew did not form. Clear conditions could still have existed during the early mornings of days that had precipitation at another point in the day, and light precipitation could have occurred during what was an otherwise dry period. It is therefore likely that some occurrences of dew were recorded as precipitation, and that some occurrences of precipitation were misinterpreted as dew. However, the criteria helped, for the most part, to accurately discern between dew and true precipitation.

A fourth source of potential error was interference from a wooded area in very close proximity to the rain gage. The gage itself was positioned in a small clearing, but was in very close proximity to two thick lines of trees running along the north-east, north, and north-west sides of the gage with the minimum distance between the first line of trees and the gage being 11 feet (3.4 m) north-west of the gage. Numerous Colorado Spruce made up this first line of trees and were an average of 17 feet (5.2 m) tall. These trees were small at the time the data began in 1979, but grew to heights that could potentially interfere with the accurate collection of data. Of even greater concern is a line of oak trees behind the Colorado Spruce in the northwest and north directions. These trees, at minimum distance, were approximately 40 feet (12.2 m) away from the rain gage along the north edge, and were approximately 35 feet (10.7 m) tall. It is likely, especially on days when a strong north to northwest wind was observed, that a significant amount of precipitation was being intercepted by the trees before it could be collected by the bucket, and was lost either by dripping to the ground after the canopy storage capacity was reached, or was lost by flowing down the side of the tree to the ground as stem flow (Geiger, 1995). The influence of the trees may also have added to the precipitation amounts due to water drops being blown from the trees to the bucket that would not have otherwise been intercepted by the bucket. It therefore becomes rather difficult to know exactly how much actual precipitation reached the bucket. These problems can also interfere in snowfall during the wintertime.

No changes in the diameter of the opening were ever made to increase the area of catchment for the collection of snow during the winter season.

Data Processing

Converting to Digital Form

The period of record used in this study, from July 18, 1979 through March 31, 2000, yielded over 1,000 rectangular paper charts containing data for this time span. The task of converting these charts into digital data was not an easy undertaking, as it was often an incredibly tedious process that took well over 100 hours over the course of four months. The trace on each chart had to be closely examined, and then precipitation amounts had to be estimated based on considerations that have already been described in the previous section of this chapter. The estimated values for every hour of every day were individually typed into a Microsoft Excel spreadsheet. The data were listed in local time (LT). What made the task slightly easier was that the majority of hours did not have precipitation. A spreadsheet containing all zeros was therefore initially created, and the appropriate precipitation values were substituted for only those hours that had a precipitation amount of at least 0.01 of an inch. "Trace" precipitation of less than 0.01 of an inch were eliminated entirely from this study due to an inability to detect them on the paper charts. Periods that experienced near drought conditions took very little time to complete, while periods with excessive precipitation hours took a considerable amount of time. Each Excel file contained only one month of data. The calendar dates (*e.g.*, Jan-1-80) were listed in the first column of each file, and the Julian dates (*e.g.*, 1980001) were listed in the second column of each file. Each hour of the day (1, 2, 3, ..., 23, 24) was listed successively in the fifth row of each spreadsheet beginning in the third column and ending in the twenty-sixth column. Basic Excel formulas were used in the last column of each file to sum the precipitation totals for each day, and in the last row to sum the precipitation totals for each hour. This also included a formula in the far left bottom cell that summed the total precipitation for the entire month. Column widths were specified as "9" digits for the column containing the calendar dates, "10" digits for the column containing the Julian dates, and "8" digits for all remaining columns. This was done in order to meet the spacing requirements of the program that would later be used to analyze this data.

Entering the values as local time (LT) data meant that Daylight Savings Time had to be taken into consideration. An additional hour had to be added to the last Sunday of every October when the clock was turned back one hour. The row containing the hours of the day therefore had to read "1, 1, 2, ..., 23, 24" for all such Sundays. All of these "fall back" days were recorded as missing in the October data files, and were placed in a separate Excel file. Additionally, an hour had to be subtracted from the Sunday of every April when the clock was turned ahead one hour. The row containing the hours of the day therefore had to read "1, 3, 4, ..., 23, 24" for all such Sundays. This occurred on the last Sunday in April from 1979 through 1986, and on the first Sunday in April after 1986 (United States Army Meteorological Branch, 1999). All of these "spring ahead" days were reported as missing in the April data files, and were placed in a separate Excel file. Although the files for "spring ahead" and "fall back" days were created in the database, they were excluded from the overall analysis.

After the paper charts were transformed into useable digital data files, the digital data files had to be saved as text files before any analysis began. This was done by saving each of the 249 (July 1979 through March 2000) Microsoft Excel spreadsheets as a "Formatted Text (Space Delimited)" file with a *.prn extension.

Comparison to a Nearby Station

A series of quality control checks were performed on the data throughout the course of this study. The first of these checks involved an attempt to compare the data to nearby stations to check for similarities. There was some concern that the data may not have been valid because of the potential sources of errors that were described earlier in this paper. In order to check the reliability of the data, precipitation data taken at the Kalamazoo State Hospital (KSH) were acquired from the National Climatic Data Center (NCDC). KSH was located at 42° 17′ N Latitude, 85° 36′ W Longitude at an elevation of 945 feet (288 m). Data from Kalamazoo-Battle Creek International Airport initiated in 1998 were not compared with the Oshtemo data due to the short period of record. No other data were available for Kalamazoo.

The KSH data were sporadic and questionable after 1988. In spite of this, enough data were available to make a general comparison (Table 2). KSH frequently had higher rainfall amounts, but this may be due in part do the fact that the data used in this study (hereafter referred to as Oshtemo Township data) contained numerous

Table 2

Comparison of Precipitation Data With Kalamazoo State Hospital

Station A: 2258 S 4th St
Latitude: 42 16 N
Longitude: 85 44 W
Altitude: 965 ft (294 m)

Station B: Kalamazoo State Hospital
Latitude: 42 17 N
Longitude: 85 36 W
Altitude: 945 ft (288 m)

Year	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
1980	*	1.52	*	1.28	0.05	2.43	1.91	3.14	2.04	2.1	5.59	5.88	2.47	6.45	4.74	5.34	2.76	3.18	1.44	3.58	0.81	1.18	2.89	2.78
1981	0.81	0.91	1.19	1.09	1.01	1.01	3.58	5.17	1.76	3.78	2.57	3.63	1.33	1.93	4.1	4.25	5.15	5.5	2.3	2.6	2.03	2.07	1.27	1.21
1982	3.82	4.63	0.86	0.9	1.52	*	1.35	1.16	4.45	4.32	3.07	3.59	8.14	7.95	1.01	2.57	1.65	1.29	1.04	0.87	4.95	3.65	5.73	4.48
1983	0.08	0.98	1.5	1.03	3.86	3.31	3.7	3.69	4.66	5.64	1.4	2.05	1.54	3.3	4	3.3	6.56	7.75	1.61	1.92	3.5	3.74	2.5	3.73
1984	0.86	1.15	1.51	1.15	3.5	3.79	3.25	3.67	5.01	5.74	0.57	0.69	2.79	2.39	1.98	1.51	6.08	4.67	4.33	3.46	2.68	3.37	4.49	3.64
1985	1.5	4.13	4.15	3.8	3.56	3.42	2.92	4.03	3.69	2.52	2.23	2.12	3.65	4.11	3.26	3.77	2.78	3.23	4.94	4.71	6.54	*	1.06	2.01
1986	0.53	0.75	3.03	3.21	1.61	1.08	2.41	2.63	2.81	3.19	5.8	5.74	6.17	5.65	3.53	3.29	8.97	10.59	3.32	4.34	2.34	2.29	1.35	1.77
1987	1.71	*	0.49	0.05	1.54	1.83	1.84	3.39	1.92	2.63	2.22	1.9	3.15	4.7	4.69	7.63	4.15	4.02	2.56	3.14	1.9	0.57	3.19	3.5
1988	1.47	*	0.28	1.66	1.58	2.21	2.07	2.89	0.33	1.03	0.82	1.52	0.91	5.39	4.01	3.43	5.95	6.8	5.06	3.58	5.27	*	2.14	*
1989	0.99	*	0.72	*	2.6	*	1.03	*	5.52	*	1.84	*	1.95	*	2.35	*	4.46	*	1.1	*	2.97	*	0.8	*
1990	1.66	*	4.2	*	2.08	2.21	2.21	3.21	4.18	4.79	3.66	3.68	3.14	2.76	3.42	3.41	2.85	1.8	6.62	7.03	6.16	6.45	2.85	2.61
1991	1.16	*	0.32	0.3	3.86	*	4.66	5.09	2.4	*	1.28	1.88	3.1	4.41	5.04	4.72	1.43	1.9	6.39	*	4.57	*	2.54	1.41
1992	1.32	*	0.85	*	2.25	*	2.44	*	1.16	*	1.67	*	5.73	*	1.65	*	5.95	*	2.36	*	4.5	*	3.17	*
1993	3.64	*	1.69	*	3.01	*	3.73	*	2.08	*	6.57	*	6.29	*	4.48	*	4.16	*	4.35	*	1.61	*	1.71	*
1994	2.7	1.87	1.75	*	1.01	0.14	2.53	2.35	0.69	0.58	2.37	4.47	3.85	4.46	6.84	6.58	2.27	2.07	2.49	1.21	3.54	4.78	2.43	*
1995	3.22	1.75	1.02	0.58	1.91	0.51	4.04	0.77	3.46	*	4.02	*	4	*	1.89	*	1.8	*	2.93	2.66	4.14	2.56	1.26	*
1996	1.64	*	1.41	*	1.18	*	3.91	*	3.56	*	4.63	*	1.67	*	1.97	*	3.62	*	3.35	*	1.94	*	3.21	*
1997	4.24	*	4.7	*	3.8	*	2.04	*	3.49	*	6.45	*	0.99	*	4.2	*	5.26	*	1.71	*	1.53	*	2.12	*
1998	4.09	*	1.78	*	4.03	*	3.87	*	1.43	*	3.65	*	3.89	*	3.48	*	1.68	*	2.92	*	2.29	*	1.56	*
1999	2.8	*	2.01	*	1.47	*	5.63	*	1.23	*	2.96	*	5.16	*	2.8	*	1.08	*	1.06	*	1.08	*	3.53	*

missing hours, especially during the early years (Table 1). Generally speaking, however, precipitation amounts observed at KSH were similar to those observed at Oshtemo Township. There are notable exceptions, such as July 1988 when KSH reported 5.65 inches while Oshtemo Township reported only 0.91 of an inch.

CHAPTER V

PRECIPITATION TIME SERIES

Diurnal Analysis

All BASIC programs used in this study were written by Brian Goodman from the University of Wisconsin and were modified by William A. Sauck and Elen M. Cutrim.

The first BASIC program, called the Hourly Surface Rain Data Program ("Raindiuc.exe"), summarized the diurnal cycle for each year, month, series of months, season, and all years combined for the entire period of record. It transformed the *.prn files into a data string of hourly data.

Yearly Analysis

Processing with Raindiuc began by prompting for the name of the location (i.e. Kalamazoo), the longitude and latitude coordinates and elevation of the station, the local time offset from UTC, the units of the precipitation values (whether millimeters or inches), and the number of header lines in the *.prn file. It next required the names of all the *.prn files to be processed. If data for the year 1999 were analyzed, for example, "JAN,1999" (case sensitive) was entered following the prompt "Enter First Month, Year to be Processed," and "DEC,1999" (case sensitive) was entered following the prompt "Enter Last Month, Year To Be Processed." The names of the *.prn files were entered one at a time beginning with the January 1999 file following the prompt "Enter Name of Input Data File #1," and ending with the

December 1999 file following the prompt “Enter Name of Input Data File #12.” A name for the output file (with a *.diu extension) was entered following the prompt “Enter Path and Name of Output Data File,” and the twelve *.prn files were summarized in one output file.

An “HOUR” column in the output file listed all hours of the day in the format of the 24-hour clock. A “COUNT” column summarized the total number of wet hours for all hours. A “SUM” column presented the total accumulation of precipitation for all hours. An “AVG” column listed the precipitation rates for all hours by dividing the “SUM” by the “COUNT.” An “STD” column listed the calculated standard deviations for all hours. The final row in the output file (named “ALL”) summarized the year by presenting the total count of all wet hours, a sum of all precipitation accumulations, the mean hourly precipitation, and the standard deviation from the mean. These output *.diu files were converted into Microsoft Excel files in order to easily perform statistical analysis and produce graphs highlighting the specifics of the diurnal cycle.

Monthly Analysis

A slight variation of the above method was used to analyze individual months. If, for example, only the month of January 1999 was analyzed, “JAN,1999” (case sensitive) was entered both following the prompt “Enter First Month, Year to be Processed” and following the prompt ”Enter Last Month, Year to be Processed.” The name of the *.prn file for January 1999 was entered following the prompt “Enter Name of Input Data File #1.” The names of no other input data files were required. As before, a name for the output file (with a *.diu extension) was entered following the prompt “Enter Path and Name of Output Data File,” and the one *.prn file was summarized in an output file having the same format as described for the yearly summary files. The monthly *.diu files were converted into Microsoft Excel files which were later used to analyze the series for each of the twelve months.

In order to insure accuracy in the data, a quality control check was performed on the monthly diurnal files. Twenty-four months for which to perform this check were randomly selected. The diurnal files for each of these months were closely examined by comparing each hour with what was found in the Excel file of the same month. For example, the June 1984 diurnal file indicated that there were two hours of precipitation during the second hour that totaled 0.57 of an inch (13 mm). The original Excel file for June 1984 was examined and the number of hours of precipitation at 0200 LT were counted to make sure that the number lined up with the diurnal file. There were indeed two hours of precipitation that added up to 0.57 of an inch (13 mm). This was done for almost every hour in every month selected. No errors or anomalies whatsoever were found. This confirmed that the program was working properly and was producing legitimate results.

Monthly Series Analysis

A different method was used to summarize each series of months. It was not possible to use the Raindiuc.exe program to analyze all files of a given month because they are not successive in time. In order to summarize the diurnal cycle for a series of a particular month, it was necessary to place all the diurnal files for that month into the same Excel file. If the diurnal cycle for all of the April months was summarized, for example, all the April diurnal files were pasted side by side into a Microsoft Excel spreadsheet. The “HOUR” column for 1980 was placed in Column A, the “COUNT” column for 1980 was placed in Column B, the “SUM” column for

1980 was placed in Column C, the "AVG" column for 1980 was placed in Column D, and the "STD" column for 1980 was placed in Column E. The columns for 1981 were placed in the same order in Columns F through J, the columns for 1982 were placed in the same order in Columns K through O, and so on through the columns for April 1999 which were placed in columns CR through CV. Excel formulas were used in each of the 24 rows in columns CX through CZ to generate a summary of the diurnal cycle for all the months of the series. A formula was used in the CX column to add up all the values in the "COUNT" columns; a second formula was used in the CY column to add up all the values in the "SUM" columns; and a third formula was used in the CZ column to calculate the mean rates for each hour. A row labeled "ALL" was included at the bottom of each column to calculate the total "COUNT," the total "SUM," and the mean rate for all hours in the series. The final results for April, for example, showed 928 hours of precipitation, 59.12 inches (1,502 mm) of total precipitation, and a mean precipitation rate (accumulation per number of wet hours) of 0.064 inches (2 mm) per hour.

The number of wet hours ("COUNT") for each series was divided by the number of years in that series. For example, there were 20 January months from 1981 through 2000. The total "COUNT" in every row (hours 1 through 24) was therefore divided by 24. Line graphs showing all 24 hours on the x-axis and the mean count on the y-axis were created for each year. The same procedure was performed for the total accumulation of precipitation ("SUM"). Graphs were also made showing the mean rates per hour ("AVG") for each series.

Seasonal Analysis

It was necessary to define the extent of each season before beginning this part of the analysis. The months of December, January, and February were considered to be the winter months. The months of March, April, and May were considered to be the spring months. The months of June, July, and August were considered to be the summer months. The months of September, October, and November were considered to be the autumn months.

It was not possible to use the Raindiuc.exe program to analyze all files of a given season because they are not successive in time. Therefore, a similar method as described for the monthly series analysis was employed for the seasonal analysis. In order to summarize the diurnal cycle for a given season, it was necessary to place all the monthly series analysis results for that season into the same Excel file. If the diurnal cycle for winter was analyzed, for example, the December, January, and February diurnal files were pasted side by side into a Microsoft Excel spreadsheet. Excel formulas were used in each of the 24 rows in columns W through Y to generate a summary of the diurnal cycle for all the months of the season. A formula was used in the W column to add all the values in the "COUNT" columns; a second formula was used in the X column to add all the values in the "SUM" columns; and a third formula was used in the Y column to calculate the mean rates for each hour. A row labeled "ALL" was included at the bottom of each column to calculate the total count, the total sum, and the mean rate for all hours in the season.

The number of precipitation hours ("COUNT") for each season was divided by the total number of years. For example, there were 20 full winter seasons during the period of analysis. (The winter of 1979-80 was excluded because January and February were missing.) The total seasonal "COUNT" in every row (hours 1 through

24) was therefore divided by 20. This procedure was also done for 20 spring seasons, 20 summer seasons, and 21 autumn seasons. Line graphs showing all 24 hours on the x-axis and the mean count on the y-axis were created for each season. The same procedure was performed for the total accumulation of precipitation ("SUM") for each season. Graphs were also made showing the mean rates ("AVG") for each season.

Total Analysis

In order to examine the diurnal cycle for the entire period, a method similar to the one summarizing each series of months was used. All of the diurnal files for the years 1981 through 1999 were pasted side by side into a Microsoft Excel spreadsheet, and formulas were used to calculate the "COUNT," "SUM," and precipitation rates for the entire 19-year period. The years 1979, 1980 and 2000 were excluded because all months were not available for those years. The final results showed that there were 10,159 hours of precipitation and 664.79 inches (16,886 mm) of precipitation during the 19-year period. The mean precipitation rate for all hours was 0.065 inches (2 mm) per hour.

The precipitation "COUNT" for each hour was divided by 19, the total number of years from January 1981 to December 1999. A line graph showing all 24 hours on the x-axis and the mean "COUNT" on the y-axis was created for the period 1981 through 1999. The same procedure was performed for the total accumulation of precipitation ("SUM"). Graphs were also made showing the mean rates ("AVG") for the entire period.

Pulsatile Analysis

The time series was divided into precipitation pulse and interlude periods in order to create a conceptual model of the storm event (Butzow, 1993; Cutrim, *et al*, 1999). This analysis necessitated the use of two BASIC programs. The first of these, namely the Hourly Surface Rain Data Format Transformation Program ("Rainxfrc.exe"), was a transformation program. Processing with Rainxfrc began by prompting for the name of the location (i.e. Kalamazoo), the longitude and latitude coordinates and elevation of the station, the local time offset from UTC, and the number of header lines in the *.prn file. It next required the names of all the *.prn files to be processed. If data from 1997 were analyzed, for example, "JAN,1997" (case sensitive) was entered following the prompt "Enter First Month, Year to be Processed," and "DEC,1997" (case sensitive) was entered following the prompt "Enter Last Month, Year to be Processed." The names of the *.prn files were entered one at a time beginning with the January 1997 file following the prompt "Enter Name of Input Data File #1," and ending with the December 1997 file following the prompt "Enter Name of Input Data File #12." A name for the output file (with a *.xfr extension) was entered following the prompt "Enter Name of Output Data File," and the twelve *.prn files were transformed into one large output file.

The first line of the output file was merely a statement that the output file was a time-series. The values in the second line indicated, from left to right, the station location, latitude, longitude, elevation, and the time off-set from UTC (0 hours). The next four numbers (1, 1997, 12, 1997) indicated that this file contains data for the first month of 1997 through the twelfth month in 1997. The third line of this file was where the actual data began. The first number on this (and on all successive lines) was the Julian date (*e.g.*, 97001 = January 1, 1997), the second number was the hour in the context of a 24-hour clock (*e.g.*, 0100 = 1:00 A.M.), the third number was a repeat of the Julian data but added the hour in the form of a percentage (*e.g.*, 97001.04 = 4% of the first day of the year), and the last number indicated how much precipitation fell in that hour. A value of –1 was used if a precipitation value was missing for a given hour. Every hour of the year was summarized in like manner.

The second BASIC program used in this part of the analysis, namely the Hourly Surface Rainfall Pulsatile Analysis Program ("Rainan-g.exe"), produced two output files that were based on the *.xfr transformation files created by the Rain.xfrc program. Processing with Rainan-g began by asking for the name of the transformation file to be analyzed. If data from 1991 were analyzed, for example, the name of the *.xfr file for 1991 was entered following the prompt "Enter Name for Input File." A name was then entered for the output pulse file, with the extension *.opp, following the prompt "Enter Name for Output Pulse Profile File." Finally, a name was entered for the pulse parameter file, with the extension *.par, following the prompt "Enter Name for Output Pulse Parameter File."

The output file with the *.par extension identified individual precipitation pulses. An individual precipitation pulse was defined as "…the interval of time between the first non-zero value following a zero value and the last zero value following the last non-zero value" (Butzow, 1993). Each *.par file summarized the pulses. Each row in the file summarized a specific precipitation pulse. There were sixteen numbers in each row, most of which were derived pulse parameters defined by simple formulas (Butzow, 1993). I is the item, or the pulse number. T1 is the start time of the precipitation pulse, or the time of the first non-zero entry. T2 is the time of the peak precipitation rate. T3 is the end time of the precipitation pulse, or the time of the last non-zero entry. T31 is the duration of the precipitation pulse, or the last non-zero entry of a pulse minus one hour less than the next precipitation pulse. T13 is the duration of the dry period between precipitation pulses, or the first entry of a given precipitation pulse minus one less than the last non-zero entry of the previous precipitation pulse. T11 is the time between the start of successive precipitation pulses, or the first non-zero entry of a given precipitation pulse minus the first non-zero entry of the previous precipitation pulse. T22 is the time between the peak precipitation rates of successive pulses, or the time of the peak value for a given precipitation pulse minus the time of the peak value for the previous precipitation pulse. T33 is the time between the end of successive precipitation pulses, or the last non-zero entry of a given precipitation pulse minus the last non-zero entry of the previous precipitation pulse. T21 is the duration between the start of a precipitation pulse and the peak of the precipitation pulse, or T2 minus T1 for a given precipitation pulse. T32 is the duration between the peak of a given precipitation pulse and the end of that same precipitation pulse, or T3 minus T2 for a given precipitation pulse. MAX is the maximum precipitation rate for a given precipitation pulse. SUM is the total precipitation accumulation for a given precipitation pulse. SUM1 is the total precipitation before and including the peak time of a given precipitation pulse. SUM2 is the total precipitation after the peak time of a given precipitation pulse.

It should be noted that the program "assumed the most recent state" when encountering missing data values (Butzow, 1993). This meant that if a missing value was found between the start of a precipitation pulse and the end of that same precipitation pulse, the hour with the missing value was counted as part of the precipitation pulse. It should also be noted that if duplicate peak rate values ("MAX") were observed in the same precipitation pulse, the earliest peak rain rate was selected. For example, if the peak rate for a given precipitation pulse was 0.07

inches, and if that precipitation rate occurred in both the third and fifth hours of the pulse, the third hour was selected as the time of peak.

The *.par files were then converted into a Microsoft Excel format. The data for the period of April 1980 through March 2000 were copied from each individual file and pasted into one large Excel file. The mean, mode, median, maximum, and other basic statistics were calculated for all derived pulse parameters. A few changes had to be made to the large Excel file. The Rainan-g.exe program created each year separately and was unable to detect pulses and interludes that began during the end of one year and ended during the beginning of the next year. Some of the derived parameters therefore had values of "0" at the transitions between years. These transitions therefore had to be individually examined, and the numeric values calculated and entered into the file manually.

The output files with the *.opp extension contained profiles of each individual precipitation pulse. These "pulse profiles" were summarized in a simple format. The first line of the output file was merely a statement that the output file was a list of pulse profiles. The values in the second line indicated, from left to right, the station location, latitude, longitude, and elevation. The next four numbers (1, 1991, 12, 1991) indicated that this file contained data for the first month of 1991 through the twelfth month in 1991. The third line of this file was where the actual data began. The first number on this (and on all successive lines) was the number of the precipitation pulse. The second number indicated the total number of hours that made up the precipitation pulse (including both the first and last hours of the pulse), and the remaining numbers were a complete list of all precipitation totals from all hours that had precipitation during that pulse.

Another quality control check was performed on the data to ensure that the programs were working correctly, and to check for errors in the data. One hundred of the original rectangular paper charts (two from 1979, three from 1980, and five from all remaining years) were selected for this procedure. Each of the selected charts were examined and compared to the spreadsheet that was produced from them. They were then compared to each of the output files from the three basic programs described in the above paragraphs. This procedure took approximately 22 hours to complete. Most errors were found to be very minor. Two or three hours of precipitation were missed, a few entries were placed in the wrong cell, and occasional entries were incorrectly typed (such as 0.02 being typed as 0.2, or 0.05 being typed as 0..05).

Inter-Annual Analysis

An examination of the variability of the precipitation from year to year, also known as an "inter-annual" analysis, was performed for the years 1981 through 1999. This was done in order to examine the wetter than normal and drier than normal years. The years 1979, 1980, and 2000 were excluded from this analysis because several months of data were missing from each of those years.

Microsoft Excel was used to perform the inter-annual analysis. The year values of 1981 through 1999 were placed in Column A, the total number of wet hours for each year were placed in Column B, and the total accumulation of precipitation for each year was placed in Column C. Excel formulas were used to calculate the mean number of wet hours and the mean accumulation of precipitation for all 19 years. The mean number of wet hours was subtracted from each of the year values and was placed in Column F. The mean accumulation of precipitation was subtracted from each of the year values and was placed in Column G. Graphs showing the inter-annual variability of the number of wet hours and the precipitation accumulation were then created using Columns F and G.

CHAPTER VI

RESULTS

Diurnal Analysis

Precipitation in Oshtemo Township occurs at all hours of the day and, generally speaking, is evenly distributed. There are no unusual dry or wet periods in the diurnal cycle. Plots of the diurnal distribution of the mean precipitation accumulation, the mean number of wet hours, and the mean precipitation rates for each hour of the day are presented graphically in Figure 2.

For the period January 1981 through December 1999, a nocturnal maximum was observed in both the mean accumulation and mean rate. On average, precipitation accumulation and precipitation rate peaked around 2000 LT at values of 1.87 inches (47 mm) and 0.08 inches per hour (2 mm h^{-1}) respectively. A secondary maximum period for the mean accumulation occurred during the morning between 0600 LT and 1000 LT peaking at a value of 1.72 inches (44 mm). The minimum mean accumulation occurred around 1300 LT at a value of 1.12 inches (28 mm).

A somewhat different picture manifested itself when the mean number of precipitation hours was examined. A 1000 LT maximum at a value of 27.1 hours was observed. A secondary nocturnal maximum in the mean number of hours occurred during the hours between 1800 LT and 2200 LT with a peak value of 25.1 hours. This coincided with the hour of the maximum mean accumulation and maximum rate.

These results show that for the period of 1981 through 1999, there were more hours with precipitation during the morning, but the actual precipitation amounts

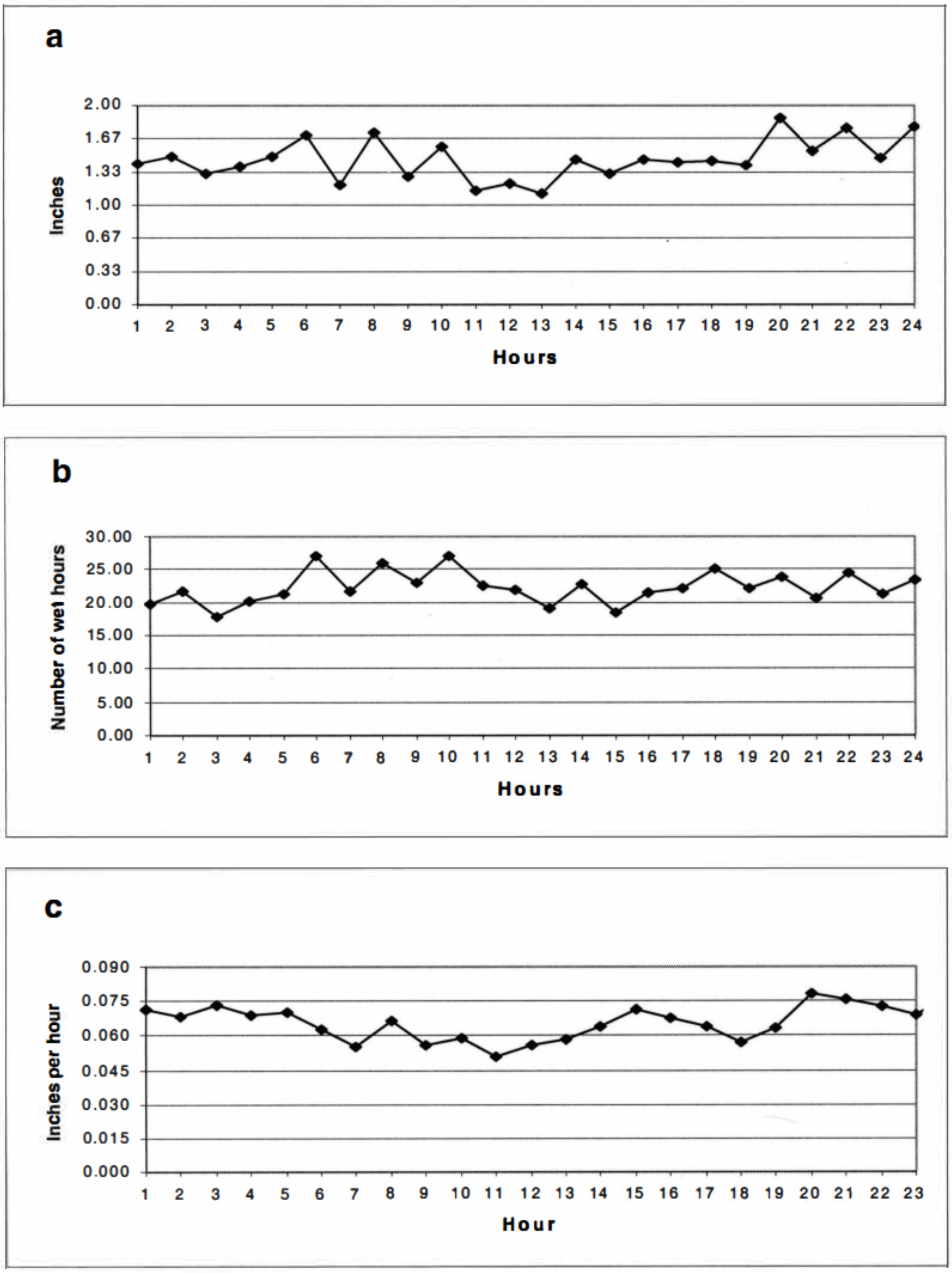

Figure 2. Diurnal Cycle for the Period 1981 – 1999. (a) Mean precipitation accumulation (in), (b) mean number of precipitation hours, (c) mean precipitation rate (in h^{-1}).

were heavier in the evening.

Seasonal Analysis

Plots of the diurnal distribution of the mean precipitation accumulation, the mean number of wet hours, and the mean precipitation rates for each hour of the day during the winter season (December through February) are presented graphically in Figure 3. During this season, the accumulation peaked around 0500 LT at a value of 0.35 of an inch (9 mm), and a slightly smaller peak occurred around 1000 LT at a value of 0.31 of an inch (8 mm). A secondary maximum period in the accumulation was observed between 1800 LT and 2200 LT peaking at a value of 0.30 of an inch (8 mm). The minimum in winter occurred around 1500 LT at a value of 0.18 of an inch (20 mm). The maximum mean number of wet hours during winter occurred around 1000 LT at a value of 9.75 hours, while slightly smaller peaks were observed before 0600 LT and 1800 LT. The maximum mean rate occurred around 0500 LT at a value of 0.047 inches per hour (1 mm h^{-1}). These results show that during the winter season, the heaviest accumulation of precipitation and the greatest number of wet hours both occurred during the morning hours.

Plots of the diurnal distribution of the mean precipitation accumulation, the mean number of wet hours, and the mean precipitation rates for each hour of the day during the spring season (March through May) are presented graphically in Figure 4. The maximum mean accumulation of precipitation during this season occurred around 2200 LT at a value 0.47 of an inch (12 mm), while a slightly smaller peak occurred around 2000 LT at a value of 0.42 of an inch (11 mm). A secondary maximum period was observed between 0600 LT and 0800 LT peaking at a value of 0.42 of an inch (11 mm). The minimum in spring occurred around 1300 LT at a

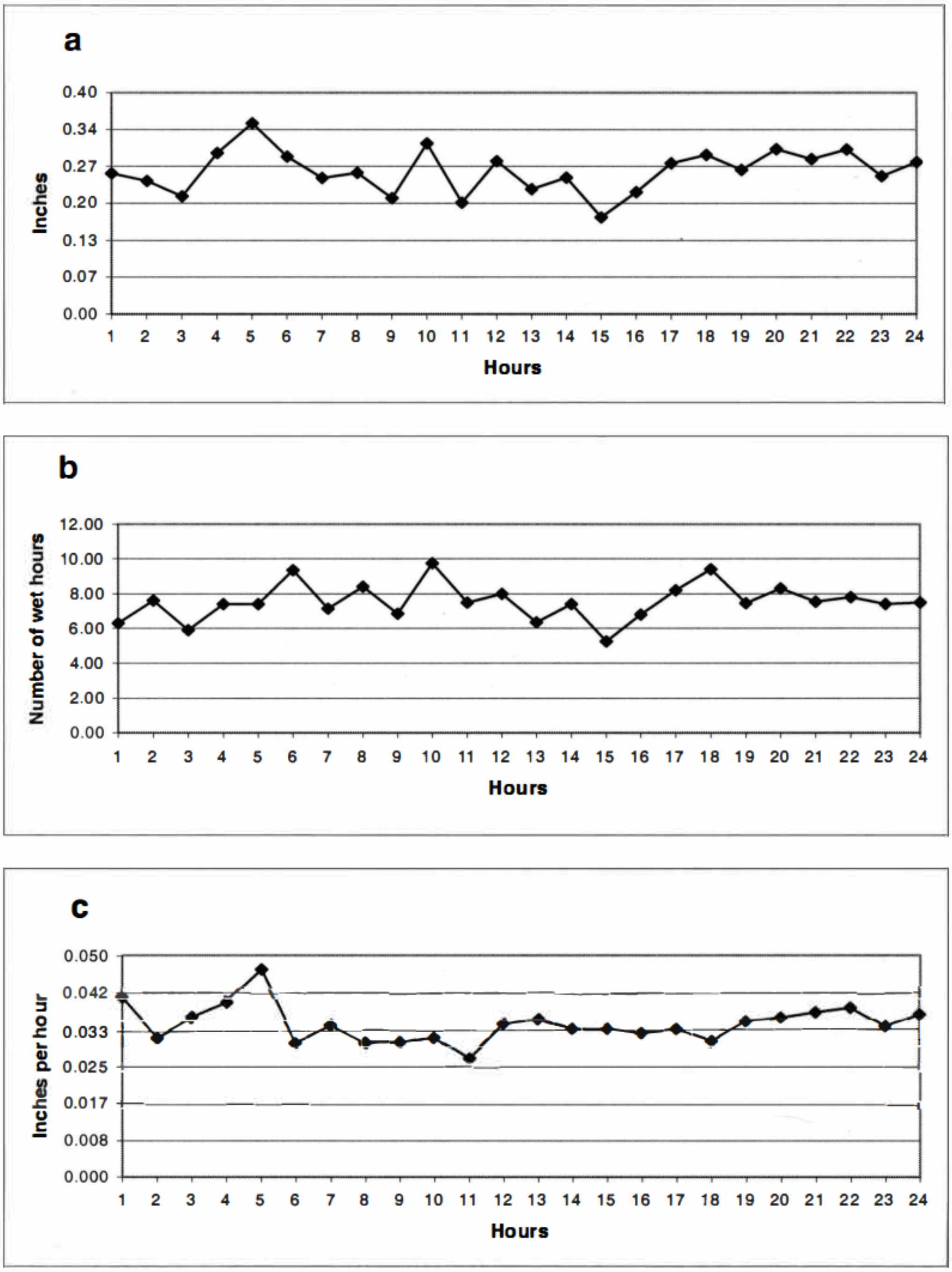

Figure 3. Diurnal Cycle for the Winter Months (Dec - Feb) From December 1981 Through February 2000. (a) Mean precipitation accumulation (in), (b) mean number of precipitation hours, (c) mean precipitation rate (in h^{-1}).

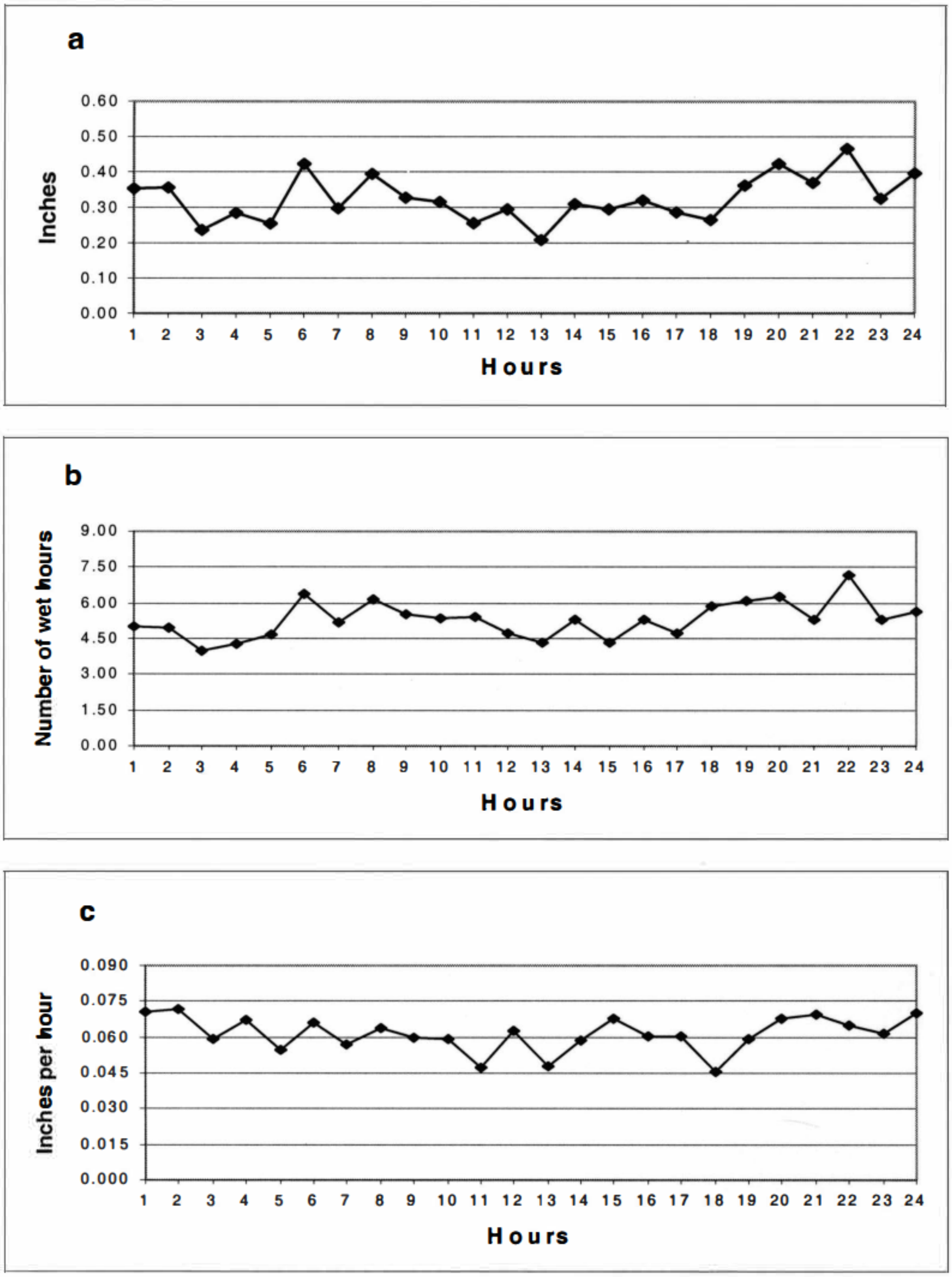

Figure 4. Diurnal Cycle for the Spring Months (Mar - May) From March 1981 Through May 1999. (a) Mean precipitation accumulation (in), (b) mean number of precipitation hours, (c) mean precipitation rate (in h^{-1}).

value of 0.21 of an inch (5 mm). The maximum mean number of wet hours occurred around 2200 LT at a value of 7.2 hours, which coincided with the maximum mean accumulation. Slightly smaller peaks in the mean number of wet hours occurred around 0600 LT, 0800 LT, 1800 LT, and 2000 LT. A morning maximum is therefore dominant during the spring season in both the number of wet hours and accumulation of precipitation. The maximum mean rate of precipitation occurred around 0200 LT at a value of 0.072 inches per hour (2 mm h^{-1}).

Plots of the diurnal distribution of the mean precipitation accumulation, the mean number of wet hours, and the mean precipitation rates for each hour of the day during the summer season (June through August) are presented graphically in Figure 5. The maximum mean accumulation of precipitation during the this season occurred around 0600 LT at a value of 0.67 of an inch (17 mm), while slightly smaller peaks occurred around 0500 LT and 0800 LT. A secondary maximum period in the mean accumulation was observed between 2200 and 2400 peaking at a value of 0.57 of an inch (14 mm). The minimum mean accumulation occurred around 1900 LT at a value of 0.30 of an inch (8 mm). The maximum mean number of wet hours occurred around 0600 LT at a value of 4.40 hours, which coincided with the time of the peak mean accumulation. Slightly smaller peaks in the mean number of wet hours occurred around 0800 LT and 1000 LT. A morning maximum is therefore dominant during the summer season in both the number of wet hours and accumulation. The peak rate occurred around 2000 LT at a value of 0.187 inches per hour (5 mm h^{-1})

Plots of the diurnal distribution of the mean precipitation accumulation, the mean number of wet hours, and the mean precipitation rates for each hour of the day during the autumn season (September through November) are presented graphically in Figure 6. Precipitation accumulation during this season peaked around 2000 LT at

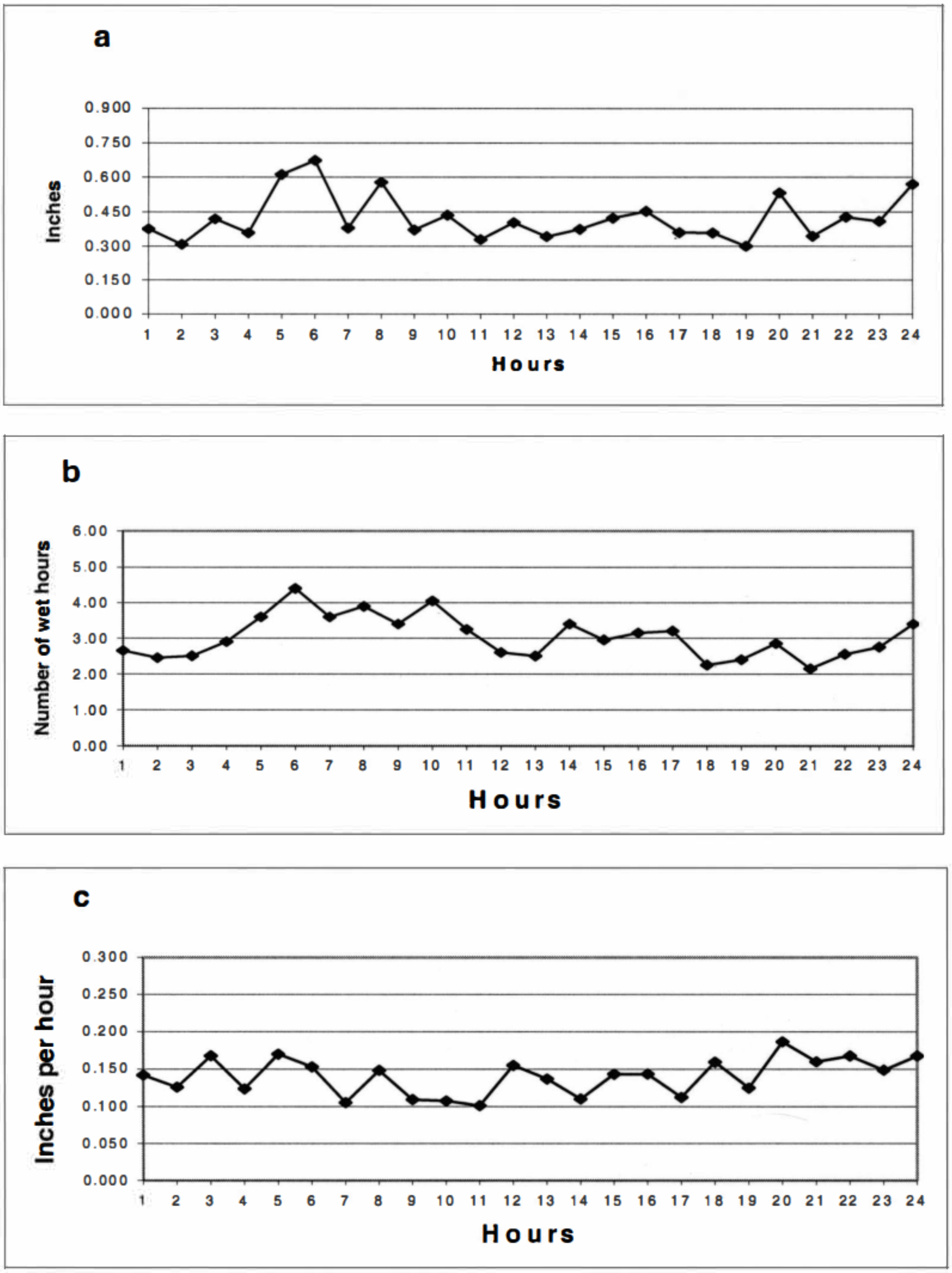

Figure 5. Diurnal Cycle for the Summer Months (Jun - Aug) From June 1980 Through August 1999. (a) Mean precipitation accumulation (in), (b) mean number of precipitation hours, (c) mean precipitation rate (in h^{-1}).

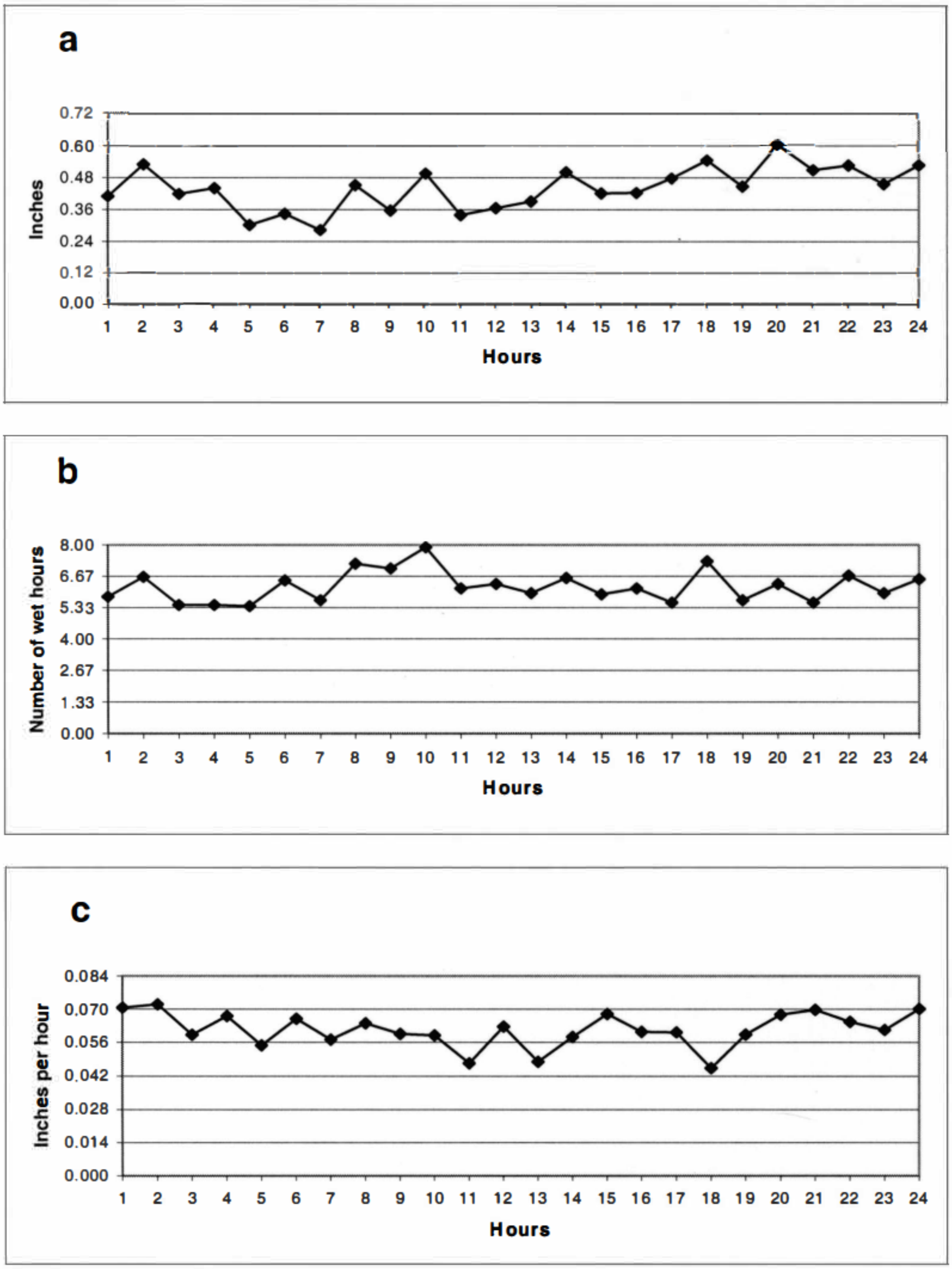

Figure 6. Diurnal Cycle for the Autumn Months (Sep - Nov) From September 1979 Through November 1999. (a) Mean precipitation accumulation (in), (b) mean number of precipitation hours, (c) mean precipitation rate (in h^{-1}).

a value of 0.60 of an inch (15 mm), while slightly smaller peaks occurred during the hours before 1800 LT and 0200 LT. The minimum mean accumulation occurred around 0700 LT at a value of 0.28 of an inch (2 mm). The maximum mean number of wet hours occurred around 1000 LT at a value of 7.9 hours, which did not coincide with the time of the peak mean accumulation. A slightly smaller peak in the mean number of wet hours occurred around 1800 LT at a value of 7.3 hours, which coincided with the time of one of the smaller peaks in the mean accumulation. The peak mean rate occurred around 2000 LT at a value of 0.095 inches per hour (2 mm h^{-1}). These results show that during the autumn season, the heaviest accumulation of precipitation occurred during the nighttime hours while the greatest number of wet hours occurred during the morning hours.

It was observed from the seasonal analysis that precipitation patterns during the transitional seasons of spring and autumn were responsible for the 19-year evening maximum in the mean accumulation. It was also observed that the precipitation patterns during the winter and summer seasons were responsible for the 19-year secondary maximum detected in the mean accumulation between 0600 LT and 1000 LT.

Monthly Series Analysis

Diurnal analysis was performed on every available month from July 1979 through March 2000. These files were combined into series of months (*e.g.*, all months of January were combined, all months of February were combined, *etc.*), and statistical analyses were performed. The peak mean accumulation, peak mean number of wet hours, and peak mean rate for all months are shown in Table 3. There was a dominance in morning maximums for the mean number of wet hours. There were a total of eight months when the mean number of wet hours peaked during the early morning hours between 0500 LT and 1000 LT, including all summer and autumn months, and two out of the three winter months. Other trends were easily found. A 2200 LT maximum in the mean number of wet hours occurred during all the spring months. Nocturnal maximums between 2100 LT and 0100 LT were found in the mean rates for all autumn months and spring months.

Some seasonal maximums described in the previous section seemed to be the result of individual months and not general seasonal characteristics. For example, the winter maximum that occurred around 0500 LT for the mean accumulation of precipitation seemed to be the result of a strong peak in the mean accumulation during only the month of January at a value of 0.15 of an inch (4 mm). The peak mean accumulation of precipitation occurred around 1000 LT in December at a value of 0.16 of an inch (4 mm); however there was a secondary maximum around 0500 LT at a value of 0.13 of an inch (3 mm). The maximum mean accumulation in February occurred during the period from 2000 LT to 2200 LT at a value of 0.10 of an inch (3 mm).

The highest values of the mean accumulation occurred during the summer months. The mean accumulations ranged from 0.28 of an inch (7 mm) in July to 0.10 of an inch (3 mm) in February. The highest values of the mean number of wet hours occurred during the winter. The mean number of wet hours ranged from 1.5 hours in June, July, and August to 3.65 hours in December. The highest values of the mean rate occurred in the summer. Mean rates ranged from 0.048 inches per hour (1 m h^{-1}) in December to 0.255 inches per hour (7 mm h^{-1}) in July.

Yearly Analysis

There didn't appear to be much consistency from year to year when the diurnal cycle for individual years was examined. The peak mean accumulation, peak mean number of wet hours, and peak mean rate for each year from 1981 to 1999 are shown in Table 4. The peak time in the mean accumulation of precipitation varied considerably from year to year, although a nocturnal maximum did occur most often. An unusual phenomena occurred in the mean number of wet hours. A nocturnal maximum was dominant during the earlier years, but gradually shifted to a morning maximum in the later years. The peak number of wet hours was observed during the hour before 1000 LT in all years from 1996 through 2000. The peak mean rate varied from year to year, but occurred most often during the evening hours between 1900 LT and 2400 LT, and during the early morning hours between 2400 LT and 0600 LT.

The highest peak accumulation occurred in 1993 at a value of 4.33 inches (110 mm), and the lowest peak accumulation occurred in 1987 at a value of 2.09 inches (53 mm). The highest peak number of wet hours occurred in 1993 at a value of 46 hours, and the lowest peak number of wet hours occurred in 1989 at a value of 23 hours. The highest mean rate occurred in 1989 at a value of 0.17 inches per hour (4 mm h^{-1}), and the lowest mean rate occurred in 1984 at a value of 0.08 inches per hour (2 mm h^{-1}).

Pulsatile Analysis

All precipitation pulses and interludes found by the Hourly Surface Rainfall Pulsatile Analysis Program during the period of April 1980 through March 2000 were analyzed in order to develop a "storm event" model. A storm is defined as "at least 1 h of rain bounded on either side by at least 1 h without rain" (Cutrim, *et al*, 2000).

Table 3

Monthly Peaks

	Mean Accumulation			Mean Wet Hours		Mean Rate		
	Hour	(in)	(mm)	Hour	(h)	Hour	(in)	(mm)
Ja	5	0.15	3.8	10	3.4	5	0.054	1.4
Fe	19,20,22	0.10	2.5	18	2.8	1	0.048	1.2
Ma	22	0.16	4.1	22	2.65	21	0.064	1.6
Ap	2	0.18	4.6	22	2.35	24	0.092	2.3
My	22	0.18	4.6	22	2.2	1	0.111	2.8
Jn	12	0.21	5.3	10	1.5	12	0.247	6.3
Jl	8	0.28	7.1	5,6	1.5	20	0.255	6.5
Au	6	0.23	5.8	6	1.5	2	0.181	4.6
Se	20	0.25	6.4	8	1.86	20	0.181	4.6
Oc	2	0.19	4.8	10	2.67	21	0.093	2.4
No	14	0.19	4.8	10	3.1	22	0.070	1.8
De	10	0.16	4.1	10	3.65	5	0.048	1.2

Table 4

Yearly Peaks

	Accumulation			Wet Hours		Mean Rate		
	Hour	(in)	(mm)	Hour	(h)	Hour	(in)	(mm)
1981	22	2.97	75.4	22	26	21	0.13	3.3
1982	6	3.16	80.3	20	33	6	0.1	2.5
1983	24	2.87	72.9	6	34	1	0.13	3.3
1984	5	2.36	59.9	22	34	5,9,15,16,17,23	0.08	2.0
1985	19	3.07	78.0	8	33	11,19	0.11	2.8
1986	10	3.12	79.2	10	33	4,20,21	0.12	3.0
1987	15	2.09	53.1	6	31	22	0.1	2.5
1988	21	2.96	75.2	20	25	2,22	0.13	3.3
1989	5	2.56	65.0	14	23	5	0.17	4.3
1990	8,18	3.3	83.8	13,16,17	29	24	0.14	3.6
1991	8	2.88	73.2	8	28	3	0.12	3.0
1992	20	2.43	61.7	5	33	1	0.13	3.3
1993	24	4.33	110.0	10	46	24	0.12	3.0
1994	20	2.37	60.2	20	29	20	0.12	3.0
1995	14	2.46	62.5	11	35	14,15	0.11	2.8
1996	23	2.29	58.2	10	29	1	0.11	2.8
1997	4	3.2	81.3	10	36	4	0.12	3.0
1998	9	2.37	60.2	10	33	12	0.12	3.0
1999	6	2.76	70.1	10	29	6	0.11	2.8

An event is defined as “a storm and the interlude that follows it” (Cutrim, *et al*, 2000).

Table 5 presents the statistical summary of all pulses during the 20-year period. There was an average of 34.74 inches (882 mm) of precipitation per year, which is consistent with other stations in southwest lower Michigan (Eichenlaub, 1990). The mean accumulation per pulse (“SUM”) was 0.16 of an inch (4 mm), the median accumulation per pulse was 0.05 of an inch (1 mm), and the mode accumulation per pulse was 0.01 of an inch (0.3 mm). A total of 62.9 % of the study period yielded less than 0.10 of an inch (3 mm) with almost 18.8 % of these being 0.01 of an inch. Approximately 98 % yielded 1.00 inch or less. From the total of 4,362 pulses, only 11 of these pulses yielded two inches or more of precipitation. The greatest accumulation that fell in any pulse was 4.11 inches (104 mm) during an 8-hour period in the summer of 1982, and the greatest maximum precipitation for 1-hour was 1.80 inches (46 mm), which occurred in the summer of 1980.

The mean maximum precipitation per pulse (“MAX”) was 0.09 of an inch (2 mm), the median maximum precipitation was 0.04 of an inch (1 mm), and the mode maximum precipitation per pulse was 0.01 of an inch (0.3 mm). The sum of all “MAX” values was 398.97 inches (10,134 mm), which was 57.43 % of the total precipitation accumulation of 694.76 inches (17,650 mm). The mean precipitation sum from the start of the precipitation pulse to and including the peak of the precipitation pulse (“SUM1”) was 0.12 of an inch (3 mm), the median was 0.05 of an inch (1 mm), and the mode was 0.01 of an inch (0.3 mm). The sum of all “SUM1” values was 519.38 inches (13,192 mm), which was 74.76 % of the total precipitation accumulation. This meant that 17.33 % of the precipitation fell before the peak hour. The mean precipitation sum from the hour after the peak of the pulse to the end of

Table 5

Pulsatile Analysis Table for the Period April 1980 - March 2000

	T31 Pulse (h)	**T13** Interlude (h)	**T21** Start to Peak **(h)**	**T32** Peak to End **(h)**	**MAX** Peak Accum. **(in)**	**SUM** Pulse Accum. **(in)**	**SUM1** Start to Peak **(in)**	**SUM2** Peak to End **(in)**
Mean	2.44	37.74	1.51	1.92	0.09	0.16	0.12	0.04
Median	1.00	6.00	1.00	1.00	0.04	0.05	0.05	0.00
Mode	1.00	1.00	1.00	1.00	0.01	0.01	0.01	0.00
Maximum	28.00	817.00	22.00	27.00	1.80	4.11	2.62	1.84
SD	2.42	70.50	1.27	1.74	0.14	0.28	0.20	0.12
Variance	5.86	4970.37	1.61	3.04	0.02	0.08	0.04	0.01
Skewness	3.40	3.28	5.03	3.92	4.01	4.16	3.96	6.29
Kurtosis	19.00	14.50	43.85	27.00	23.81	26.72	22.38	55.50
Sum	10633.00	164609.00	6599.00	8392.00	398.97	694.76	519.38	175.38
Sum / yr	531.65	8230.45	329.95	419.60	19.95	34.74	25.97	8.77

the pulse ("SUM2") was 0.04 of an inch (1 mm), the median was 0, and the mode was 0. A "0" indicated that the peak occurred during the last hour of pulse. The sum of all "SUM2" values was 175.38 inches (4455 mm), which was 25.24 % of the total precipitation.

The mean duration of the pulse ("T31") was 2.44 hours, the median duration of the pulse was 1 hour, and the mode duration of the pulse was 1 hour. There were a total of 10,633 hours with precipitation during the 20-year period, which was an average of 531.65 hours per year. The mean interlude between pulses ("T13") was 37.74 hours, the median interlude between pulses was 6 hours, and the mode interlude between pulses was 1 hour. There was an average of 8,230.45 hours per year without precipitation. The mean time between the start of successive precipitation pulses ("T11") was 40.2 hours, the median was 9 hours, and the mode was 2 hours. The same numbers were found for the mean, median, and mode for the mean time between successive pulse peaks ("T22"), and the mean time between the end of successive pulses ("T33").

The frequency histogram of the pulse duration during the period of April 1980 through March 2000 is shown on Figure 7. Slightly more than half (50.30 %) of the pulses were only one hour long, and over two-thirds (69.56 %) of the pulses were of a duration of one to two hours. Slightly over 91.1 % of the pulses lasted 5 hours or less. The longest pulse duration was 28 hours, which occurred on two separate occasions. A total of 1.26 inches (32 mm) of precipitation fell during a continuous 28-hour period in February of 1990, and a total of 2.35 inches (60 mm) of precipitation fell during a continuous 28-hour period in November of 1990. There was also a continuous 27-hour period in February of 1985 when 1.83 inches (46 mm) fell, and a continuous 26-hour period in November of 1988 when 0.86 inches (22 mm) fell.

The frequency histogram of the interlude between precipitation pulses during the period of April 1980 through March 2000 is shown in Figure 8. A total of 3,039

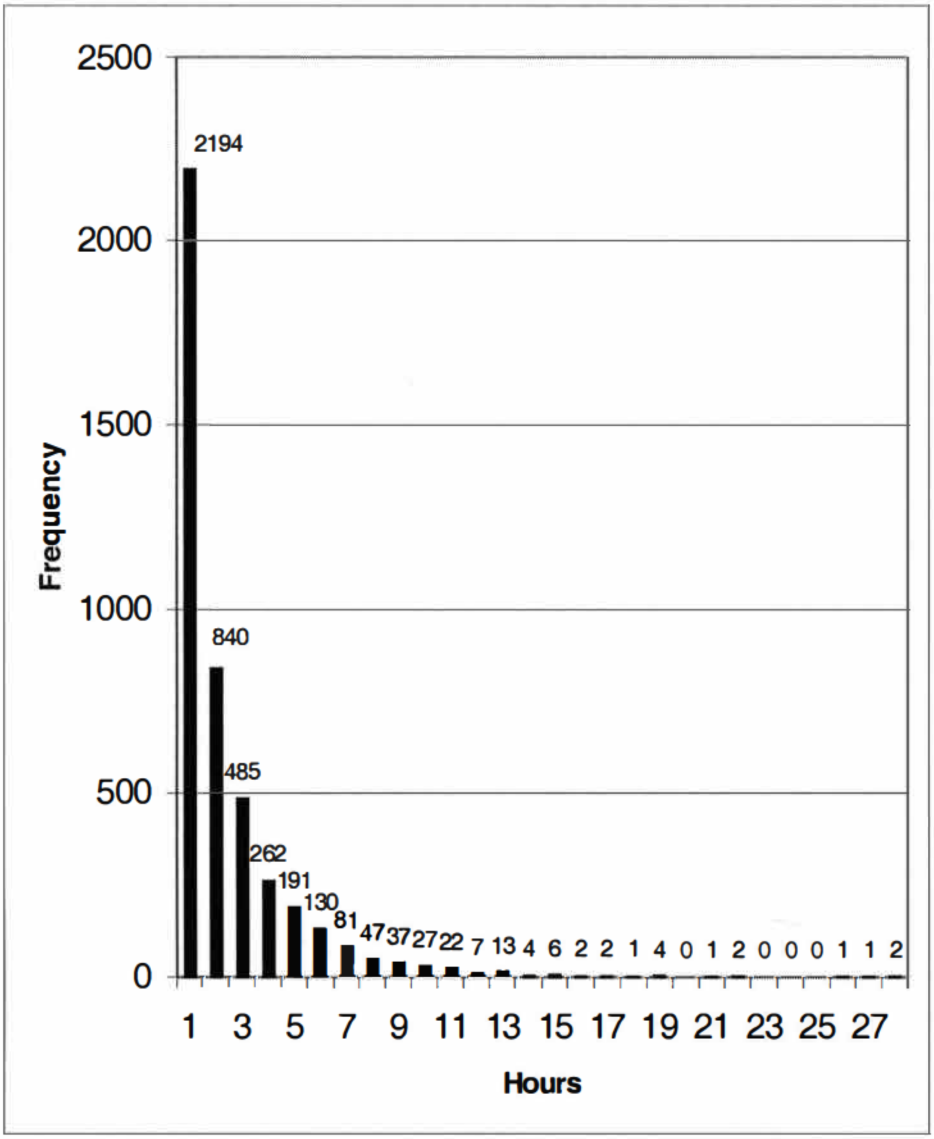

Figure 7. Frequency Distribution for Duration of Precipitation Pulses

interludes, or 69.67 % of the total number of interludes, were from 1 to 25 hours long. Of these interludes, 890 (20.40 %) were only one hour long, and 1,370 (31.41 %) were from 1 to 2 hours long. The longest interlude of 817 hours occurred during

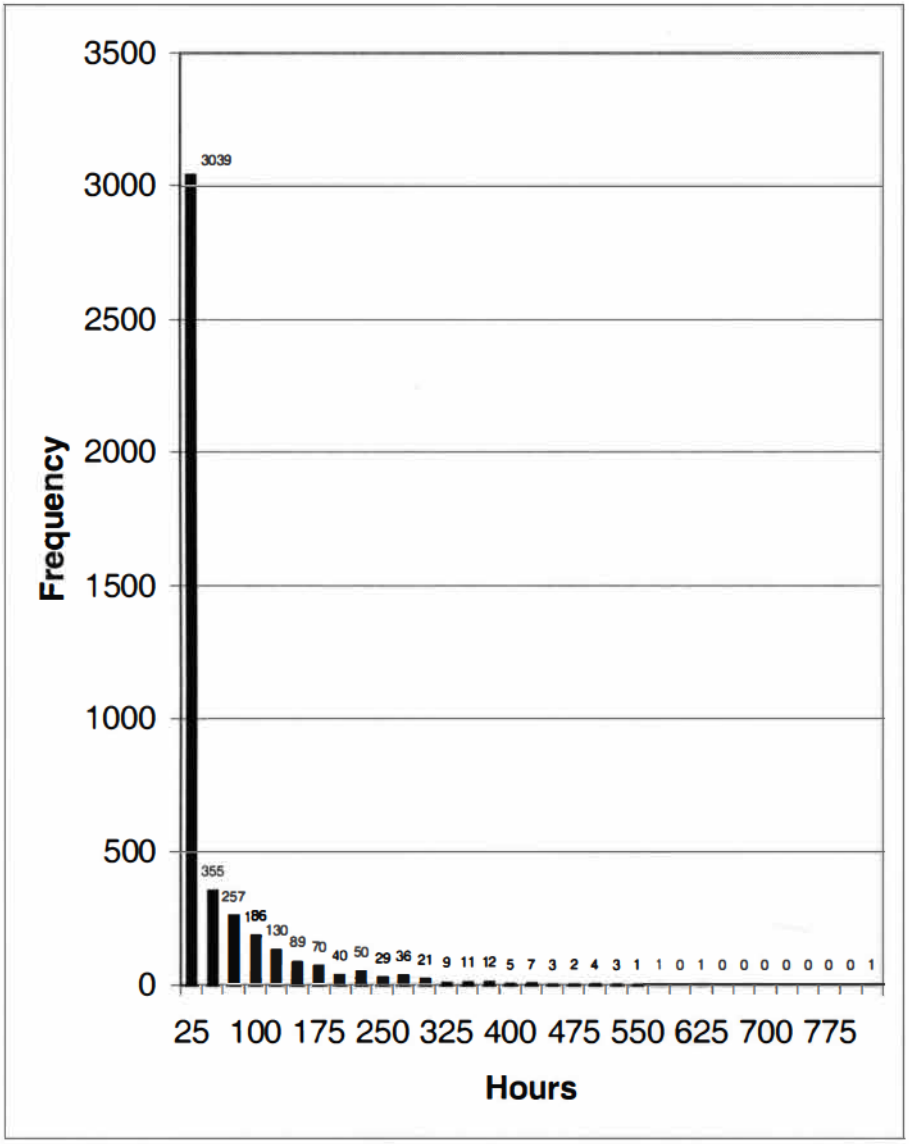

Figure 8. Frequency Distribution for Interludes Between Pulses

the months of February and March of 1988. However, there were extensive missing data during this period, and thus the length of the interlude cannot be legitimately taken as the highest. The second highest interlude was 618 hours, which occurred during a period from May through June of 1990. There were no missing values during this period; this is therefore taken as the highest legitimate interlude during the 20-year period. There were seven interludes of over 500 hours, but three of them had to be rejected because of extensive missing values. The four highest legitimate interludes were 618 hours (May through June of 1990), 570 hours (March through April of 1999), 538 hours (August through September 1994) and 502 hours (September through October 1989). A total of 58.1 % of the interludes lasted 10 hours or less.

Table 6 shows that the mean precipitation duration after the peak was an average of 0.43 hours longer than the precipitation duration before the peak. It was also shown that the mean accumulation after the peak hour was 0.01 of an inch (0.3 mm) greater than the mean accumulation before the peak hour. This meant that the mean precipitation rate was greater before the peak hour than it was after the peak hour.

A storm event model was developed using the numbers in Tables 6. The values in Table 6 were based on the following two assumptions (Butzow, 1993):

1. Peak precipitation is recorded over a period of 1 hour.
2. The sum of the early, peak, and late precipitation periods will equal the total accumulation.

The storm event model is shown in Figure 9.

Table 6

Model Storm Event

	Duration (h)	Acumulation (in)	Rate (in / h)	Interlude (h)
Early	0.51	0.03	0.05	*
Peak	1.00	0.09	0.09	*
Late	0.92	0.04	0.04	*
Total	2.44	0.16	0.06	37.74

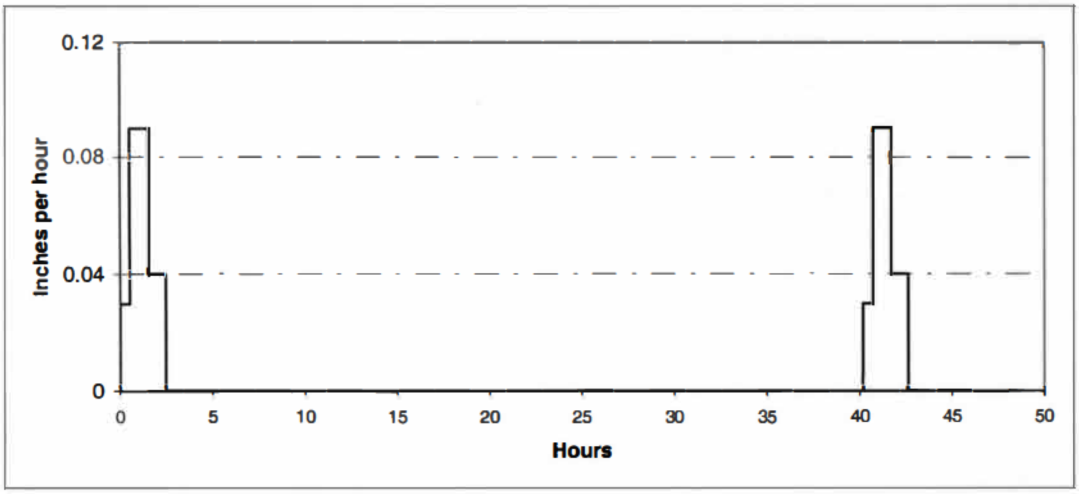

Figure 9. Storm Event Model for Oshtemo Township

Inter-Annual Analysis

Figure 10 shows the results of the inter-annual analysis. A high variability was found in the yearly variation from the mean accumulation. Positive values from 5 to 9 inches (127 to 229 mm) above the mean were evident during five separate years, and negative values from 5 to 9 inches (127 to 229 mm) below the mean were evident during four separate years. The highest positive value was 8.33 inches (212 mm) above the mean in 1993, and the lowest negative value was 8.66 inches (220 mm) below the mean in 1989.

A high variability was also found in the yearly variation from the mean number of wet hours. Two years had positive values more than 100 hours above the mean, and two years had negative values more than 100 hours below the mean. The highest positive value was 185.32 hours above the mean in 1993, and the lowest negative value was 170.68 hours below the mean in 1989.

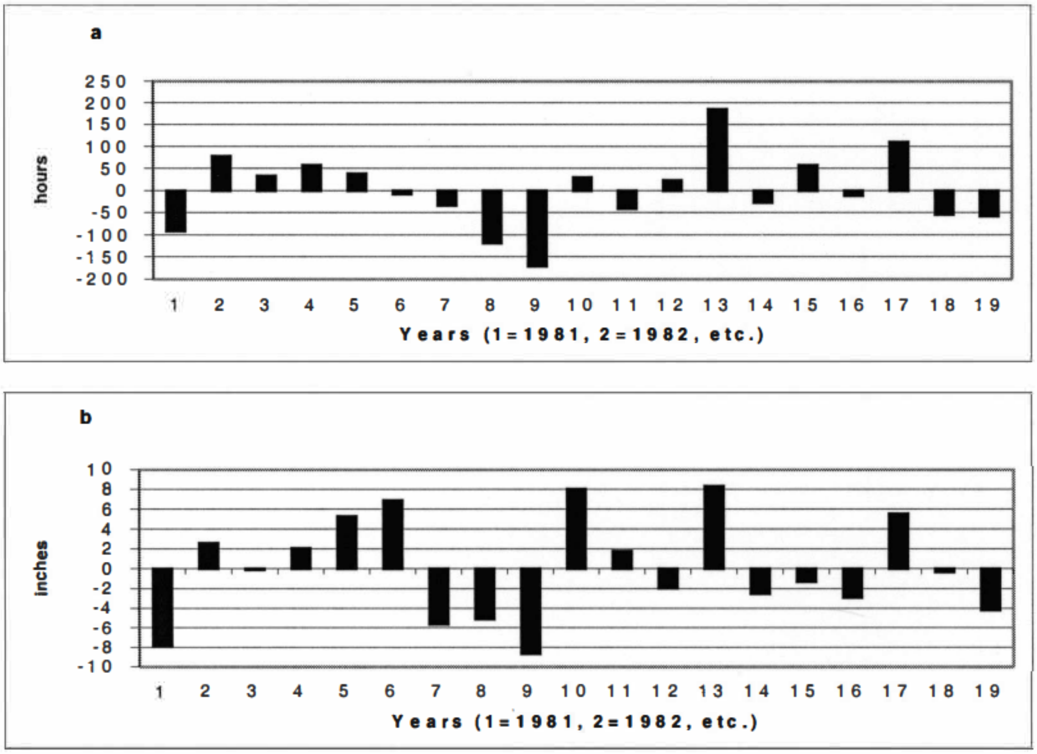

Figure 10. Inter-annual Analysis (1981-1999). (a) Yearly deviation from the mean number of wet hours, (b) yearly deviation from the mean sum accumulation.

CHAPTER VII

CONCLUSIONS

This twenty-year study of ground-based precipitation observations generated a unique data set for Oshtemo Township, its surroundings, and the Great Lakes for the period of July 18, 1979 through March 31, 2000. Processing and analysis of the data reliably portrayed the precipitation climatology of southwest lower Michigan. The concerns that flaws in the data collection (such as chart readability, extensive missing data, and possible tree line interference) could be potentially detrimental to the data were not supported. Indeed, the time series of the hourly precipitation was successfully validated by the data from a neighboring station and by the regional climatology. Monthly totals were generally consistent with available data from the Kalamazoo State Hospital (National Climatic Data Center). The mean annual amount of 34.74 inches (882 mm) was consistent with the Climatic Atlas of Michigan which placed Oshtemo Township in a region averaging 34 inches (864 mm) to 36 inches (914 mm) of precipitation per year (Eichenlaub, 1990).

Overall, the diurnal analysis of the hourly precipitation was evenly distributed during all hours of the day, *i.e*, there were no exceptionally dry or wet hours. An evening precipitation maximum was detected in the mean accumulation around 2000 LT and a secondary maximum was detected in the mean accumulation between 0600 LT and 1000 LT. The seasonal analysis of the diurnal cycle indicated that the elevated spring and fall accumulations were responsible for the evening maximum, and the elevated winter and summer accumulations were responsible for the morning secondary maximum.

Pulsatile analysis of the Oshtemo Township data shows that about 70 % of the precipitation pulses lasted from 1 to 2 hours. Slightly over 91 % of the pulses lasted 5 hours or less. The longest duration was 28 hours which occurred on two separate occasions in winter and fall of 1990. The interlude between pulses of 1 to 25 hours was also about 70 %. Slightly over 58 % of the interludes lasted 10 hours or less. Approximately 97 % of the study period had dry periods under 10 days long. Approximately 63 % of the pulses yielded less than 0.10 of an inch (3 mm), with almost 19 % of these being precipitation of 0.01 of an inch (0.3 mm). Approximately 98 % yielded 1.00 inch (25 mm) or less. From the total of 4,362 pulses, only 11 of these pulses yielded 2 inches (51 mm) or more of precipitation with the record maximum being 4.11 inches (104 mm) in the summer of 1982.

A storm event model for the region was developed with the mean parameters obtained from the pulsatile analysis. This model will help scientists and engineers to better plan Oshtemo Township and surrounding areas on environmental and ground water management issues.

Inter-annual analysis of Oshtemo Township from 1981 to 1999 showed that there was a high variability in the mean accumulation from year to year. Positive values from 5 to 9 inches (127 mm to 229 mm) above the mean were evident during five separate years, and negative values from 5 to 9 inches (127 to 229 mm) below the mean were evident during four separate years. A high variability was also observed in the mean number of wet hours. Two years had positive values more than 100 hours above the mean, and two years had negative values more than 100 hours below the mean.

These results create a better understanding of the precipitation climatology of the region and will benefit both the general and scientific community in several ways.

First, the research performed here serves as a baseline for future research on the local climate change. This is the first in-depth time series analysis of such magnitude performed for a location in southwest lower Michigan. Secondly, results may be compared with neighboring areas not under the influence of the Great Lakes. Similarities and differences between regions may be analyzed to gain a better understanding of the "lake-effect" phenomena. While climatologists have a general understanding of many of the effects of the Great Lakes, there are still many specifics that are not yet understood. Third, results may provide benefits to the community of Oshtemo Township which is currently experiencing growth in urban development. Issues such as storm drainage management and ground water supply increase in importance as the township continues to grow. The township will not have to look elsewhere for accurate precipitation data. Finally, the evening nocturnal maximum in the mean accumulation detected in spring and autumn, and the morning maximum in the mean accumulation detected in winter and summer warrant further analysis. The causes of these seasonal variations are as of yet unclear, but factors could include the effects of Lake Michigan, synoptic activity, and convectional instability.

The hourly data used in this study will be made available to the public and will be placed on the Internet for easy access.

Appendix

Images of the Oshtemo Township Rain Gage
(Taken in June 2000)

Image 1. The Rectangular Paper Chart

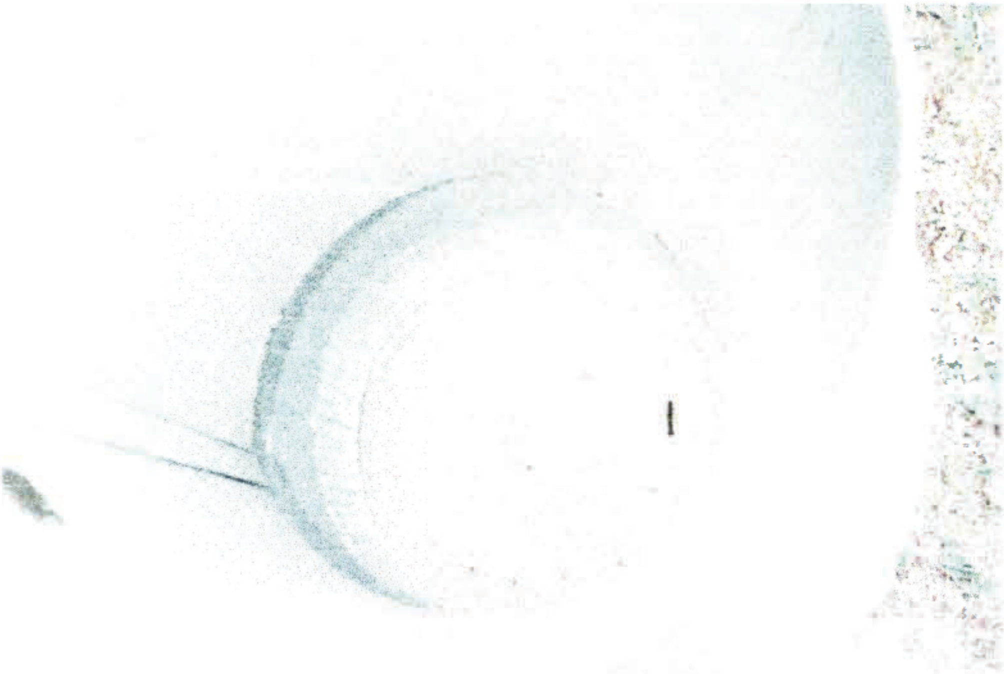

Image 2. The Bucket

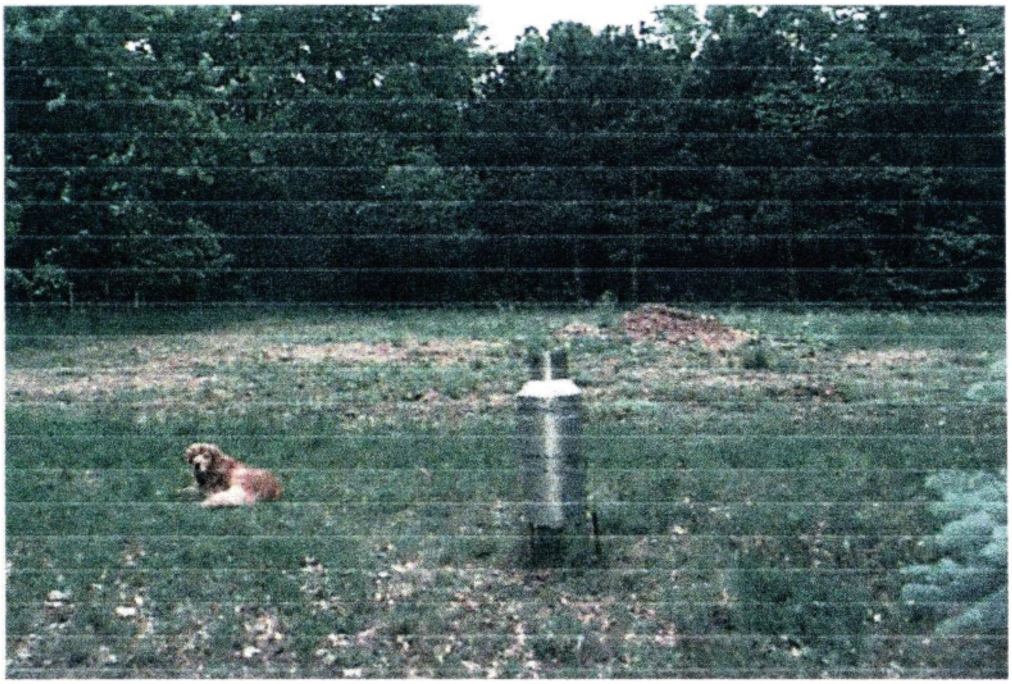

Image 3. The Rain Gage

Image 4. The Station

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