THE UNIVERSITY OF CALGARY

PRECIPITATION CLIMATOLOGY OF THE LAKE SUPERIOR BASIN

by

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ABSTRACT

The study of the precipitation climatology of the Lake Superior Basin, for the period 1900-1980, was undertaken to produce results that could be used for determining the extent of a possible relationship between the amount of precipitation falling within the basin and the water level of Lake Superior. The objectives were as follows: (i) explain the spatial distribution of annual precipitation; (ii) investigate and quantify the physical controls on basin precipitation; (iii) determine the presence, tendency and significance of primary and secondary trends; (iv) examine the data for any cyclic patterns; (v) analyze the degree of variability of basin precipitation and any patterns associated with annual change and (vi) investigate the seasonal characteristics shown by basin precipitation in a two season (surplus/deficit) year.

The data used consisted of annual and monthly EUD precipitation compiled by the Great Lakes Environmental Research Laboratory (GLERL). Additional data from 41 meteorological stations dispersed throughout the basin were used to compile maps of various distributions relating to precipitation. Analysis for primary and secondary trends by regression analysis as well as for cycles and patterns by autocorrelation. In addition multiple regression was used in determining the relative strength of five determinant factors.

The following results were produced by the research: (i) the presence of Lake Superior and the location of the basin in the mid-latitude westerly wind belt combine to create a significant increasing west to east trend in annual precipitation; (ii) the average monthly lake surface temperature has a significant influence (42%) on amount of monthly precipitation. For each degree increase in water temperature, precipitation is expected to increase 3.81 mm; (iii) longitudinal location is the most important factor on explaining the distribution of annual precipitation; (iv) for the century annual precipitation has increased at a significant 2.14 mm/yr. (v) Contained in the general increase were three periods

exhibiting a decrease ranging between 7.57 mm/yr and 31.03 mm/yr; (vi) while there are no cycles at periods up to 20 years, a pattern exists indicating that the time between a peak positive departure and a negative one is 14 years; (vii) only recently, from 1960, has there been a tendency towards greater annual variability in which there has been large changes in precipitation between successive years; (viii) there exists a cycle indicating that differences between successive annual precipitation amounts occur every 15 years. There is a significant pattern having a period of 6 to 7 years separating precipitation that shows large changes from year to year with below average change and (ix) the monthly data was successfully classified into a two season (surplus/deficit) year. Both the deficit and surplus seasons show an increase in precipitation at 1.34 mm and 0.801 mm, respectively.

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After three years of work the task at hand is finally finished. This thesis would not exist nor mean as much if it were not for a number of people providing academic as well as financial assistance. Therefore, I would like to acknowledge those persons who deserve recognition. First and foremost I would like to acknowledge my parents and family, for their love and understanding. In addition, I would like to thank those in the Department of Geography for accepting me into their graduate program, and for providing the assistance that made this thesis possible. My supervisor, Dr. Lawrence C. Nkemdirim deserves much credit for putting up with me, providing the needed assistance and guiding me through my research. Much appreciation is passed along to my examining committee of Dr. Art Limbird and Dr. Ivan Muzik for being fair and objective. I would like to thank Drs. Charlie Matsch and Matti Kaups from the University of Minnesota, Duluth campus, for their recommendation on a graduate program.

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Thanks to the people on those very educational field trips down to Whitefish. I have left my legacy with the softball team who had better repeat this year or else Capt. Jim will be back. The people involved with the Palliser Club, especially RJ, Tim, Joel and Jake, who made my two years as the NVGR very interesting to say the least. At last, no more doughnut sales. Thanks to Cathy of the Grad Lounge for making it a place which proves it is not the quantity of beer consumed that is important but the quality of time spent.

In the end, I would like to thank myself for not giving up when numerous opportunities presented themselves. Hopefully, I am better for sticking with it. A closing thanks to all the people I have met in my time in Calgary. I thoroughly enjoyed the experience of the Olympics, skiing, the mountains and all the social activities that were not necessarily at the graduate student level. I will miss this city as well as all the people that I have met. I wish I could stay, but being from across the border I'd best get home and get a real job.

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CHAPTER 1

INTRODUCTION

1.1 Research Goals

The goal of this thesis is to research the characteristics of annual and seasonal precipitation during this century in the Lake Superior Basin. In doing so, the following objectives were set for investigation:

i. Explain the distribution of average annual precipitation in the Lake Superior Basin.

ii. An examination of the physical controls which may influence the distribution and nature of annual precipitation.

iii. An analysis for possible trends and their significance in the annual basin precipitation for the the period 1900-1980.

iv. Determine the length and significance of any cyclic patterns found in annual basin precipitation.

v. Examine the degree of variability exhibited by the basin precipitation and any patterns associated with annual change.

vi. Investigate the seasonal characteristics shown by basin precipitation in a two season (surplus/deficit) year.

The thesis research is a beginning towards a final goal of understanding to what degree the water level of Lake Superior may be influenced by variations in basin precipitation. By first understanding precipitation patterns more knowledge will be available for use in determining the extent of a possible relationship between the amount of precipitation falling within the watershed and change in the water level of Lake Superior. The annual water supply for Lake Superior results from precipitation falling within the drainage basin. Therefore, it is assumed a relationship would exist between basin precipitation and lake level. Without clearly understanding the precipitation characteristics first, any study dealing with influences on lake level change may be lacking an important subject area.

1.2 Relationship Between Precipitation and Lake Level

Change in the water level of Lake Superior is influenced by climatological and hydrological factors. The major factors are precipitation, evaporation, runoff, underground water flow, water diversions into the lake and natural outflow. The Great Lakes Basin Commission (GLBC) (1975) show how the factors are part of a general water balance equation (1.1) for Lake Superior :

$$S = P + R + U + D - E - O \tag{1.1}$$

where S = change in water supply,

P = precipitation on lake surface and basin,

R = runoff from the basin,

U = underground water flow,

D = water diversion into the lake,

E = evaporation from the lake

and O = natural outflow.

Of six factors contained in equation 1.1, the emphasis for the thesis research is placed on precipitation falling over the land. The International Joint Commission (IJC) (1976) has determined the level of Lake Superior is dependent upon the balance between total water supplied, with precipitation being the source, and evaporation, the lost. This dependency allows for a general discussion on the influence precipitation has on lake level.

During approximately the last twenty years there has been a noticed change in the annual precipitation depth for the Great Lakes region. Hartmann and Croley II (1987) suggest the change in annual precipitation amounts may have been the result of a distinct change in the climatology of the region starting around 1970 to a relatively wetter, cooler climate. In this period, the volume of water in the Great Lakes increased due to greater precipitation and accompanying runoff combined with lower evaporation rates. Being part of the Great Lakes system, the Lake Superior Basin should also show similar changes in precipitation corresponding to changes experienced in the Great Lakes Basin. Throughout the century there has been variations in average annual precipitation which were accompanied by changes in the lake level of Lake Superior. In periods of below normal precipitation, lower than average lake levels soon followed, while during periods that are wetter than average, above normal lake levels would occur. Hartmann (1987) has attributed the recent above normal and record lake levels to the persistent greater than average precipitation since about 1970. The annual water level of Lake Superior during this century are shown in Figure 1.1.

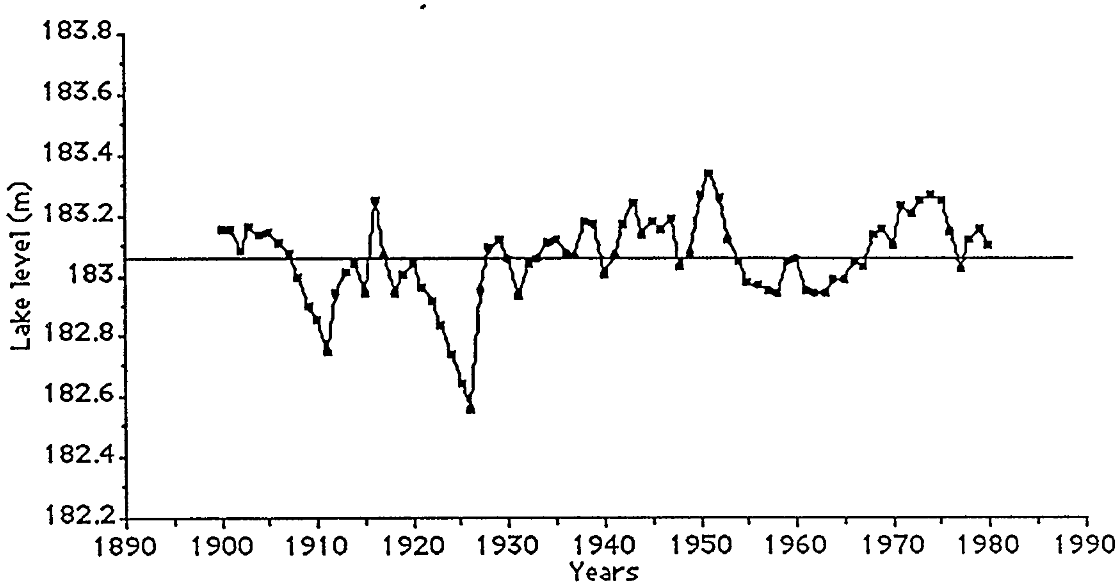


Figure 1.1 Water levels of Lake Superior, 1900-1980

In response to lower than normal precipitation the average annual water levels of Lake Superior from 1923 to 1926 ranged from 182.88 m to 182.57 m and were at or below the datum level (182.88 m). The datum level, as defined by the IJC (1976), is referenced to the lowest water level acceptable for maintaining hydroelectric generation and water borne commerce. The U. S. Army Corps of Engineers (1985) calculated the average water level for Lake Superior at 183.06 m. In a ten year period from 1955 to 1965, the lake level was below average 9 out of the 10 years. The highest lake level was 183.06 m (1960) with the lowest being 182.94 m (1963). Five of the lowest lake levels had an average water level of 182.95 m. The annual precipitation during this period was below normal when compared to surrounding periods. On the opposite side of the spectrum, periods of greater than average precipitation during the early 1950's and 1970's also had a distinct influence upon the lake level. From 1950 to 1955 four out of five years the lake level was above average with a high of 183.34 m in 1951. The precipitation in the 1970's had a slightly greater impact with all five year levels above average with four greater than 183.18 m.

These events illustrate the association between precipitation and lake levels at least in times of sustained periods of above or below average precipitation. For transition periods the relationship may not be as clear. Before any relationship can be established there should first be a complete understanding of precipitation characteristics in the Lake Superior Basin. A general showing of the effect precipitation has on lake level without showing the exact degree of influence allows for a way of indicating that, for at least one component, change in precipitation amount can affect the water level of Lake Superior. Personal awareness of lake levels throughout this century, in conjunction with the general relationship between the water level of Lake Superior and the amount of precipitation falling on the watershed, proved useful in investigating the precipitation patterns of the Lake Superior Basin.

1.3 Recent Research

Regarding scientific research in the Lake Superior Basin Munawar (1978) states that since the first scientific expedition carried out by Louis Agassiz 140 years ago during 1848, that detailed various disciplines of limnology, there has been relatively little scientific interpretations concerning Lake Superior as well as the climatological and hydrological characteristics of the basin. While the other Great Lakes have been analyzed more thoroughly, Lake Superior often has been looked at on a broader Great Lakes scale and not so much on an individual basis with few exceptions.

Bennet (1978) researched the water budgets for Lake Superior and Whitefish Bay and the factors controlling their nature. Whereas precipitation falling directly on the lake accounts for 51% of water input with the remainder (49%) coming primarily from surface runoff. Water derived from other sources contributes negligible amounts. Any significant change in precipitation amounts may have substantial impact on the hydrologic and climatological environments of the Lake Superior Basin. Precipitation change and characteristics may be related to the presence of Lake Superior. Phillips (1978) determined that the presence of Lake Superior with a large surface area and great depth is by far the most important local climatic control in the basin.

In four years of searching, research has yet to be found regarding characteristics of precipitation in the Lake Superior Basin. However, meteorological research has been carried out on other Great Lakes. Changnon (1966 and 1968) investigated the effects of Lake Michigan on intensity and frequency of thunderstorms and overall precipitation climatology and determined that degree of influence changes with season and time of day. Whereas thunderstorm activity was suppressed by 20% in summer, with activity increasing 50% during the fall as the lake surface temperature approached and surpassed that of the air. Blust and DeCooke (1960 and 1962) studied precipitation relationships between land and island based stations in and around Lake Michigan. They found the amount falling on land during the warm season was 9% greater than over the lake and 8% less in the cold season. Powers (1962) found that average annual precipitation is about 10% greater on highland areas, above and distant from the lake surface, than over the lowlands.

With the recent, 1980 to present, highly variable Great Lakes water levels from record setting high levels in 1985 that were greater than 183.45 m, to the lowest levels seen in many years during 1988, below 182.88 m, there has been a rebirth of research pertaining to the hydraulics and climatology of the lakes and the factors that may be of influence. The IJC has set up a task force to study lake level fluctuations. A background paper to the study plan for the Great Lakes Levels Reference Study has been completed. In addition, the IJC will be reviewing possible measures either to affect fluctuating lake levels or to modify the impacts of fluctuating levels around the Great Lakes. Hartmann (1983 and 1984) and Croley II (1982, 1983 and 1984) in association with the Great Lakes Environmental Research Laboratory (GLERL) have developed an accurate model of weekly runoff volumes from the Lake Superior drainage basin. Application of the model has shown good to excellent correlation (0.89 to 0.94) with available flow data where flows are unregulated.

With the severe summer drought of 1988 that plagued much of Canada and the United States, it has been suggested by Congressmen in the United States to divert water from the Great Lakes (Lake Michigan) to provide adequate water discharge on the Mississippi River to maintain water borne commerce. Botts and Krushelnicki (1987) give evidence suggesting the idea to divert water from the Great Lakes is quite common. The U. S. Army Corps of Engineers under the direction of the U. S. Congress studied the possibility of diverting water from the Great Lakes via the Mississippi and Missouri Rivers to compensate for rapid depletion of groundwater from the Ogallala aquifer. Other proposals suggested that water be sold and transported by pipeline or canal to the economically thriving, but dry, American Southwest. Though all such plans have failed to materialize, the idea lingers on to divert water out of the Great Lakes Basin.

It may be natural for residents of dry regions to look upon the Great Lakes to furnish them with an adequate supply of water. Not enough information is presently known about the factors influencing the water levels of the Great Lakes to allow large scale water diversions. There still is much to be learned about the Great Lakes region in general and the Lake Superior Basin in particular. With the research contained in this thesis it is hoped that one facet of the climatology of the Lake Superior Basin is no longer unknown.

1.4 Thesis Organization

The thesis is organized to give a historic background to the Lake Superior Basin while explaining the physical and climatological characteristics prior to the analysis of the precipitation data. The first chapter states the reasons behind undertaking the investigation and what objectives are to be met through the research. Chapter 2 covers the physical environment of the basin, how the Lake Superior Basin originated, the physical characteristics and influences it has on the climatology. The third chapter examines the precipitation station network and the differences between the Canadian and United States networks. The point of this chapter was to determine the adequacy of the network as well as the data derived from it. Consistency testing of the data as well as quality control for missing data was performed.

Chapters 4 through 6 contain the analysis on the precipitation. Chapter 4 is geared towards the investigation of precipitation distribution and the degree of influence exhibited by climatological factors. Through simple, multiple and step-wise regression the influence of primary factors was determined as well as the influence contributed by the surface temperature of Lake Superior. Chapter 5 contains the analysis of annual precipitation for the period 1900-1980. Of importance was the location and definition of trends and cycles in the precipitation data. In addition an investigation was performed to determine the variability exhibited by the data. Chapter 6 involves examining the seasonal characteristics of annual precipitation. A two season classification of surplus and deficit was calculated using a water budget method. From the classification analysis was conducted on each season for the occurrence of possible trends and cycles. Chapter 7 concludes the thesis with a discussion of the important findings and final summations. The bibliography with suggested readings follows chapter 7.

CHAPTER 2

THE LAKE SUPERIOR BASIN

2.1 Origin of the Lake Superior Basin

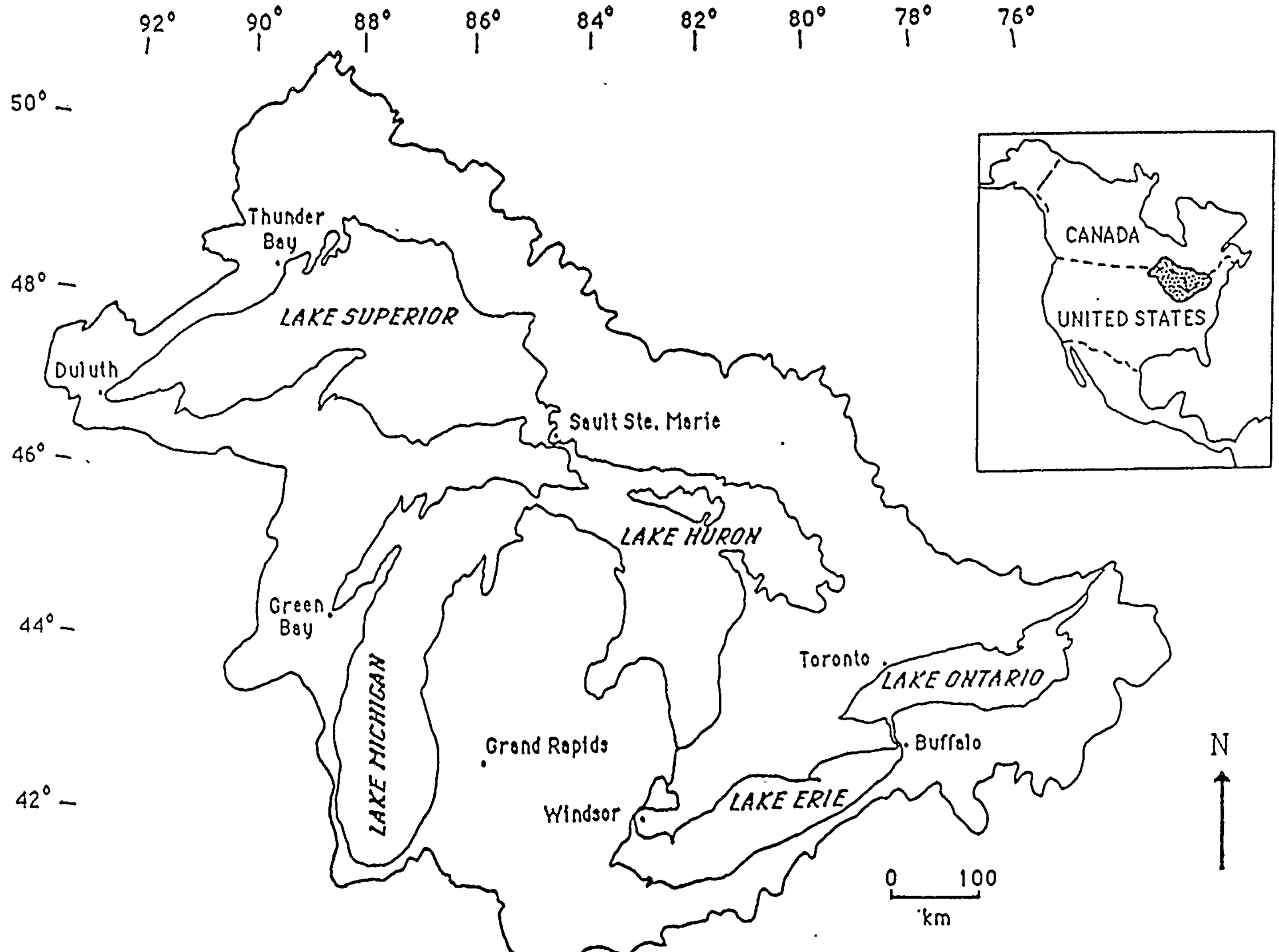
The Lake Superior Basin lies near the geologic transition border between the Precambrian Canadian Shield comprised of granitoid basic, volcanic and metamorphized sedimentary rocks and the Michigan Basin to the southeast containing younger sedimentary rocks of Cambrian to more recent periods. The shape of the lake follows the trend of a Late Precambrian mid-continental rift valley. A depression may have been produced from crustal subsidence after the cessation of volcanic extrusions. Within the depression an ancient drainage system may have existed providing an important prerequisite for the formation of the present day basin. Ojakangas and Matsch (1982) suggest the ancient valley and associated drainage system may have provided an avenue for at least four glacial advances (Nebraskan, Kansan, Illinoian and Wisconsin) from the Laurentide Ice Sheet during the Pleistocene epoch. The subsequent glacial erosion deepened the pre-Lake Superior drainage depression to formed the present lake basin.

Natural outflow through the eastern end came into existence after the last glacier lobe vacated the Lake Superior Basin. The Geologic Survey of Canada (GSC) (1987) shows this to occur between 8,000 and 9,000 years ago. Matheson and Munawar (1978) have determined the outlet sill at Sault Ste. Marie came into existence roughly 2000 years ago to established the present drainage channel out of Lake Superior. There was an approximate 7000 year span from the last glacial retreat out of the basin (9,000 years ago) until the existence of the present St. Mary's River outlet. Prior to the final establishment of the present Lake Superior there existed a number of glacial lakes above and below the present lake level. Of note was Glacial Lake Duluth (11,000 y.a.) which occupied primarily the western half of the basin at elevations between 323 and 335 m. Evidence for the lake consists of lacustrine deposits and wave cut terraces found in western portion of the lake basin. Other glacial lakes include Lake Minong (9,000 y.a.), Lake Houghton (8,400 y.a.) and Lake Houghton-Nippissing (8,000 y.a.) (GSC, 1987).

2.2 Regional Setting

Phillips and McColloch (1972) place the Lake Superior Basin in the center of regional air mass convergence of diverse air masses originating over the Arctic, Pacific and Atlantic Oceans, western North America and the Gulf of Mexico. As a result of air mass convergence, cyclonic storm cells develop within the region along the boundary between the different air masses. Trewartha and Horn, (1980) found storms which originate to the west pass through the region along commonly traveled storm tracks. Two common storm tracks include the 'Alberta Clipper' track running from western Canada southeast across the Great Lakes. The second storm track transports the 'Colorado Low' northeast from the east slopes of the Rocky Mountains into the Great Lakes region.

The Lake Superior Basin is situated between 46 and 51 degrees north latitude and 83 and 94 degrees west longitude, near the geographical center of North America (Fig. 2.1). Matheson and Munawar (1978) determined the location of the basin is in the zone of mid-latitude westerly winds. According to Phillips (1978) the northwest to southwest winds have an annual frequency of about 40% with average velocities between 8 to 15 ms^{-1} with velocities greater during the spring and fall and lower in the summer. The upper level westerlies for the most part control the intrusion into the basin of air masses with different characteristics.



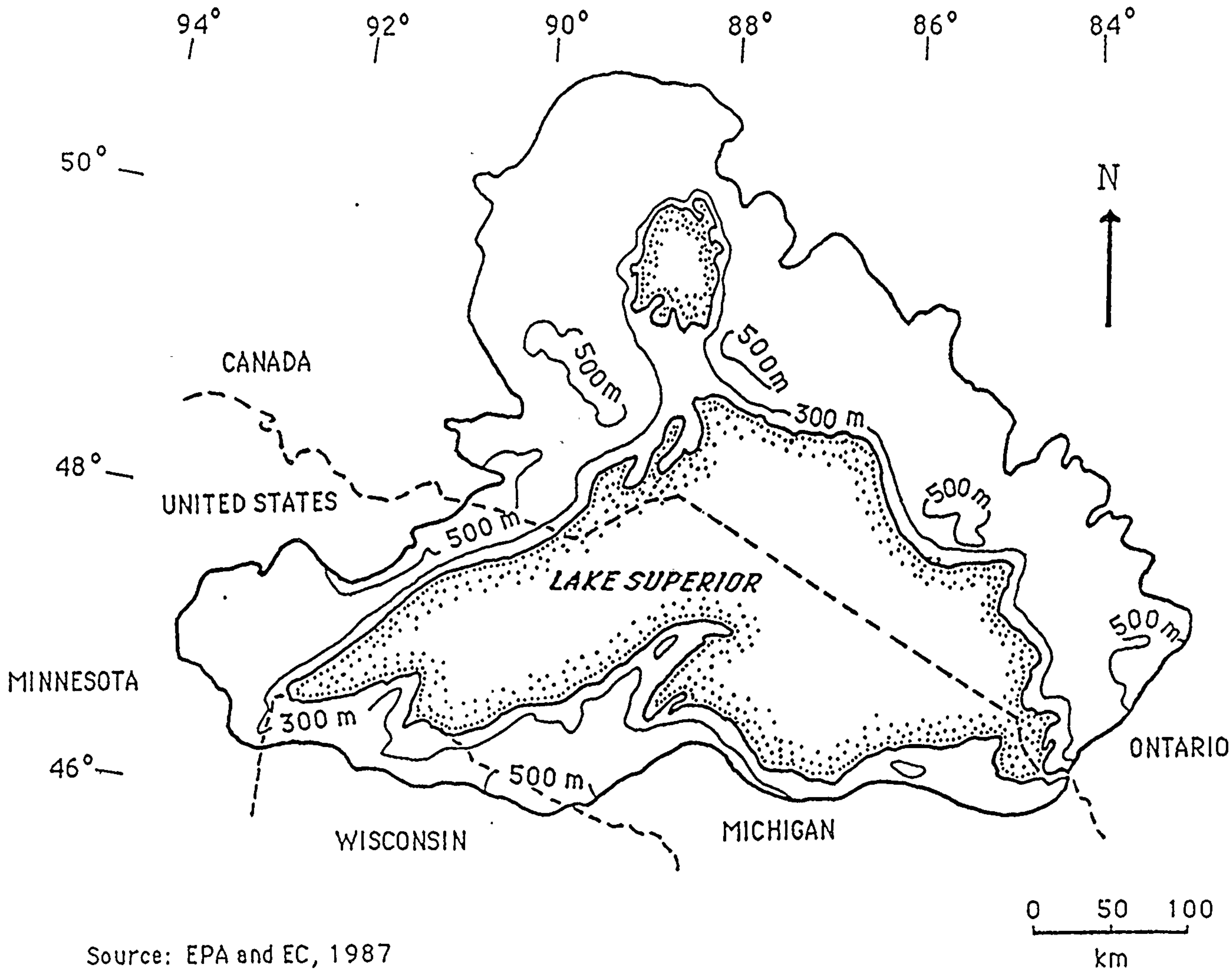
Source: Phillips and McColluch, 1972

Figure 2.1 Location of the Lake Superior Basin

2.3 Physical Characteristics

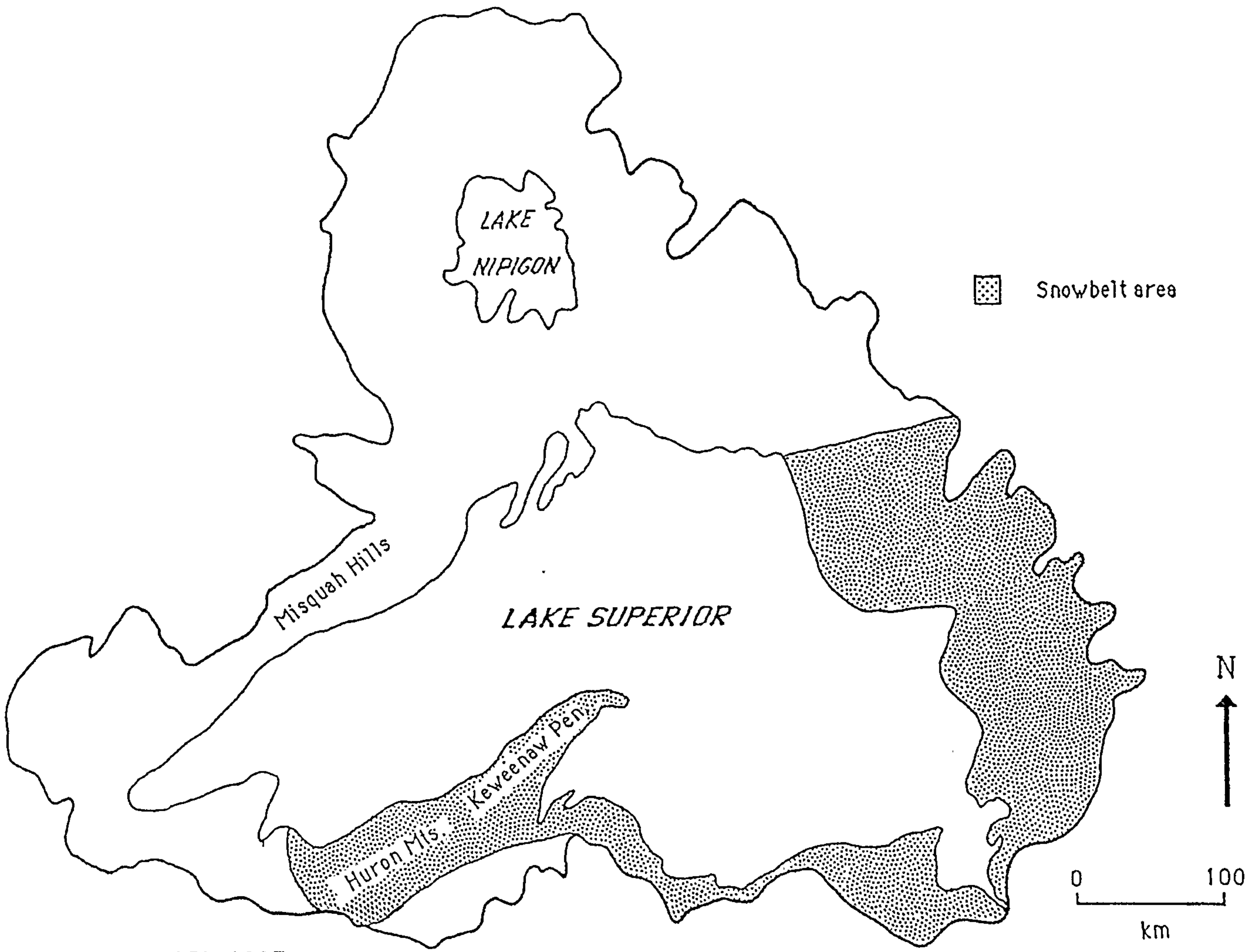
As part of the largest freshwater system in the world, the Great Lakes, Lake Superior has the greatest surface area of the lake system as well as any other freshwater lake. A surface area of 82,100 km^2 combined with a mean depth of 149.0 m gives Lake Superior an average volume of 12,230 km^3. The water volume represents approximately 53% of the water contained in the entire Great Lakes system and approximately one-tenth of the readily accessible fresh water in the world. Lake Superior is by far the largest, deepest and coldest of the five Great Lakes.

The topography contained in the Lake Superior Basin is a direct result of the glacial advances and the establishment of a post-glacial drainage system. The land is characteristic of shield areas having little topographic variation. The existing relief of eroded hill and small mountain-like features can be attributed to remnants of ancient (Precambrian) volcanic and orogenic activity. The elevation increases from lake level, 182.88 m, to interior highlands at between 300 m and 500 m with specific points rising over 500 m (Fig. 2.2). Located in northeastern Minnesota, Eagle Mountain at 701 m is the highest point in the basin. Basin relief ranges up to 500 m, with the greatest occurring near Lake Superior and the least occurring in areas of glacial lake deposits in Minnesota, extreme northern Wisconsin and eastern Upper Michigan. Highlands in the northwest and south-central sections of the basin are remnants of the rift valley. Physical features from the ancient valley are the Misquah Hills in Minnesota and the Gogebic Range and Keweenaw Peninsula of northern Wisconsin and Upper Michigan (Fig. 2.3).



Source: EPA and EC, 1987

Figure 2.2 Topography of the Lake Superior Basin



Source: EPA and EC, 1987

Figure 2.3 Physical features of the Lake Superior Basin

Glacial activity during the Pleistocene epoch left a land surface comprised of erosional depressions which are filled with water and kettle lakes and swamps associated with terminal and ice stagnation moraines. Lake Superior covers nearly forty percent (39.13%) of the drainage basin. The entire water surface coverage in the basin is over 50%. Phillips (1978) has defined the amount of surface water occurring in the drainage basin, excluding Lake Superior, at approximately 11% or 14,000 km^2. The availability of moisture from these numerous water bodies may be an influential factor on the climatology of the basin, especially when combined with the presence of Lake Superior. Table 2.1 contains the descriptive statistics for the Lake Superior Basin.

Table 2.1 Lake Superior Basin statistics

Variable	Value
Lake Superior	82,100 km^2
Land Area	127,700 km^2
Total Area	209,800 km^2
Water volume	12,230 km^3
Average depth	149 m
Lake elevation	183.06 m
Length	
Land	700 km
Lake	560 km
Width	
Land	480 km
Lake	288 km

With the basin covering a relatively large latitudinal range, approximately five degrees, it is divided into two general climatic regimes, Boreal (sup-polar) in the north and Temperate in the south. Phillips (1978) concluded regional variations in temperature, precipitation, radiation, wind as well as the lakes physical nature result in a climate mosaic that makes generalizations about a homogeneous basin climate very difficult. One would expect to encounter a heterogeneous climate throughout the basin.

2.4 Basin Climatology

The influence Lake Superior can have on the climatology of the basin may be directly attributed to the heat energy the lake absorbs during the spring/summer and subsequently release during the fall/winter referred to as the annual heat income. Matheson and Munawar (1978) calculated for Lake Superior an annual heat income, from the time of the lake temperature minimum, usually in March, to the maximum temperature, commonly in September, amounting to 65,500 cal/cm^2. The spring income, on average, requires 35,500 cal/cm^2 to raise the mean lake temperature from 1.40°C to 3.82°C. In general, Assel (1978) determined, for a dimictic lake as Lake Superior, whose mean body temperature passes through the maximum density temperature for water (3.82°C) twice each year, the greater the depth, the greater the spring heat income will be, 54% of total in this case. The normal summer heat income of 30,000 cal/cm^2 is the amount required to raise the mean lake temperature from the temperature of maximum density to the average maximum value of 5.88°C.

The lake surface temperature may be considered a main component in the type of climate/weather that is experienced in any one portion of the basin. The amount of precipitation an area receives is dependent upon many individual variables with Lake Superior playing a potentially influential role on them.

The existence of the temperature difference between the land and over the water affects the stability of the air environment. Phillips (1978) found the average mixing depth can be 30% higher downwind during winter, with the opposite being true in summer. An atmospheric stability index has been developed by Phillips (1978) for the near lake surface environment with the stated numbers contained in Table 2.2 defining the difference between air-water temperature (^{o}C).

Table 2.2 Air stability index for Lake Superior

Class	Difference
Very stable	> +10.4
Stable	+3.5 to +10.4
Neutral	-3.4 to +3.4
Unstable	-3.5 to -10.4
Very unstable	< -10.4

The Lake Superior Basin experiences two distinctly different air circulation patterns throughout a year due to the establishment of high and low pressure areas. In response to the seasonal absorption and release of heat the lake region has the ability to assume the characteristics of a localized area of low pressure and that of an area of high pressure. The air environment over Lake Superior has the ability to assume the mechanics of a high pressure area during the spring and summer when the surface water temperature is less than the temperature over the land. The lake basin assumes the characteristics of a low pressure area during the late fall and winter when the lake surface temperature exceeds that of the land.

High evaporation is associated with unstable conditions found during winter when a large negative temperature difference exists between the water and air. This coincides with reduced seasonal precipitation, low runoff, decreasing outflow and large withdrawal of water from lake storage. The unstable atmosphere, moisture from evaporation and low pressure can contribute to the occurrence of precipitation. Summer, the low evaporation season, is associated with a stable atmosphere when a large positive temperature difference exists between the land and water. The season coincides with increased seasonal precipitation, high runoff, increasing outflow and high storage of water on the lake. A correlation exists between seasonal precipitation and air stability. Summer is classed as stable with high precipitation and winter unstable with low precipitation. However, in regions situated downwind from Lake Superior, precipitation may be relatively greater during the winter due to increased moisture in the atmosphere from evaporation. Precipitation may be less in summer as a result of the suppression of convective activity associated with the influence of the water temperature of Lake Superior.

2.4.1 Winter Circulation

During the winter, as the mean land temperature falls below the lake surface temperature, air subsidence over the land due to cooling temperatures is balanced by air rising over the warmer lake surface creating atmospheric instability. As a result a localized area of cyclonic activity is produced in the basin independent of synoptic controls. Assel (1984) states, "winter surface winds usually have a westerly component at the western end of the lake and an easterly component at the eastern end of the lake; this is in agreement with the general cyclonic circulation pattern along the lake perimeter". Phillips and McColloch (1972) found in periods of light winds the thermal contrast between the relatively warm lake waters and the cold air aloft, drives the circulation towards the lake from all sides. The requisite low velocity winds are normally associated with the presence of anticyclones which normally contain the coldest winter temperatures. The intensity of the air circulation pattern is dependant upon the ice cover and temperature difference between the land and water. It would follow that the circulation pattern would be stronger during the early winter months from November to January than the later months, between February and April, as a result from less ice cover and a warmer lake surface temperature.

2.4.2 Winter Precipitation

As storm systems enter the influence range of the Great Lakes, they tend to move more northeast. Once over the lakes, given minimal ice cover, intensification may result. As Trewartha and Horn (1980) state, "the open water acts as a large energy source contained within the center of a large and cold continent and as a consequence, wintertime cyclones passing over often intensify". The nature of low pressure systems is to draw air into their center allowing for incorporation of the large quantities of heat and moisture added to the atmosphere from evaporation. As a result a single storm center in Wisconsin would be able to draw directly upon the energy and moisture from the lakes Michigan and Huron in addition to Lake Superior. The degree of intensification would depend upon the position and original strength of the storm. The result may lead to an enhancement of storm snowfall. According to Trewartha and Horn (1980) after a cyclone leaves the basin, the low pressure cell tends to 'trough' back over the warmer lake resulting in extended periods of snowfall, especially lake effect, and clouds.

Two important storm systems that frequent the Lake Superior Basin originate in two different regions and have quite different weather associated with them. The 'Colorado Low' forms on the east side of the Rocky Mountains usually in Colorado. This type of storm brings the greatest amount of winter time precipitation to the Lake Superior Basin. Combining warm moist air from the Gulf of Mexico with cold dry air from northern Canada the storms bring some of the most violent weather found in the region. Observed snowfalls from this type of storm have exceeded 50 cm. The second storm, the 'Alberta Clipper' gets it namesake from the point of origin. The storms develop over the western Prairie Provinces of Canada. The storm travels southeast into the Great Lakes Region. Light snow, strong winds and very cold temperatures accompany the system. The storms seldom produce more than seven centimeters of snow, but with a high frequency of occurrence the precipitation amount accumulates. Once passed, the much colder air pulled down behind the storms sets the stage for the development of lake effect snow.

An important regional contribution to annual precipitation is lake effect snow. This phenomenon occurs when relatively colder, drier air following the passage of a cold front travels over the warmer lake surface it absorbs heat as well as moisture. The greater the distance travelled, the greater the modification. As modified air reaches landfall the air is forced to rise mechanically over the escarpment into the unmodified colder air aloft that can hold less moisture. As condensation continues precipitation can be produced in direct association with Lake Superior. Two distinct regions that experience lake effect snowfall include, Upper Michigan, which trends towards the east-northeast, and the eastern basin area surrounding Wawa, Ontario, having a west aspect (Fig. 2.3). Botts and Krushelnicki (1987) determined the two areas on average, annually receive 20 to 30% more frozen precipitation (water equivalent) than liquid precipitation. Their average snowfall ranges between 250 and 350 cm. So while overall basin precipitation is reduced during the winter, regions in the lake effect snow belt experience seasonally enhanced precipitation.

2.4.3 Summer Circulation

In the warm season, May - August, convective activity occurs as the land temperature exceeds that of the lake surface temperature. This is balanced out by air subsidence over the colder lake. The process produces a localized area of anticyclonic activity producing a clockwise circulation pattern of lake winds in a stable environment. In addition to localized high pressure, Trewartha and Horn (1980) found that during the summer, anticyclones tend to stagnate and intensify as they move into the Great Lakes region.

Evidence for localized subsidence are the prevailing onshore winds, separate from synoptic controls, during the summer months. The near lake environment is more greatly influenced by Lake Superior in partial response to the development of local circulation patterns than inland areas. Lyons (1970) has calculated that for the Great Lakes, half of all summer days have light off-lake winds with features characteristic of a lake breeze. The frequency of a night land breeze and lake breezes during the day is very similar in spring and summer. The presence of the south facing bluffs along the north shore allows for an enhancement of the radiant heating of the land. Together, the bluff feature and radiant energy contribute the prerequisite for establishing the circulation pattern.

Advected air from the southern regions enhances air stability through inversions. As the relatively warm moist air encounters the colder lake surface, lake breezes, fog, as well as low level advection inversions are usually the result. Phillips (1978) has determined that these mesoscale phenomena occur on the average about 60% of the time during the spring and into summer and are confined to the lower levels, under 150 m above the lake surface. The 150 m height limitation for the inversion depth may be related to the average height of the escarpment surrounding the lake making the Lake Superior Basin an effective catchment for the development of temperature inversions.

2.4.4 Summer Precipitation

Summer precipitation normally is associated with frontal activity. Cold fronts passing through the region can bring heavy rainfall of short duration. Warm front activity produces extended periods of drizzle to light rain. As observed a cold front would move south of Lake Superior before redeveloping as a warm front. Into early summer the advected warm air seldom displaces the relative cold dense air confined in the Lake Superior Basin. This results in extended periods of drizzle and light rain. The development of a quasi-stationary front, independent of the lake, running from the southwest to the northeast across the basin has produced some of the greatest rainfall experienced over a period. The pattern depends on the stagnation of the upper level circulation. The rainfall associated with it is similar to a cold front but of higher frequency.

It is common to experience thunderstorms three times in a 24 hour period depending on the frequency of disturbances travelling along the stationary front.

Through spring and into the summer the water temperature of Lake Superior contributes to a dampening of precipitation associated with convective storm activity. According to Phillips and McColloch (1972) the lake has the ability to suppress thunderstorm activity during the day, while, at times, enhancing frontal thunderstorms during the night. The influence of the lake changes through the season resulting from the warming of the surface water. When the water is near the temperature of maximum density, suppression of convective activity would be far greater than with the water temperature closer to the air temperature.

Regarding how the lake can influence convective type storms is a matter of the lake being able to reduce or eliminate the influx of warm, moist, unstable air needed to promote the storm events. As the storm crosses the basin boundary of influence it experiences a reduction in the input of warm, moist, unstable air due to the colder, more stable air, in the basin. From radar and site observation the end result may be the reduction in intensity or a splitting of one major cell into two minor cells to the north and south of the lake.

In the late summer, when the surface water temperature is approaching the seasonal maximum, convective type showers may occur especially along the south facing portion of the escarpment as the moist lake air is drawn into the area by the warming of the bluff face and resulting air convection. A phenomena found during late summer into early fall is lake effect showers. Similar to the lake effect snow process and distribution, only the precipitation is liquid. The occurrence usually accompanies the first cold outbreak of the season.

CHAPTER 3

LAKE SUPERIOR METEOROLOGICAL STATIONS

3.1 Precipitation Station Location

The 1980 U. S. Census indicated that there were 558,100 people residing on 43,418 km^2 of the U. S. basin for 6.62 persons/km^2. According to the 1981 Canadian Census, 180,440 people reside in the 84,282 km^2 Canadian portion of the basin. This results in a density of 2.14 persons/km^2. A total of 738,540 persons reside on the 128,000 km^2 of land area contained in the Lake Superior Basin. The resultant basin population density is a relatively low 5.78 persons/km^2. The density values could be construed as misleading by the fact that a near majority of residents in each country reside in two metropolitan areas. The Duluth/Superior metropolitan area is comprised of St. Louis County, Minnesota, and Douglas County, Wisconsin, contains nearly half of the total United States population and approximately 38% (280,000) of the entire basins population. Likewise, the area surrounding Thunder Bay, Ontario contains 76% (133,000) of the Canadian population.

Development of the Lake Superior Basin began in the mid to late 19th century. In response to the economic conditions promoted by the resource base many of the early settlements have continued on to become the main urban locations of the present. The station network in the Lake Superior basin is distributed in a way that reflects the population distribution. Generally, areas of higher population density tend to have a more dense network as opposed to areas of lower population density. Of 41 stations, 22 are located within five kilometers of the shoreline, an additional 10 stations are located about 30 km from the shoreline (Fig. 3.1). The precipitation station network covers 127,700 km^2 for a station density of 1 station for every 3114.63 km^2. Table 3.1 contains the general characteristics for the political divisions found in the Lake Superior Basin.

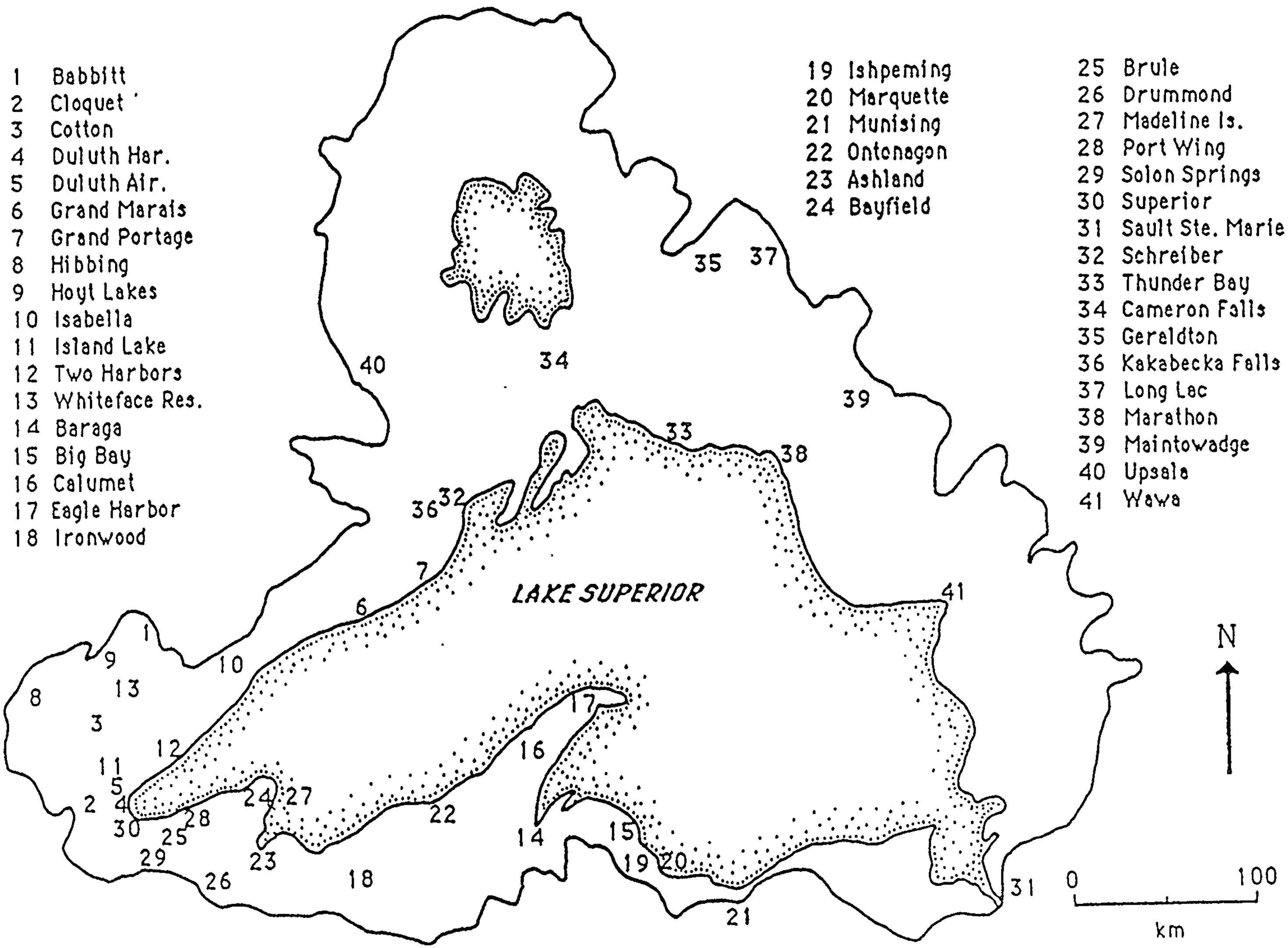


Figure 3.1 Location of precipitation stations

Table 3.1 State and province population and precipitation stations

State/Prov.	Population	Stations	Record (yrs.)	Area (km^2)
Michigan	204,945	8	496	18,705
Minnesota	262,182	13	542	17,176
Ontario	175,690	13	358	84,282
Wisconsin	95,715	9	335	7,537
Total	738,540	43	1731	127,700

3.1.1 Canadian Precipitation Station Network

The Ontario portion of the Lake Superior Basin shows a relatively sparse distribution of precipitation stations. Eleven land based stations are used to cover 84,282 km^2 resulting in an overall density of one station for 7662 km^2. It should be noted that two island stations, Caribou and Slate, were not included in the density calculation given their limited seven month season for recording data. The precipitation station density in Ontario is well under the recommended minimum density of 600 - 900 km^2 per station for precipitation networks in temperate zones, while within the required 1500 to 10,000 km^2 per station for polar climates as described by Linsley *et al.* (1982). A modified classification is needed due to the fact that it is in the transition belt between temperate and polar climates. Only the extreme southern portion of the Canadian part of the basin is classified within the temperate zone.

It should be noted that at the time of research there were a total of 24 operating meteorological stations in the Ontario portion of the basin. Due to the lack of complete data and short record length caused, in part, to the tendency for stations to pass quickly into and out of operation, only 13 stations with the most complete record were used for the research. In addition to the sparse nature of the station network, the records themselves were incomplete. The total complete record length of the 13 stations was 356 years for an average of 27.38 years of complete data years per station. An incomplete data year is defined as any year that cannot be summed or recorded due to errors in measurement or having periods when measurements were not performed.

Even though the station density may be less than desired for regional networks, it may or may not be a hindrance to an understanding of the climatology and hydrology of the Lake Superior Basin. Because of the relatively homogeneous nature to the land and Boreal/sub-polar climate classification, the precipitation station network may not be a significant hindrance. Croley II (1983) concluded that with the station coverage relatively sparse, it would appear likely that the addition of a few permanent stations in Ontario would improve hydrologic models used for Lake Superior. Figure 3.1 shows the lack of stations in the eastern and northern regions of the basin.

3.1.2 United States Precipitation Station Network

In comparison to the relative sparse Canadian network, the United States network is denser, with a longer record. The total number of complete data years for the 30 stations incorporated is 1375 years or 45.83 yrs per station which is 18.45 years greater than the Ontario portion. Within the 43,418 km^2 land area, the resultant coverage per station is 1447.27 km. The station density is still slightly below the recommended density of 600-900 km^2 per station. However, the U. S. station coverage is 6214.73 km^2 less per station when compared to the station density in Ontario.

The definition of a denser United States network, in itself, could be considered misleading. The stations do not appear to be evenly distributed within the basin, but tend to appear clustered in some areas while in other areas tend to be fairly distributed (Fig. 3.1). The result is an uneven coverage of the basin area in which land areas around Duluth/Superior and the Iron Range have dense station coverage. Specifically, on the Iron Range there are five stations (Hibbing, Babbitt, Hoyt Lakes, Cotton and Whiteface

Reservoir) within an approximate 30 km radius of one another. Contained in and surrounding the Duluth/Superior metropolitan area there is a total of nine precipitation stations (Duluth Harbor, Duluth Airport, Superior, Two Harbors, Island Lake, Cloquet, Brule, Solon Springs and Port Wing) that are no more than roughly 50 km from the metropolitan area.

The station coverage of the Lake Superior Basin would not appear to be improved on a permanent basis. The present data (U.S.) is collected by volunteers employed by the National Climatic Center to maintain and take readings from meteorological stations. The reliance on civilian volunteers results in the stations being located near settlements. Permanent recording stations outside settled areas would provide important additional data for future research. The adequacy of the present network is examined in the following section 3.2 and subsection 3.2.1.

3.2 Adequacy of Precipitation Station Location

The decision to use the 41 precipitation stations at this time was determined by the length of record, the location of the station with respect to proximity with other stations, their location within the basin and by record availability. Whether the chosen stations provide for a satisfactory determination of the climatology and hydrologic phenomena will be investigated. It may be determined that fewer stations would be required to provide adequate information. Or it may require the use of all 53 stations to provide the most satisfactory information regarding precipitation distribution.

A question raised by the distribution of stations relates to how well their distribution represents the mean condition over the basin in terms of precipitation depth. Whether the land type of the stations corresponds to the land type of the entire basin is also debatable. For example, 53% of the stations are located in built up (urban) areas while only a trace of the basin surface could be considered built up. In addition, the land area they cover is relatively close to Lake Superior. A dense coverage results around Lake Superior with nearly three-quarters (74.4%) of the stations located within 30 km of the lake.

Indicated by Table 3.2 the station locations may not be reflective of the physical characteristics contained in the basin land area. The precipitation amounts recorded in the built up areas may be influenced enough to be different than the depth falling on natural areas. Linsley *et al.* (1982) state urban activities can have an effect on local precipitation and climatology. The only way to determine the possible influence experienced in the Lake Superior Basin would be to research the problem. But until research is conducted the existing precipitation network has to be used for climatological studies requiring historical data.

Table 3.2 Surface cover comparison between precipitation station location and the land basin

Land Basin		Station Location	
Type	% Coverage	Type	% Coverage
Forest	79	Built Up	53
Water	11	Forest	38
Bog	10	Grass	6
Built Up	<1	Rock	3
Grass	<1		
Rock	<1		

Source: Phillips, 1978

To compensate for the potentially clustered station distribution and misrepresentation, the GLERL method described by Quinn and Kelley (1983) for basin precipitation uses a grid-square algorithm to determine representative areal weights for an individual station in a modified Thiesssen approach. The Thiessen method is designed to compensate for nonuniform distribution of precipitation gages. The assigned weighting number, is representative of the area covered by each station, the greater the areal coverage the higher the number. Station 41, Wawa, Ontario has the largest coverage area, hence the assigned weighting number of 9.8%. On the other hand, the stations around the Duluth/Superior metropolitan area have weightings around 1.0.

3.2.1 Assessment of Precipitation Station Network

In regard to the question of adequate coverage, the existing meteorologic station network was evaluated respecting the potential for predicting net basin supply to each of the Great Lakes. Only the quantity of and useful information gained from gages were considered for the assessment. To determine the goodness-of-fit, Croley II (1983 and 1984) and Hartmann (1984) use daily precipitation and air temperature values in the GLERL Large Basin Runoff Model to derive estimated runoff values. The estimated flows were compared to the recorded flows at 35 outflow stations. The goodness-of-fit was measured by the root mean squared error between model and actual weekly runoff volumes and by the explained variance of weekly runoff.

The test required 19 years of daily readings and consisted of two lengths of records that were considered for the data set. The data set ran 6940 days from 1 January 1960 through 31 December, 1978, in which the first 1260 days were used only for initialization of model boundary conditions and the remaining 5680 days were used for calibration and goodness-of-fit estimation.

Table 3.3 shows that the explained variance (r^2) for precipitation, given by the number of meteorological stations, peaks at 33 stations at 0.775. The addition of more stations slightly decreases r^2 by 0.1% (0.773 at 53 stations). The greatest explained variance occurs between 23 (0.771) and 53 stations (0.773). The error is nearly constant between 23 and 53 stations with only a 0.001 cm difference from 0.181 to 0.182. With less than 23 stations the error increases at a greater rate.

Table 3.3 Assessment of the coverage provided by the precipitation stations

Number of Stations	Root Mean Error^2 (cm)	Explained Variance
53	0.181	0.773
43	0.181	0.774
33	0.181	0.775
23	0.182	0.771
13	0.188	0.757
12	0.191	0.750

Source: Croley II and Hartmann, 1984

With the 41 land based precipitation stations, it may be assumed that no significant additional explained variance would be added through the incorporation of more stations nor would there be a significant loss of explanation with a reduced number of stations. The statement is dependant upon the fact that the test was based on 19 years of records from 1960 to 1978. No station records prior to 1960 would have been considered for the test. Given the test requirements, stations included in this study with records ending prior to 1960 were not included in nor available for the assessment. Using the results from the assessment, it would appear that the number of stations chosen for this research will provide an adequate coverage area for studying the precipitation characteristics of the Lake Superior Basin.

3.3 Data Quality

Before any accurate statements can be made concerning the hydrological and climatological phenomena that may occur within the Lake Superior Basin, the reliability of the data must be determined by testing it for consistency. The data from stations in the

United States goes through a quality control process before it is released. The control examines an individual value to see whether it is accurate according to weather that was experienced for the region on a given day or for an entire month. The value also is compared to values from surrounding stations that have been determined to have a higher reliability. With the data from the United States stations checked prior to release, only the Canadian stations were tested for consistency. The test for consistency as described by Linsley *et al.* (1982), is the double mass analysis test which compares one station's accumulated annual precipitation values with the accumulated annual average values for a group of neighboring stations.

Table 3.4 contains the meteorological stations tested for consistency in annual precipitation. The stations within each group are located within close proximity to one another with the exception of Group 3. Wawa and Sault Ste. Marie were tested individually by comparing the actual accumulated values to the accumulation of their means.

Table 3.4 Listing of meteorological stations tested for consistency

Group 1	Group 2	Group 3
Cameron Falls	Geraldton	Sault Ste. Marie
Kakabecka Falls	Long Lac	Wawa
Thunder Bay	Manitowadge	
Upsala	Schreiber	

In using the double mass analysis, if the stations cumulative values showed a distinct and significant break from the group cumulative values, then the data lacks consistency. If the break is significant, then a conversion factor is calculated by dividing the slope of the data determined to be inconsistent by the slope of the consistent data. The factor is then applied to the portion in the data set that created the break in consistency. Given that some stations are situated at a relatively great distance (more than 100 km) from each other, a sign of inconsistency may signal a change in precipitation tendency and not a problem in the reliability of the data.

3.3.1 Group 1 Consistency Testing

Group 1 gives an indication of the low density of the precipitation network in Ontario. The four stations in this group are as spread out as any other stations in the study. As a result of their sparse distribution, the stations show only a slight degree of consistency with the group score, but they show a higher degree of consistency with each other. The values for Kakabecka Falls and Thunder Bay are also consistent with one other (Fig. 3.2). In addition,the cumulative values for Cameron Falls and Upsala are consistent with each other (Fig. 3.3). The precipitation data from the station appears to be consistent without breaks from the expected accumulation. Therefore the data in this group will be used without modification

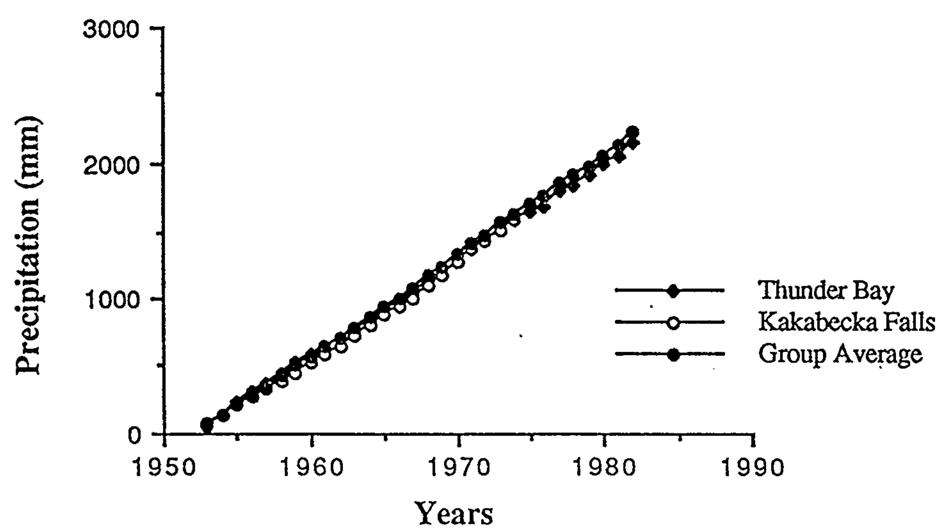


Figure 3.2 Group 1 consistency testing, south stations

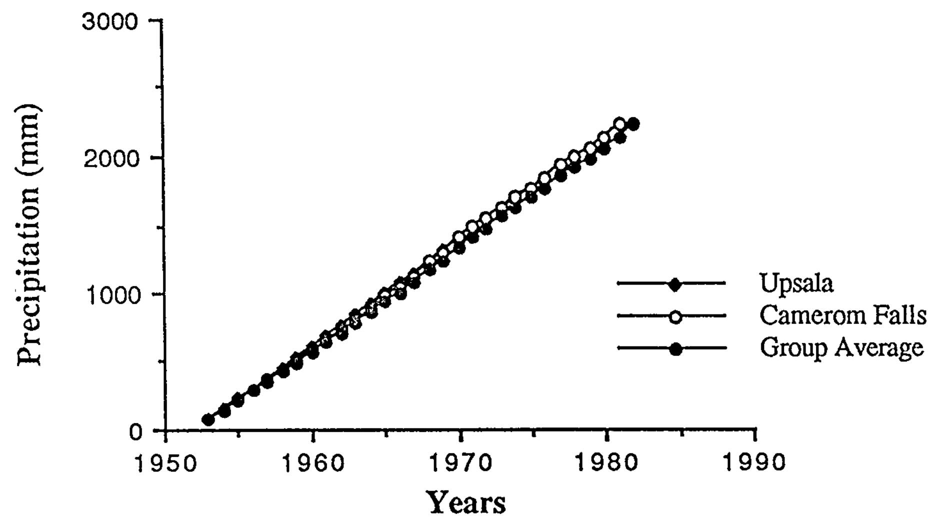


Figure 3.3 Group 1 consistency testing, north stations

3.3.2 Group 2 Consistency Testing

With the stations of Long Lac, Geraldton, Manitowadge, Marathon and Schreiber dispersed throughout the basin they were grouped to represent their distance from Lake Superior. Whereas Long Lac, Geraldton and Manitowadge are inland stations (Fig. 3.4) with Marathon and Schreiber shoreline stations (Fig. 3.5). Only one station exhibit inconsistency with the group cumulative average scores. Long Lac, Marathon, Manitowadge and Schreiber, show a degree of consistency with the group average score. Geraldton shows a slight deviation from the expected cumulative scores starting around 1970, indicating a decrease in the accumulation.

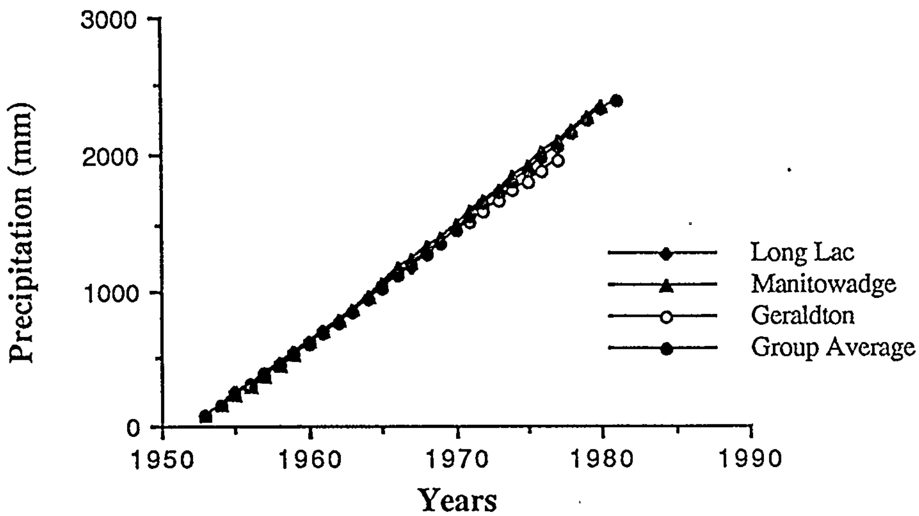


Figure 3.4 Group 2 consistency testing, inland stations

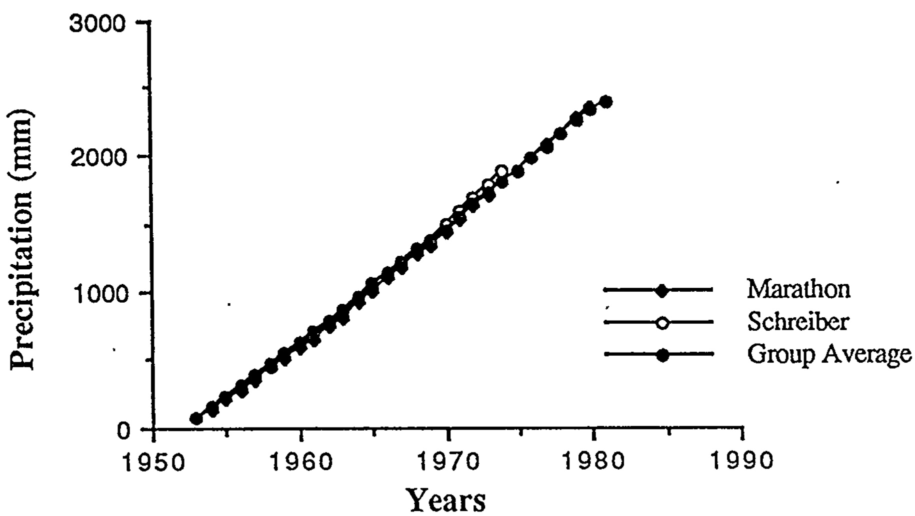


Figure 3.5 Group 2 consistency testing, shoreline stations

To determine whether the apparent break is of significance a Student's t - test was performed on the slope prior to 1970 and the slope after the break. The calculations for the test followed those described in Davis (1974). The resultant t-value 0.007 is less than the critical value of 1.714 at the 95% confidence level with 23 degrees of freedom indicating no significant difference exists between the two slopes Therefore the precipitation data for Geraldton is to be regarded as consistent.

3.3.3 Consistency testing for Wawa and Sault Ste. Marie

Figures 3.6 and 3.7 show that the accumulated precipitation values for Wawa and Sault Ste. Marie exhibit a similar pattern to the expected accumulation of their means. The precipitation for Wawa was individually tested due to the relatively recent (1968) development as a meteorological data collection station. In addition, Wawa is situated the farthest from neighboring stations as any other stations. Sault Ste. Marie was tested individually because of the distance between the nearest neighbor having similar record lengths. With no clear deviations from the expected accumulations the data for the two stations will be used without modification.

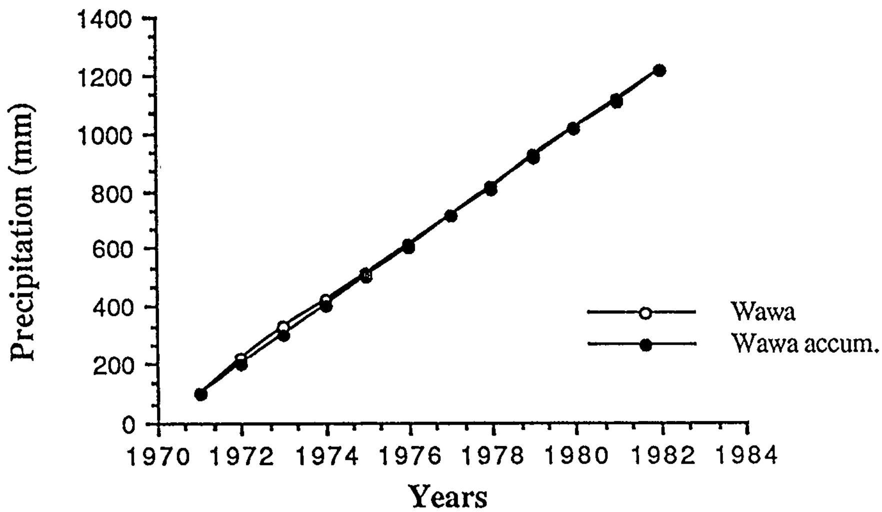


Figure 3.6 Group 3 consistency testing, Wawa

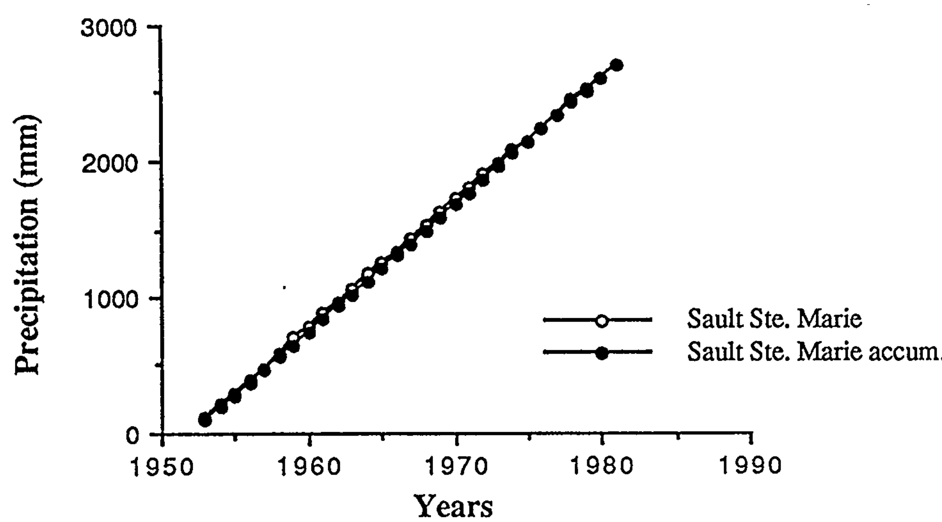


Figure 3.7 Group 3 consistency testing, Sault Ste. Marie

3.4 Quality Control for Missing Data

In the United States, volunteers are used to make the meteorological readings at meteorological stations. Given that the individuals are not professionally trained in meteorology nor is it their primary job, the occurrence of missing data usually arises from not passing quality control or when the volunteer reporter can not make readings for various reasons. Reasons for not reporting that were found on the meteorological sheets include vacations with no reader replacement, broken or no longer functioning instruments, bad weather and just a lack of continued interest in taking readings.

Station groupings according to location and climatological characteristics were used for reference when the calculation of missing precipitation values was needed. The process for determining missing precipitation values followed the guidelines set by the U. S. Environmental Data Service in the normal-ratio method. The amounts for the index stations are weighted by their ratios between normal annual precipitation and the value for the period missing. As defined by Linsley *et al.* (1982) the normal-ratio equation is

$$P_X = \frac{(Nx/Na)Pa + (Nx/Nb)Pb + (Nx/Nc)Pc}{3} \qquad (3.1)$$

where P_X is the missing value for the station in question, P defines the precipitation experienced for the missing time period at stations a, b, and c with N representing the normal annual precipitation for all four stations. Slightly more than 9% (162 years) of the total 1731 data years were defined as missing and needed replacements calculated. Table 3.4 classifies the stations by the percentage of their precipitation record missing. The values in parentheses gives the missing data percentage for an individual station. Table 3.5 contains the specific statistical information for each station including the record period of precipitation data, average annual precipitation (mm), elevation above sea level (m), longitude and latitude coordinates, average annual temperature (^{o}C), straight-line distance from Lake Superior, percent of effect the surface water temperature of Lake Superior, standard deviation of annual precipitation (mm) and the amount of variation (%).

Table 3.5 Percentage of missing data record per station

Over 20%	11 to 20%	1 to 10%	Less than 1%
Big Bay (53)	Bayfield (18)	Munising (10)	Baraga (0)
Port Wing (40)	Cotton (18)	Two Harbors (10)	Calumet (0)
Isabella (35)	Kakabecka Falls (18)	Solon Springs (9)	Drummond (0)
Grand Portage (30)	Upsala (17)	Marquette (7)	Duluth Air.(0)
Marathon (25)	Eagle Harbor (15)	Ashland (6)	Hoyt Lakes (0)
Geraldton (25)	Sault Ste Marie (14)	Babbitt (6)	Island Lake (0)
Schreiber (24)	Superior (13)	Hibbing (5)	Manitowadge (0)
Cameron Falls (22)	Madeline Is.(13)	Cloquet (2)	Thunder Bay (0)
	Brule (12)	Ishpeming (2)	Wawa (0)
	Long Lac (12)	Duluth Har.(1)	Whiteface Res.(0)
	Ontonagon (11)	Ironwood (1)	
	Grand Marais (11)		

Table 3.6 Listing of meteorological stations with statistics

Meteorological Stations	Record Period	Average Annual Precip. (mm)	Elevation (m)	Longitude	Latitude	Average Annual Temp.
Babbitt	1939-1984	702.31	492	91.55	47.41	3.7
Cloquet	1912-1984	758.19	386	92.31	46.42	4.0
Cotton	1969-1984	686.56	418	92.25	47.11	3.9
Duluth Harbor	1900-1984	696.72	186	92.11	46.50	3.6
Duluth Airport	1961-1984	766.06	432	92.05	46.46	3.8
Grand Marais	1924-1984	678.18	209	90.17	47.45	3.7
Grand Portage	1959-1984	795.78	198	89.44	47.55	3.6
Hibbing	1960-1984	774.19	483	92.56	47.24	3.8
Hoyt Lakes	1959-1984	711.45	471	92.08	47.30	3.7
Isabella	1953-1084	762.25	436	91.22	47.42	3.6
Island Lake	1960-1984	728.73	410	92.06	46.93	3.8
Two Harbors	1895-1984	723.90	190	91.41	47.01	4.4
Whiteface Res.	1960-1984	693.17	455	92.11	47.17	3.9
Baraga	1896-1984	845.57	212	88.30	46.48	5.5
Big Bay	1966-1984	764.29	187	87.52	46.53	5.4
Calumet	1895-1950	874.78	430	88.28	47.30	5.6
Eagle Harbor	1924-1969	898.40	298	88.06	47.25	5.5
Ironwood	1902-1984	885.95	466	90.06	46.27	4.7
Ishpeming	1900-1984	810.00	434	87.39	46.29	5.0
Marquette	1914-1984	804.42	224	87.34	46.32	5.4
Munising	1912-1984	848.36	192	86.40	46.24	5.3
Ontonagon	1939-1984	800.01	199	89.18	46.53	5.2
Ashland	1914-1984	783.08	198	90.58	46.35	4.8
Bayfield	1940-1984	786.13	216	90.50	46.48	4.4
Brule	1950-1984	808.74	303	91.35	46.32	5.2
Drummond	1963-1972	837.18	422	91.15	46.20	5.3
Madeline Is.	1945-1984	757.43	188	90.38	46.50	4.2
Port Wing	1955-1984	774.95	220	91.22	46.45	4.4
Solon Springs	1915-1984	800.10	330	91.49	46.31	5.3
Superior	1914-1984	738.38	203	91.60	46.40	4.3
Sault Ste. Marie	1954-1982	927.61	192	84.30	46.29	4.2
Schreiber	1910-1975	860.20	302	89.19	48.22	1.2
Thunder Bay	1942-1982	786.13	302	87.16	48.22	2.3
Cameron Falls	1956-1982	797.56	229	88.21	49.09	1.7
Geraldton	1954-1981	730.50	331	86.57	49.42	0.0
Kakabecka Falls	1953-1974	712.72	278	89.24	48.24	2.0
Long Lac	1953-1968	801.12	343	86.32	49.45	-0.1
Marathon	1953-1982	847.34	189	86.22	48.45	1.9
Manitowadge	1960-1982	861.70	332	85.48	49.09	1.1
Upsala	1953-1976	798.20	484	90.31	49.46	1.2
Wawa	1971-1982	1014.22	430	84.47	48.04	2.3

Table 3.6 continued

Meteorological Stations	Distance from Lake (km)	% of Temperature Effect	Standard Deviation	Coefficient of Variation
Babbitt	65.0	43.2	122.02	17.37
Cloquet	28.0	29.9	121.24	15.99
Cotton	52.0	34.5	101.07	14.72
Duluth Harbor	01.0	33.7	119.64	17.17
Duluth Airport	08.0	33.7	137.10	17.89
Grand Marais	01.0	36.3	137.58	20.29
Grand Portage	01.0	38.2	136.34	17.13
Hibbing	97.0	33.3	121.66	15.71
Hoyt Lakes	65.0	34.3	128.46	18.06
Isabella	30.0	29.7	137.80	18.08
Island Lake	25.0	38.3	124.49	17.08
Two Harbors	01.0	34.3	132.01	18.23
Whiteface Res.	45.0	34.5	131.00	18.90
Baraga	01.0	46.7	141.01	16.68
Big Bay	01.0	42.1	146.12	19.12
Calumet	02.0	38.0	156.48	17.89
Eagle Harbor	01.0	59.2	143.89	16.02
Ironwood	22.0	40.5	119.46	13.48
Ishpeming	22.0	41.9	130.59	16.12
Marquette	02.0	14.8	111.28	13.83
Munising	01.0	53.9	157.89	18.61
Ontonagon	01.0	37.9	123.33	15.42
Ashland	01.0	36.9	116.68	14.90
Bayfield	01.0	23.4	167.02	21.35
Brule	23.0	27.5	148.17	18.32
Drummond	38.0	33.5	145.03	17.32
Madeline Is.	01.0	26.2	124.38	16.42
Port Wing	01.0	25.2	132.73	17.13
Solon Springs	42.0	33.5	148.70	18.59
Superior	05.0	30.9	146.24	19.81
Sault Ste. Marie	01.0	51.7	127.98	13.80
Schreiber	05.0	61.4	142.25	16.54
Thunder Bay	05.0	49.7	158.92	20.26
Cameron Falls	29.0	71.9	143.26	17.96
Geraldton	80.0	48.7	098.01	13.42
Kakabecka Falls	25.0	64.3	106.84	13.34
Long Lac	135.0	53.5	136.44	19.14
Marathon	01.0	66.8	091.35	10.78
Manitowadge	63.0	71.7	136.95	15.89
Upsala	119.0	41.2	125.85	15.77
Wawa	10.0	77.6	102.46	10.08

CHAPTER 4

LAKE SUPERIOR BASIN PRECIPITATION CHARACTERISTICS

4.1 Distributions Showing Precipitation Characteristics

The purpose of this chapter is to examine the characteristics of and influences on annual precipitation in the Lake Superior Basin. General explanations will be given for the areal distribution patterns of annual average precipitation, standard deviation, coefficient of variation and the amount of influence on precipitation provided by Lake Superior. From the discussion, factors providing controls on the distributions will be determined and quantified. The maps showing the distributions were generated using values found in Table 3.5 and the Surface II computer graphics package developed by Sampson (1974).

4.1.1 Distribution of Average Annual Precipitation

Figure 4.1 shows the distribution of average annual precipitation (mm) for the Lake Superior Basin. The average annual precipitation values from 41 land based meteorological stations were used to derive the isohyets. The influence of westerly winds as well as snow belt areas can be inferred from the spatial distribution of average annual precipitation. The downwind regions of Michigan and Ontario have greater precipitation than areas upwind. The isohyets generally follow the shape of the lake with a southwest to northeast trend. The precipitation increases from less than 700 mm in northern Minnesota to over 900 mm in Ontario.

The impact snow belt regions have on the distribution of annual precipitation is indicated by an increase in isohyet value. The Michigan region has two areas of average annual precipitation in excess of 875 mm separated by an area with less than 825 mm. The southeastern basin area has the greatest amount of annual precipitation with annual depths exceeding 975 mm. The annual precipitation amount for the area is increased by greater winter precipitation than regions outside of the snow belt. With less than 800 mm per year, the area situated around Big Bay, Michigan, may receive less precipitation from being situated on the drier leeward side of the Keweenaw Peninsula than other neighboring stations. The regional topography may play an important role in the localized precipitation amounts experienced in Upper Michigan. By comparing a similar geologic and topographic feature in northeastern Minnesota, the Misquah Hills, an indication of the combined influence topography and westerly winds have on the distribution of annual precipitation is possible.

The Misquah Hills in Minnesota are physically similar to the southern escarpment, yet the climatology during winter can be distinctly different. Northern Upper Michigan has an average annual precipitation greater than 800 mm (876 mm) while the north shore receives on average less than 775 mm. The Minnesota region averages around 25 mm of precipitation for each winter month while the snow belt areas may receive over 50 mm. A main reason for the difference is the fact that the Michigan region lies in a lake effect snow belt area. The greater winter precipitation contributes to greater annual precipitation, hence the higher isohyet values.

4.1.2 Distribution of Standard Deviation

Figure 4.2 shows the distribution of the standard deviation values. The map generation process used the standard deviation in average annual precipitation for each meteorological station. The purpose is to give some idea of the degree of variability in annual precipitation. The standard deviation decreases from greater than 145 mm over Lake Superior to less than 110 mm in the far west. This may provide evidence that Lake Superior contributes to the variability found in precipitation from year to year. The distribution shows variability in precipitation decreases with increased distance from the lake. Areas adjacent to the shoreline of Lake Superior generally have standard deviations exceeding 130 mm.

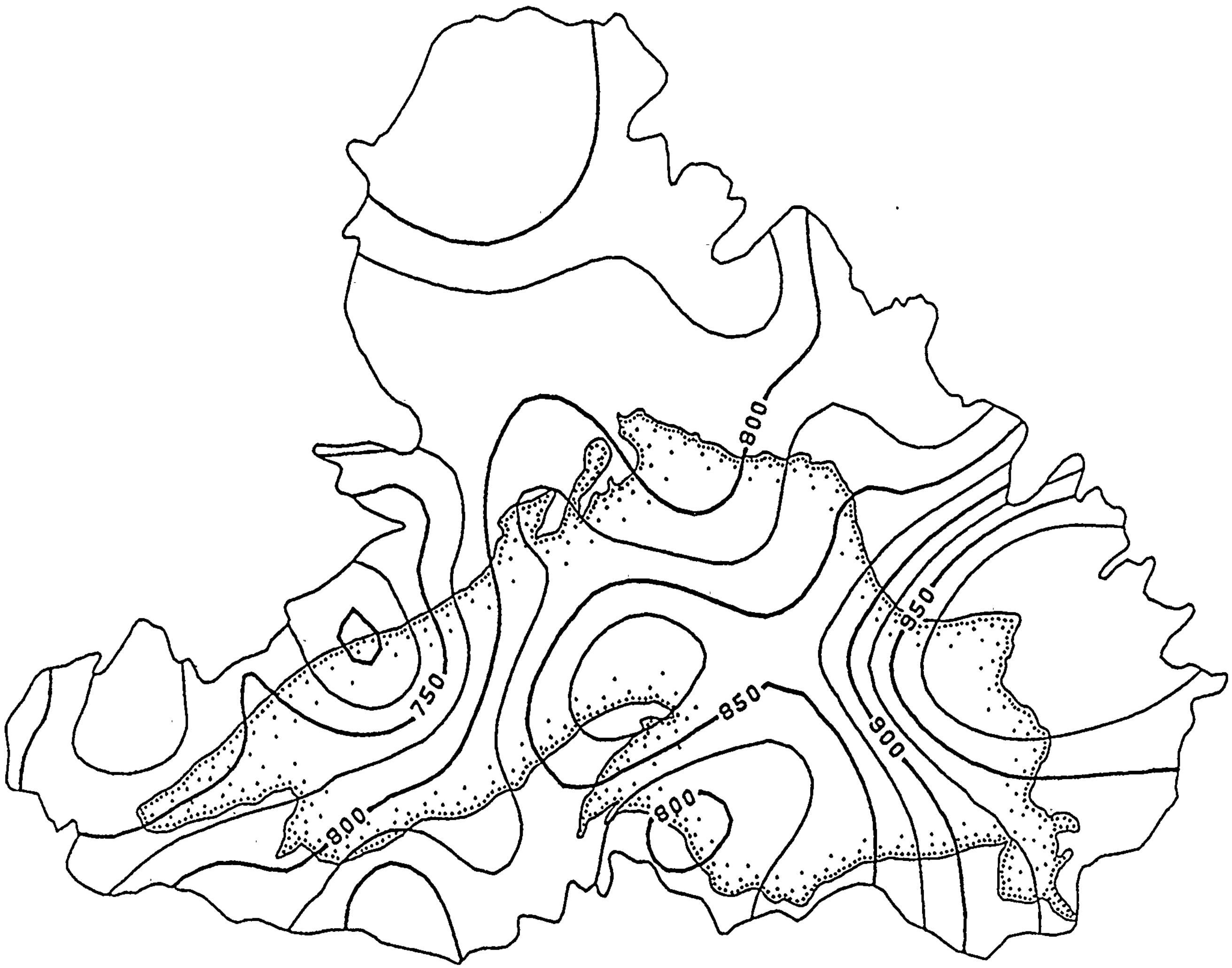


Figure 4.1 Distribution of average annual precipitation (mm)

Figure 4.2 Distribution of standard deviation (mm)

The distribution pattern for standard deviation varies from the distribution of average annual precipitation. It would appear that variability lacks the general east to west increasing tendency. Instead the variability decreases away from the lake in all directions. While the precipitation distribution is more influenced by the prevailing wind direction, the standard deviation distribution is associated more with Lake Superior. This may infer that temperature found around and over Lake Superior is a salient factor.

4.1.3 Distribution of the Coefficient of Variation

For further analysis, a map was produced showing the distribution of the coefficient of variation (Fig. 4.3). The values for the map construction were calculated by dividing the standard deviation value for the stations by their average annual mean giving a standardized indication of the variability exhibited by the precipitation on a basin scale. The map indicates the percentage that the standard deviation value is of the mean. The greatest variation is found along the north shore of Lake Superior. The variability exceeds 18% of the mean precipitation. The least variation is found in the southeast with variability less than 11% of the annual precipitation. In general, with exception to the northern region, on an annual basis, the seasonal precipitation in regions situated downwind have lower relative variability than upwind areas. The relatively constant temperature of Lake Superior may provide greater consistency in annual precipitation. The difference between the eastern and western snow belts may lie with the eastern area experiencing weather more greatly modified by the lake surface given the greater distance of travel.

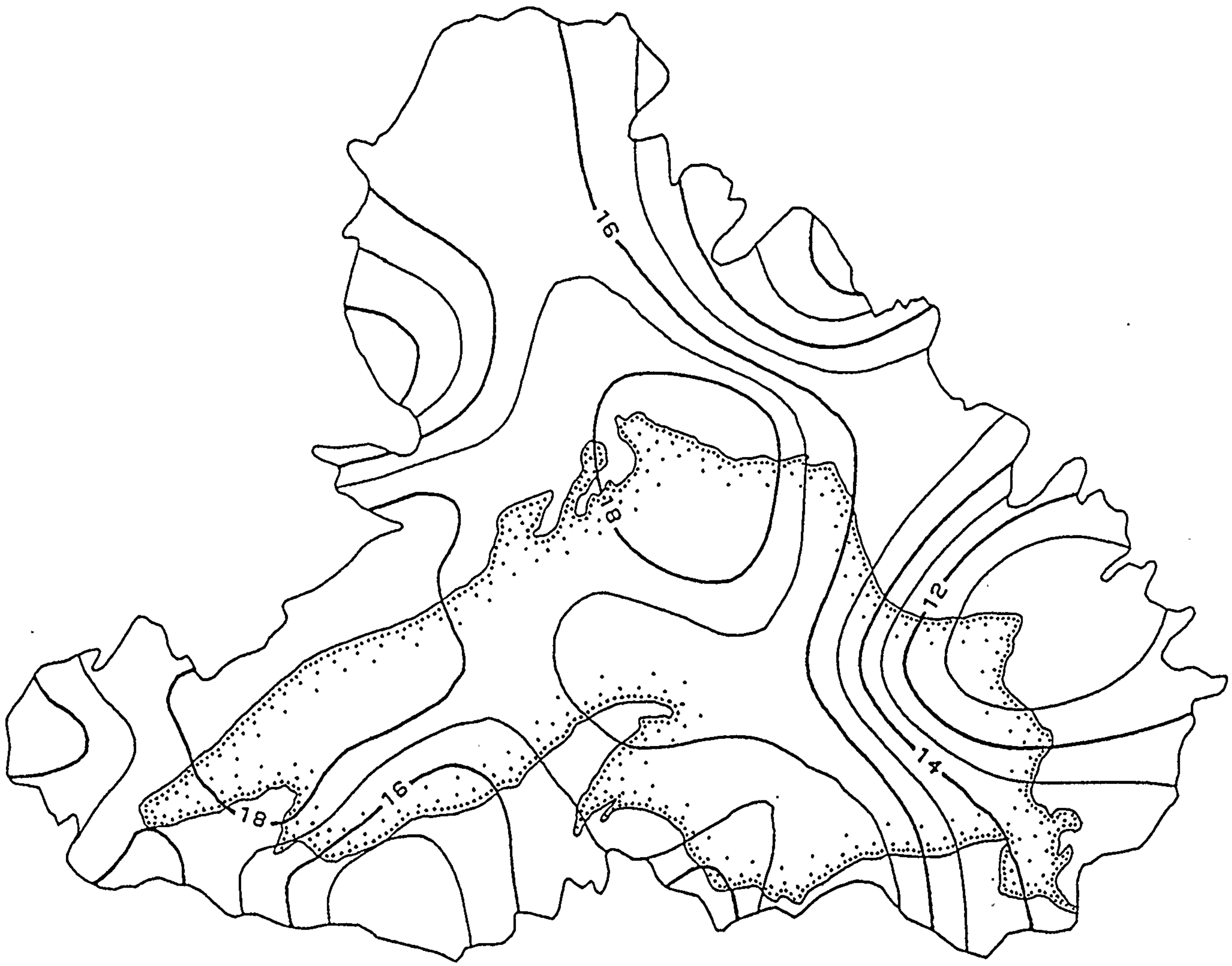


Figure 4.3 Distribution of the coefficient of variation (%)

4.1.4 Distribution of the Influence of the Water Surface Temperature of Lake Superior

Figure 4.4 shows the distribution of the percent of influence provided by the mean monthly lake surface temperature. The isolines were derived from using the percentage equivalent of r-squared values calculated by regressing average monthly precipitation for individual stations against the mean monthly lake surface temperature of Lake Superior (see section 4.2.7). Because the two terms have an indirect relationship, a surrogate factor(s) is required to allow for the measurement of the effect water surface temperature has on annual precipitation distribution and amount. Additional research beyond the scope of this thesis is needed to determine the factor(s).

The greatest lake influence tends to be in the region of greatest precipitation. The influence surface lake temperature has on average monthly precipitation increases in a general southwest to northeast trend. Greater than 60% of the monthly precipitation received by stations in the eastern basin is in association with the water surface temperature of Lake Superior.

The northerly extension of the isolines may be related to the influence contributed by Lake Nipigon as well as the numerous water bodies in that part of the basin. Depending on individual depth, their water surface temperature may closely follow that of Lake Superior. In contrast stations in the west have less than 40% of their monthly precipitation associated with water surface temperature. The Keweenaw Peninsula may be considered the division between stations that have at least 50% in the east and those with less in the west. The distribution pattern gives preliminary indication that west winds may be an important controlling factor regarding precipitation.

Figure 4.4 Distribution of the influence of the surface water temperature (^{o}C)

4.1.5 Trend Surface Distribution

Trend surface analysis was used in an attempt to determine the existence of any trends in precipitation distribution (Figure 4.5). Various trend orders were computed with a third order trend containing the most distinguishable patterns while retaining the general distribution. The third order trend provides a significant fit at the 99% confidence level for precipitation tendency with a F-calculated value of 6.32 greater than the F-critical value, 3.03, having 9 regression and 32 residual degrees of freedom.

The third order trend accounts for 64.01% of the precipitation pattern. The fit is strong as indicated by the correlation coefficient of 0.80. The trend may give further support to the notion that precipitation increases in a west to east direction. Three distinct patterns can be located in the trend distribution. The trend in the north shows a southwest to northeast expected decrease in annual precipitation. The latitudinal arrangement of isohyets near the southern drainage boundary may be a reflection of the western Upper Michigan snow belt areas. This region contradicts the overall east to west basin increase in precipitation. Precipitation stations located in the east-west trending snow belt, which is dependent in part to the escarpment of the same aspect, experience similar annual precipitation depths with little longitudinal change. In general, precipitation stations in the basin exhibit a general precipitation increase from west to east.

A lack of precipitation station data in the northern portion of the basin may have affected the significance of precipitation decrease shown. With data available from only three stations for the computation, the estimates of a decreasing trend in the extreme north may be overemphasized. Over the remaining basin, the trend generally increases from west to east. In the west half of the basin, the aspect of the trend is nearly a north to south increase. The pattern changes in mid-basin to a more west to east increasing trend.

Figure 4.5 Trend surface distribution (mm)

4.2 Exploring the Physical Controls on Precipitation

Section 4.1 and associated subsections qualitatively discussed factors having possible influence on the patterns shown by the distributions in Figures 4.1 to 4.5. By examining the distribution patterns found on the previous maps it provided a start into what factors may be controlling the distribution of precipitation. This section will attempt to quantify the degree of influence each factor possesses. For an understanding of the controls which may influence precipitation, multiple regression was performed on five independent and four dependent factors.

The independent factors analyzed consisted of elevation, distance, latitude, longitude and temperature with annual average precipitation, standard deviation and coefficient of variation dependent variables. The influence provided by the water surface temperature of Lake Superior also was included as a dependent variable. Station elevation was included to give a component for basin topography. Distance from Lake Superior provides for a measurement of the degree of influence provided by the lake. Station longitude and latitude provided east-west and north-south components, whereas longitudinal location allows for determining the degree of influence produced by westerly winds and latitudinal location allows for any north-south factor. Temperature was chosen on the basis that precipitation may be related to regional change in temperature.

The values for the multiple regression analyses were calculated from the 41 land based meteorological station network (Table 3.5 and Figure 3.1) using a computer program generated through the Statistical Package for the Social Sciences (SPSSX) (Nie *et al.*, 1986). The variables relationships can be shown by the regression equations:

$$P_a = 3337.02 - 26.44lg + 9.75T_a + 0.24e - 0.36d - 5.95lt \qquad (4.1)$$

$$S_d = 450.60 + 0.077lg + 9.82T_a - 0.05e + 0.06d + 10.35lt \qquad (4.2)$$

$$C_v = -94.30 + 0.55lg + 0.99T_a - 0.01e + 0.02d + 1.28lt \qquad (4.3)$$

$$I_{ls} = -17.97 - 2.91lg - 0.73T_a + 0.01e - 0.08d + 6.87lt \qquad (4.4)$$

where P_a is average annual precipitation, S_d standard deviation, C_v coefficient of variation, I_{ls} influence of the lake surface temperature, lg station longitude, T_a mean annual temperature (^oC), e elevation (meters) above sea level, d straight line distance (kilometers) from the nearest shoreline of Lake Superior and lt station latitude.

Table 4.1 contains the statistics derived from the analysis. The average annual precipitation for the basin using the data from 41 stations is 790.90 mm. The relative variation in precipitation is around ten percent (9.99%) of the average annual mean as indicated by a standard deviation of 70.86 mm. The standard deviation distribution for the precipitation network has an average of 131.21 mm with a variability of 13.06%. The relative variability experience with the station network has a mean of 16.69%. An average 42.06% of the precipitation received in the station network is influenced by the water surface temperature of Lake Superior.

Table 4.1 Statistical values derived from the precipitation station network

Variable	Mean	Standard Deviation	Coefficient Variation
Avg. Ppt.(mm)	790.90	70.86	9.99
Stan. Dev.(mm)	131.21	17.13	13.06
Coef. Var.(%)	16.89	2.43	14.56
Lake Inf.(%)	42.06	14.39	34.21
Elevation (m)	312.00	111.72	35.81
Distance (km)	25.78	34.22	132.74
Latitude	47.21	0.99	2.10
Longitude	89.50	2.87	3.21
Temperature (°C)	3.73	1.54	41.29

The elevation mean (312.0 m) indicates that, on average, stations are located well above the 183.0 m lake elevation. The elevation has a fairly high degree of variability as indicated by the standard deviation value 111.72 m, which is 35.81% of the mean elevation. Average distance of 25.78 km indicated that the mean location is relatively close to Lake Superior. The locations of the stations have a high degree of variability with a 34.22 km standard deviation at 132.74% of the distance mean. The central location, as defined by the station network, would be to the west of the central Keweenaw Peninsula at 47.21° N and 89.50° W. The average annual temperature for the Lake Superior Basin station network is 3.73°C. With a standard deviation of 1.54 degrees at 41.29% of the mean, the basin has a high degree of variability in mean annual station temperature. The computed mean temperature for the basin is less than the 5.17°C annual mean for the lake body.

Table 4.2 contains the results from F-tests performed individually on the relationships between the four dependent and five independent variables. In each case there was 5 regression and 35 residual degrees of freedom. The relationships for average annual precipitation and surface temperature influence were the strongest with both significant at the 99% confidence level. The five independent variables have the strongest relationship with water surface temperature influence as indicated by the multiple correlation coefficient 0.81 compared to 0.80 for annual precipitation. Over 60% of the variation in the two is explained by the five factors. The relationships for the coefficient of variation and standard deviation are weaker and lack significance at the same confidence level. The relationship for variation is significant at the 97.5% confidence level, but only 31.5% of the variation is explained. Standard deviation lacks significance at the 95% confidence level. A change in the confidence level gives indication to the

Table 4.2 F-test results from multiple regression analysis

Variable	R	R^2	F-cal.	F-crit.	Confidence Level (%)
Precipitation	0.80	0.63	12.05	3.60	99.0
Influence	0.81	0.65	13.04	3.60	99.0
Variation	0.56	0.32	3.23	2.97	97.5
Deviation	0.46	0.21	1.88	2.49	95.0

The five independent variables were analyzed in a step-wise regression process in order to determine whether the amount of explanation contributed to the pattern of annual precipitation distribution by each term was significant. Through the step-wise regression process, the SPSSX step-wise regression program determined the order of variables having the greatest to least influence on the distribution of average annual precipitation. Table 4.3 shows, in decreasing order of importance, the variables and values associated with the correlation coefficient (r), coefficient of determination (r^2), amount of explanation added by each individual factor, the degrees of freedom (Df) and the F-test statistics at the 99% confidence level.

Table 4.3 Step-wise regression analysis results

Variable	r	r^2	Explanation Added	Df	F-cal	F-crit
Longitude	0.6896	0.4756	0.4756	1,39	35.37	7.33
Temperature	0.7418	0.5503	0.0747	2,38	6.15	5.22
Elevation	0.7850	0.6163	0.0660	3,37	7.91	4.37
Distance	0.7942	0.6307	0.0144	4,36	1.76	3.91
Latitude	0.7948	0.6318	0.0011	5,35	0.09	3.61

Longitude contributes the greatest amount of explanation with 47.56. Having a 35.37 F-calculated value greater than the F-critical 7.33 with one (1) regression and 39 residual degrees of freedom longitude provides a significant amount of explanation at the 99% confidence level. The added explanation for temperature (7.47%) and elevation (6.60%) is also significant. The added explanation contributed by distance and latitude lacks significance.

From the multiple regression analysis the following correlation coefficient (r) matrix was constructed (Table 4.4) to show the strengths of relationships. The tabulated values were then transformed to coefficients of determination (r^2) values to give an indication of the degree of association provided by each combination of variables (Table 4.5). Each independent variable will be discussed individually using the information from the matrix tables and the step-wise regression analysis in terms of the influence it has on the distribution of annual precipitation as well as their affect upon the other distributions.

Table 4.4 The correlation coefficient (r) matrix

Variable	Ppt.	Elev.	Dist.	Lat.	Long.	Temp.	Inf.	Var.	Dev.
Precipitation	1.00								
Elevation	-0.04	1.00							
Distance	-0.19	0.61	1.00						
Latitude	0.03	0.16	0.55	1.00					
Longitude	-0.69	0.29	0.09	-0.39	1.00				
Temperature	0.04	-0.17	-0.55	-0.91	0.31	1.00			
Influence	0.42	-0.22	0.09	0.62	-0.69	-0.56	1.00		
Variation	-0.42	-0.08	-0.01	-0.07	0.42	0.21	-0.40	1.00	
Deviation	0.09	-0.19	-0.20	-0.19	0.07	0.32	-0.16	0.83	1.00

Table 4.5 Explained variance (r^2) matrix

Variable	Ppt.	Elev.	Dist.	Lat.	Long.	Temp.	Inf.	Var.	Dev.
Precipitation	1.00								
Elevation	0.00	1.00							
Distance	0.04	0.37	1.00						
Latitude	0.00	0.03	0.21	1.00					
Longitude	0.48	0.09	0.01	0.15	1.00				
Temperature	0.00	0.03	0.30	0.82	0.10	1.00			
Influence	0.18	0.05	0.01	0.39	0.48	0.31	1.00		
Variation	0.17	0.01	0.00	0.00	0.18	0.05	0.16	1.00	
Deviation	0.01	0.04	0.04	0.04	0.01	0.10	0.02	0.68	1.00

4.2.1 Influence of Elevation

Elevation, on a basin wide scale, has a slight influence on the distribution of annual precipitation within the Lake Superior Basin. Change in elevation may influence the amount and nature of precipitation experienced on a more local scale, especially in the snow belt regions and in areas of greater relief along the escarpment. But as indicated by the r-values the relationship is very weak with a correlation coefficient of -0.04 offering less than one percent (0.2%) of explanation for the distribution pattern for annual precipitation. From the step-wise analysis, elevation contributes a significant 6.60% of additional explanation to the relationship.

Regarding the influence on variability of precipitation, elevation continues to exhibit minimal effect. However, elevation has greater influence on variability than amount, with all three relationships (-0.22, -0.08 & -0.19) being stronger than the relationship with annual precipitation (-0.04). Elevation has the strongest relationship with water surface temperature influence as shown by the correlation coefficient -0.22. There would be a weak tendency for water surface temperature influence to decrease with increase in elevation. Elevation accounts for only 5% of the change in influence.

4.2.2 Influence of Distance from Lake Superior

Distance, like elevation, may have a greater degree of influence nearer the lake and on a more local scale, than basin wide. The relationship between annual precipitation and distance is stronger than elevation but still weak, as indicated by a coefficient value of -0.19 while contributing over three percent (3.5%) of explanation in the precipitation pattern. As distance decreases precipitation would tend to increase. The amount of explanation added, 1.44%, in the step-wise analysis is not significant. Combined, the variables of distance and elevation contribute eight percent. This amount is unexpectedly low for factors that have been thought of as major influences on precipitation. Regarding the Lake Superior Basin the two factors have minimal roles in influencing the distribution of average annual precipitation.

Distance experiences the strongest relationship with standard deviation, though relatively weak at -0.20. This indicates that variability tends to decrease with distance from the lake. Only 4% of the relationship is accounted for which is surprising considering the pattern found in Figure 4.2. The weak relationship with water surface temperature influence (0.09) indicates that distance from Lake Superior lack the expected explanation

4.2.3 Influence of Average Annual Temperature

The relationship between annual station temperature and distribution of annual precipitation is very weak at 0.04 with less than 1% explanation contributed. The variable contributes an additional 7.47% of explanation in the step-wise process, which seems surprising when compared to less than one percent found in the matrix table. The amount of added explanation is significant. The strong relationship with latitude -0.91 shows that while there is a strong tendency towards a decrease in temperature from south to north, the effect on precipitation is negligible.

Temperature generally has greater influence on the amount precipitation is related to Lake Superior. The degree of water surface temperature influence has a strong inverse relationship with temperature. This is indicated by the correlation coefficient -0.56. Nearly one-third (31.4%) of the amount of influence increase is associated with decreasing air temperature. The result would be that colder areas are more likely to have precipitation influenced by Lake Superior. Both variation and deviation have marginal relationships shown by their respective coefficients 0.21 and 0.32.

4.2.4 Influence of Latitudinal Location

With latitude having the weakest relationship of all, 0.03, it gives clear indication that there is no significant north-south trend in annual precipitation distribution. This adds evidence to the notion that the apparent south to north decreasing trend found in Figure 4.5 is not reliable. The variable contributes less than one percent (0.11%) of additional explanation in the step-wise analysis.

Similar to temperature, latitude has a moderate relationship with water surface temperature influence. With a correlation coefficient of 0.62, 39% of the change in water surface temperature influence is related to change in latitude. The influence of the water surface temperature of Lake Superior increases from south to north. For each degree of latitude water surface temperature influence increases by 6.87%. Latitude has weak relationships with variation, -0.07, and deviation, -0.19.

4.2.5 Influence of Longitudinal Location

From both regression analyses longitude is shown to have the greatest influence on the distribution of annual precipitation. The strong negative correlation coefficient (-0.69) indicates that average annual precipitation would increase as longitude decreases. For each degree of longitude annual precipitation is expected to increase 26.44 mm. Regarding the Lake Superior Basin, precipitation is expected to increase as one travels from Minnesota to Ontario. Nearly half (47.6%) of the change in annual precipitation distribution is influenced by change in longitude. Of the five variables, longitude contributes the greatest significant amount of explanation to the pattern of annual precipitation distribution. Longitude sufficiently and significantly explains the pattern of precipitation found within the Lake Superior Basin.

With a correlation coefficient, -0.69, a strong inverse relationship exists between water surface temperature influence and longitude. The influence of Lake Superior tends to increase with a decrease in longitude. Thus, the east has a greater tendency for precipitation which is influenced by Lake Superior. With each degree decrease the amount of water surface temperature influence increases by 2.91%. A fairly strong relationship exists between longitude and variation as shown by the 0.42 correlation coefficient. Variation in precipitation would tend to decrease with longitude. Longitude is by far the most influential factor on the amount and characteristics of annual precipitation.

4.2.6 Influence of Wind Direction

The high degree of influence that a stations longitudinal location has on precipitation can be attributed to the prevailing wind direction. Phillips (1978) indicates that May to September rainfall can be as much as 50 mm greater at an upwind location than downwind. In contrast, stations located in snow belt regions may receive greater annual precipitation than those situated upwind during winter. Phillips (1978) determined snowfall during can be as much as 71 cm less upwind than at a downwind location. In addition the west winds are a prerequisite for the high degree of lake surface temperature influence found in the eastern basin area as well as the low degree in the west.

Figure 4.1 showed graphically the increase as one travels from west to east. Figure 4.5 shows there is a statistically significant trend contained in the pattern of annual precipitation distribution. Finally the use of multiple regression quantifies the importance of longitudinal location. The snow belt areas would not exist in their present extent without prevailing westerly winds. With an elimination of the 20-30% more water equivalent precipitation during winter, the eastern basin would have more similar annual precipitation amounts to that in the west reducing the west to east increasing trend. There is one more influence in conjunction with winds, the surface temperature of Lake Superior.

4.2.7 Influence of the Water Surface Temperature of Lake Superior

The importance of the presence of Lake Superior has been referred to in earlier text. Figure 4.6 contains the plot of average monthly water surface temperature for Lake Superior and average monthly precipitation. The graph shows an association with monthly precipitation increasing along with increasing water surface temperature with the opposite being true. Monthly precipitation would tend to be the least during the spring when a negative temperature difference exists between the lake surface and land. As the water surface warms precipitation increases to form a common peak in September.

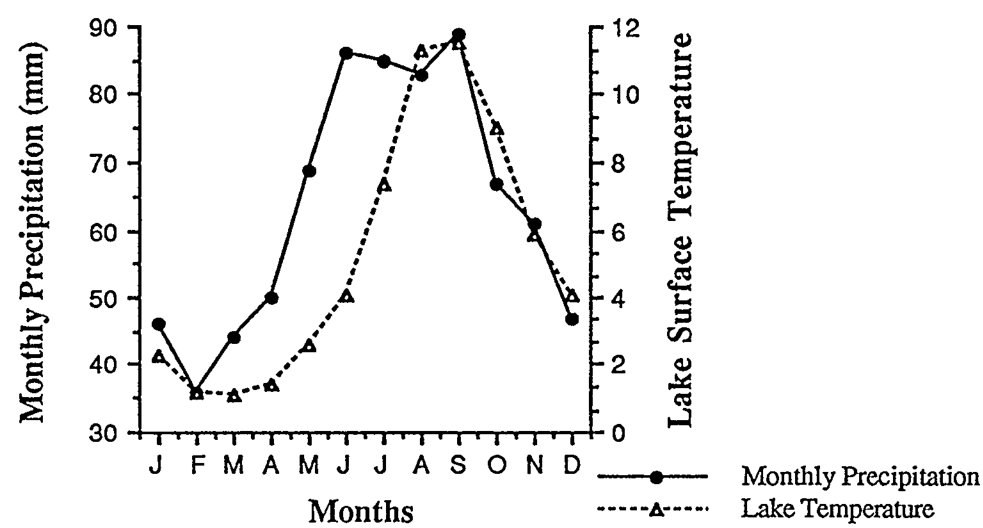


Figure. 4.6 Relationship between lake water surface temperature (°C) and average monthly precipitation

To determine the degree of association, a detailed regression analysis was performed concentrating solely on how the amount of monthly precipitation received throughout the basin is related to the average monthly water surface temperature of Lake Superior. The mean monthly basin precipitation (GLERL) was regressed against the average monthly water surface temperature of Lake Superior. The correlation coefficient of 0.77 indicates the two variables combine for a strong relationship. Fifty-nine percent of variation in average monthly basin precipitation is associated with change in water surface temperature. The relationship is stated by the regression equation:

$$P_m = 3.81T_{ls} + 43.89 \tag{4.5}$$

where P_m is the expected monthly precipitation (mm) for a given lake surface temperature T_{ls} (^oC). With 1 regression and 10 residual degrees of freedom the F-calculated value of 14.38 is greater than the F-critical value 10.04 making the relationship statistically significant at the 99% confidence level. The amount of monthly precipitation is significantly associated with the water surface temperature of Lake Superior. From the equation, for every degree increase in lake water surface temperature precipitation is expected to increase an average of 3.81 mm.

With a significant relationship existing between average monthly basin precipitation and water surface temperature further analysis of individual point precipitation amounts was performed. To determine the possible impact of the average water surface temperature on mean monthly precipitation received at an individual station, the two data set values were regressed against one another. The greater the r-squared value the more closely the monthly precipitation pattern fitted the march of lake surface temperature inferring some degree of association. A high percent of correlation would indicate that the monthly precipitation pattern closely follows the march of monthly lake surface temperature.

The analysis used a F-test at the 99% confidence level to provide a measure of significance. For all values tested there were 1 regression and 10 residual degrees of freedom allowing for a F-critical value of 10.04. The high confidence level allowed for the categorization precipitation stations influenced the most by Lake Superior. At the 99% confidence level, ten stations experienced significant relationships between monthly precipitation and lake surface temperature. In all cases the percent of precipitation explained by or associated with temperature was greater than 50%. The precipitation stations experiencing significant relationships with the exception of Kakabecka Falls, are situated in the eastern basin region, east of approximately the 88th meridian. The degree of water surface temperature influence for the remaining stations can be found in Table 3.5 under '% of Temperature Effect'. Table 4.6 contains the stations with significant association between their monthly precipitation and the monthly water surface temperature of Lake Superior.

Table 4.6 Stations with significant relationships between monthly precipitation and lake surface temperature

Station	r-squared	F-calculated
Wawa	0.776	34.67
Cameron Falls	0.719	25.58
Manitowadge	0.717	25.28
Marathon	0.668	20.11
Long Lac	0.643	18.00
Schreiber	0.614	15.89
Eagle Harbor	0.592	14.48
Munising	0.539	11.71
Kakabecka Falls	0.535	11.52
Sault Ste. Marie	0.517	11.06

Six stations, all located in Ontario, have more than 60% of their average monthly precipitation associated with average monthly water surface temperature. Marquette with 14.8% is the only station to have less than 20% of monthly precipitation influenced by lake water surface temperature. The average amount of influence for the 41 stations was calculated at 42.09%. The strongest relationship is shown by Wawa with 77.6% of the amount of monthly precipitation being associated with the water surface temperature of Lake Superior.

The difference between stations experiencing significant relationships and those that are not may rest in the degree of continental influence each station receives. The distribution clearly gives indication to the importance of the upwind-downwind relationship. With the prevailing westerly winds, the eastern basin has greater opportunity to experience lake modified conditions from Lake Superior as well as from the other water bodies. Other stations in the west may encounter lesser lake and greater continental influence. For example, one may assume the Upper Michigan snow belt region would show a more similar high degree of explanation as exhibited by the eastern region. The difference may lie in the fact that the south shore is more susceptible to incursions of continentally modified air from west to south making any accompanying precipitation independent of possible water surface temperature influence. If the path of the air mass was to continue over the lake it would be modified. Depending on the season, associated precipitation could either be increased or decreased. The western lake shore stations with less than 40% of their precipitation associated with water surface temperature indicates that the lake has some degree of impact though lesser than that in the east.

4.3 Summary of Results

The analysis has shown that Lake Superior has a major role in determining the distribution, amount and variability of precipitation falling in the basin. Overall the water surface temperature of Lake Superior contributes 42.06% towards the explanation for the amount of precipitation received at the station network throughout the year. With 59% for basin EUD precipitation, downwind stations located in the eastern basin are affected with percentages of influence exceeding 60%. The presence of Lake Superior coupled with prevailing west winds made longitudinal location the most important factor controlling precipitation amounts as well as the variation exhibited in it.

The annual precipitation as well as water surface temperature influence increases west to east. The areal trend in annual precipitation was proven to be significant. The relative variation of precipitation decreases from west to east. The combination of west wind, topography and Lake Superior contribute to the establishment of the west to east trend through the development of snow belt areas. The regions receive more water equivalent precipitation during the winter than upwind areas. With an absence of the three components the snow belts would cease to exist in present form, eliminating the west to east increasing trend. While contributing to increases in annual precipitation, Lake Superior dampens the variability in downwind areas. Little seasonal variation is found with winter months receiving similar precipitation amounts as summer months. The importance of longitude overshadows the insignificance of other factors thought to play as important roles in the basin, namely distance from Lake Superior and elevation in the basin.

CHAPTER 5

ANALYSIS OF PRECIPITATION IN THE LAKE SUPERIOR BASIN FOR POSSIBLE TRENDS AND CYCLES

5.1 Precipitation in the Lake Superior Basin 1900-1980

The data set consisted of average annual precipitation (EUD) for the Lake Superior Basin 1900-1980 compiled by Quinn and Kelley (1983) of the GLERL. It was used to show how annual precipitation amounts may have varied throughout the century. Statistics in Table 5.1 show the general characteristics for basin. The values represent the average for the entire basin. General statements may be made concerning the apparent characteristics shown by the statistics. The annual precipitation has a coefficient of variation at 11.5% resulting from a standard deviation of 87.5 mm compared to the 762.9 mm precipitation mean.

Table 5.1 Lake Superior Basin annual precipitation statistics

Statistic	Value
Mean	762.9 mm/yr
Maximum	991.1 mm (1977)
Minimum	579.1 mm (1910)
Range	412.0 mm
Standard Deviation	87.5 mm
Coefficient of Variation	11.5%

A time series plot of the annual precipitation allows for additional analysis. The plot of the data shows a general increase in precipitation with time, while lacking discernable secondary patterns (Fig. 5.1). The relationship is fairly strong with a coefficient of 0.57. Almost one-third (32.6%) of the variation in annual precipitation is associated with time. Factors other than time have influenced the pattern producing a greater degree of scatter. A pattern may exist for a dry year to be directly followed by a wet year with the opposite being true. Nearly one-quarter (23%) of successive years have differences in precipitation amounts over 150 mm. At times the annual precipitation appears to have greater consistency and less yearly difference. Examination of the plot indicates an apparent general increase in precipitation depth from 1900 to 1980. In addition, two periods occur in the plot in which annual precipitation amounts tended to decrease. Detailed analysis of the plot is needed to determine the significance of the patterns.

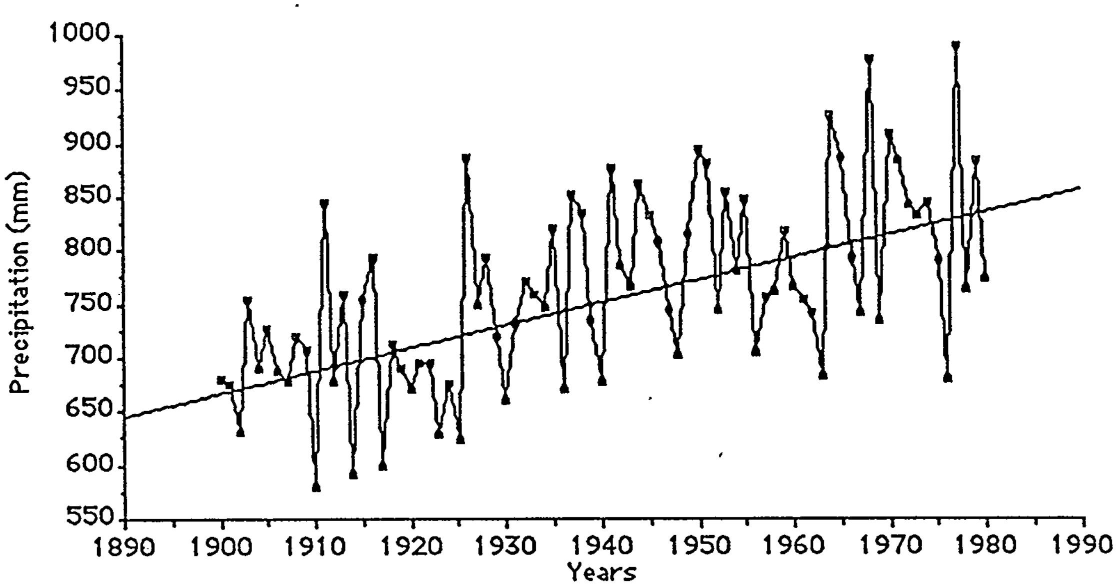


Figure 5.1 Scattergram with trend of annual precipitation

5.2 Analysis for Possible Trends

5.2.1 Major Trend

The main goal for locating any trend is to produce evidence leading towards an explanation into behavior exhibited by the water level of Lake Superior during this century.

Previous research has found a significant increase in the water level of Lake Superior at 2.10 mm/yr. It is hoped that a similar trend in annual precipitation exists. By using simple regression a trend can be derived from the data set.

The analysis revealed a significant time dependent relationship at the 99% confidence level. With 1 regression and 79 residual degrees of freedom, the F-calculated value of 38.15, was greater than the F-critical value, 7.33. The significant relationship can be indicated by the regression equation:

$$P_a = 2.12t - 3358.44 \tag{5.1}$$

where P_a is the expected annual precipitation for year t. The plot contains a statistically significant trend indicating an average depth increase of 2.12 mm/yr over the entire basin during the first 80 years of this century. With 0.02 mm/yr separating the two trends there a close rate of increase exists between the water level of Lake Superior and the amount of precipitation falling on the basin. Given the degree of scatter further examination of the plot is needed.

5.2.2 Analysis for Secondary Trends

The location of secondary trends involved using background knowledge of past water levels of Lake Superior. Through close examination of the annual precipitation values it appears there are three time periods showing a decreasing tendency in annual precipitation depth relative to adjacent years. One period is centered approximately around 1915, a second around 1958 and the third in 1973. On the other hand there is no indication suggesting the presence of increasing trends of similar lengths. To clearly determine the existence and significance of any trends, an investigation was conducted concentrated on their location. The periods tentatively suggested for decreases in annual precipitation would correspond to periods of below normal lake levels. Table 5.2 contains the characteristics of the three secondary trends contained in the original data

Table 5.2 Characteristics of decreasing trends

Period	Mean (mm)	Stand. Dev. (mm)	Coef. of Var. (%)	Trend (mm/yr)
1911-1925	694.07	70.73	10.19	-7.57
1950-1963	784.86	64.65	8.24	-10.67
1970-1976	826.65	74.36	9.00	-31.03

From the analysis two periods of similar and one of shorter length were determined to contain a decrease in annual precipitation over a number of years. The first decrease lasted 15 years from 844.1 mm in 1911 to 623.9 mm in 1925. The time dependency is moderate as indicated by the correlation coefficient 0.48. Roughly 23% of the variation is accounted for by increase in time. The analysis for the 15 year period revealed a decreasing trend in annual precipitation depth at 7.57 mm/yr (Fig. 5.2). The decrease in annual precipitation can be defined by the regression equation:

$$P_a = 15205.79 - 7.57t \qquad (5.2)$$

where P_a is the expected annual precipitation in year t. The F-calculated value of 3.86 with 1 regression and 13 residual degrees of freedom was less than the F-critical value of 4.67. Therefore the trend is not significant at the 95% confidence level. The reason for this may lie in the first seven years being more dispersed than the remaining eight. This would contribute to a standard deviation value that is over 10% of the mean. Though lacking significance the trend gives clear indication to a decrease in annual precipitation. The decrease might have been an important factor in producing the two lowest water level on record for Lake Superior in 1925 (182.68 m) and 1926 (182.57 m).

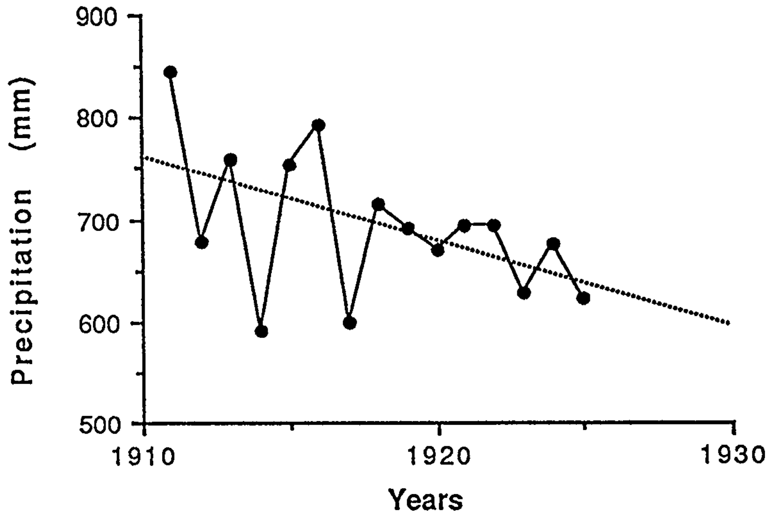


Figure 5.2 Decreasing trend, 1911-1925

The second case in annual precipitation reduction comprises a period of 14 years, 1950 to 1963. The precipitation decreases from a peak of 894.8 mm in 1950 to 682.3 mm in 1963 (Fig. 5.3). Unlike the previous trend, this decrease was statistically significant at the 99% confidence level with the F-calculated value, 10.92, greater than the F-critical value 9.33 having 1 regression and 12 residual degrees of freedom. The relationship is given by the regression equation:

$$P_a = 21656.20 - 10.67t \tag{5.3}$$

where P_a is the expected annual precipitation in year t. For 14 years the annual basin precipitation depth decreased at an average 10.67 mm/yr. A r-squared value of 0.48 indicates nearly half of the scatter in the trend was accounted for by increase in time. This was higher than the 0.23 r-squared value for the first decreasing trend. Like the previous trend, this one could be seen as having a substantial impact on the water level of Lake Superior. In 1963 the lake level of 182.93 m was the lowest recorded since 1926. In addition both 1961 and 1962 had annual levels of 182.94 m.

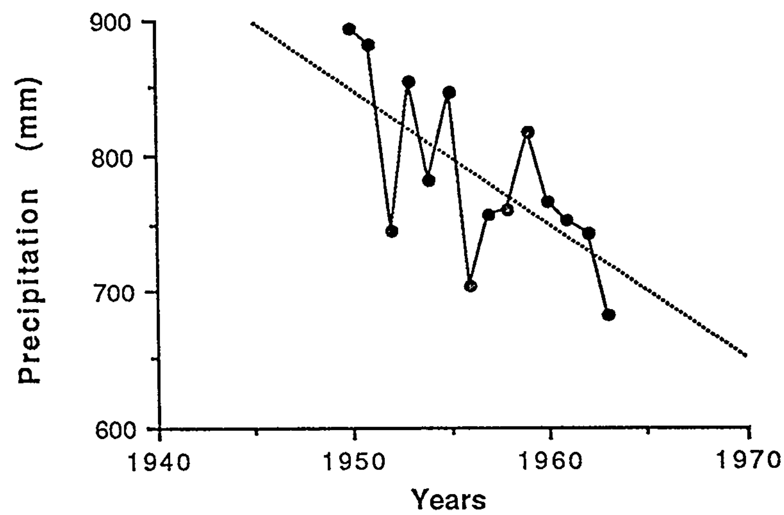


Figure 5.3 Decreasing trend, 1950-1963

The third case of decrease in annual precipitation occurs between 1970 and 1976. The annual precipitation decreases from 909.1 mm in 1970 to 681.4 mm during 1976 (Fig 5.4). The value for 1976 is the lowest since 1940. This trend is different from the previous two with only one value below annual average. The amount of annual precipitation decreases from a period of greater than normal to a time with amounts closer to average. With 1 regression and 5 residual degrees of freedom the F-calculated value of 21.67 was greater than the F-critical value, 16.26 at the 99% confidence level. The relationship is given by the regression equation:

$$P_a = 62046.03 - 31.03t \tag{5.4}$$

where P_a is the expected annual precipitation for year t. During the period annual precipitation decreased 31.03 mm/yr. The relationship is very strong as indicated by the correlation coefficient 0.90. Eighty-one percent of the variation shown in the plot is accounted for by increase in time. The mean value for the seven years is above normal at 826.65 mm. The variation contained in the values is 9% resulting from a standard deviation of 74.36 mm.

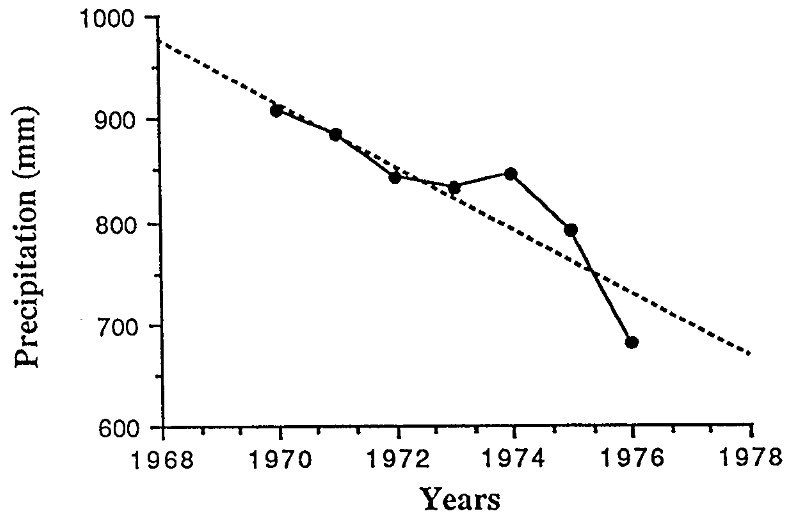


Figure 5.4 Decreasing trend, 1970-1976

The effect on the water level of Lake Superior was not as drastic as indicated by the earlier trends. While the annual precipitation was decreasing it remained above average until 1976. This gives an indication that the condition of the basin prior to a change in the amount of annual precipitation is an important factor on determining the lag time between the behavior of the lake level association and precipitation. The water level may have reflected the wet conditions of the basin by not showing a decrease until past 1974. The below average water level in 1977, at 182.98 mm, may be related to the decrease in precipitation during this period.

Comparisons between the three periods can be made from the values in Table 5.2. The first two trends were similar with the first half of each trend appeared to be more scattered than the last half. The first trend had a higher degree of variability as shown by both the larger standard deviation and coefficient of variation values. The decrease in the second trend is 3.10 mm/yr greater than the first. The third trend may be considered extreme when considering that the expected annual precipitation decreased roughly 180 mm in six years. The periods give evidence for the overall increase in annual precipitation with the first mean of 694.07 mm, 90.79 mm less than the 784.86 mm mean for the second, which is 41.79 mm less than the third. Combined, the three periods of decreasing tendency in precipitation contain 36 total years or 45% of the record length.

5.3 Analysis for Possible Cyclic Patterns

The two periods having the tendency towards decreasing precipitation at nearly the same length may give preliminary indication to cyclic patterns. Therefore analysis for possible cycles was performed using an autocorrelation method. The autocorrelation program from Davis (1974) provided the means for the calculations. As required by the program the maximum lag period was one-quarter the length of the data set. Prior to the autocorrelation analysis the significant trend was eliminated through the calculation of precipitation residual values (Fig. 5.5).

Shown by the autocorrelogram (Fig. 5.6), the coefficients revealed an alternating positive-negative pattern. The correlation coefficients for lags 1 to 20 range between 0.2006 and -0.2334. Having both positive and negative coefficient values, a two-tailed Z-test was used with +/- 1.64 being the critical value. There was only one coefficient with a significant value. Lag 14 with a coefficient of -0.2394 had a calculated test value of -1.91. Both lags 12 (-0.1968) and 15 (0.2006) were nearly significant with calculated values of 1.63.

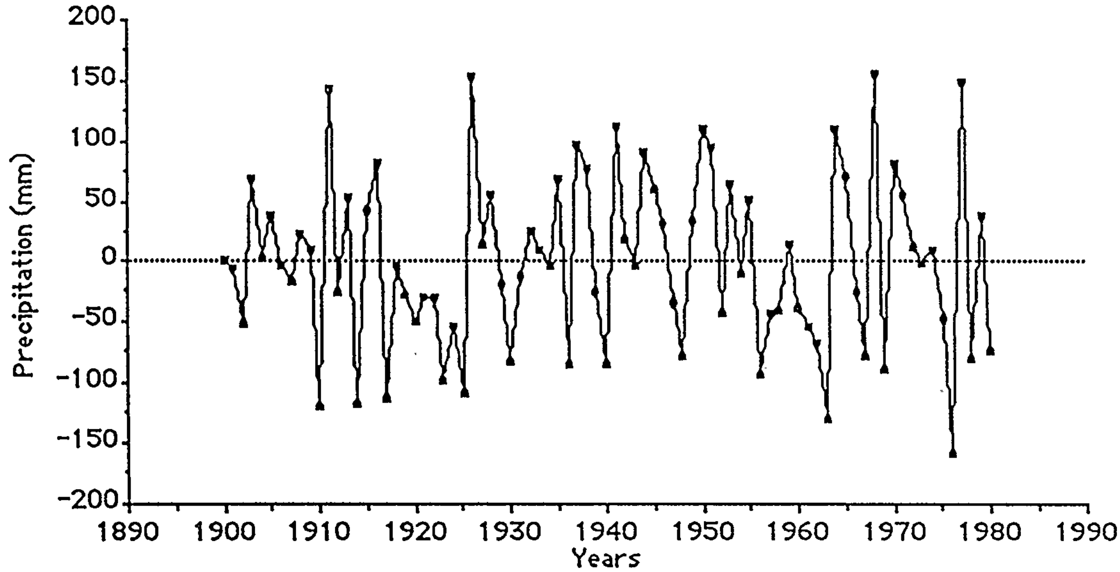


Figure 5.5 Plot of annual precipitation residuals

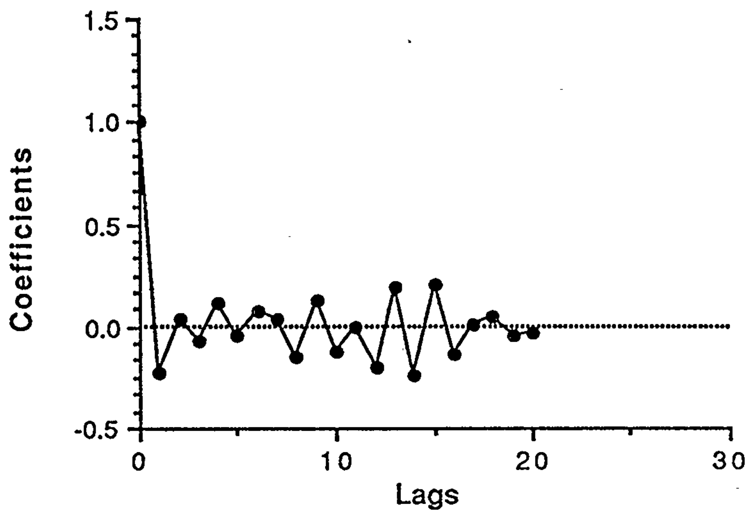


Figure 5.6 Autocorrelogram for the basin precipitation residuals shown in Figure 5.5

The negative coefficient at lag 14 provides no evidence for a cycle. The value represents the expected time period from either a high 'peak' to a low 'pit' value or vice versa. A relationship from 'peak' to 'pit' can be found on the residual plot. The 14 year lag correlates with the 14 year decreasing trend. There were five occurrences having an average 14 year period existing between high and low precipitation residual values (Table 5.3).

Table 5.3 Fourteen year partial cycle in annual precipitation

Year	Residual Value (mm)		Year	Residual Value (mm)	Period (yrs)
1903	69.47	to	1917	-113.65	14
1911	142.79	to	1925	-113.65	14
1926	154.05	to	1940	-85.07	14
1941	111.71	to	1956	-92.83	15
1950	110.70	to	1963	-129.39	13

There were two instances contained in the data when periods overlapped. The first two 14 year periods had an overlap of six years from the end of the first in 1911 to the start of the second in 1917. The fourth and fifth periods had a similar six year overlap. The second and third periods were successive 'peak' to 'pit' periods. Fourteen years from the peak the values decreased to -85.07 mm in 1940. For the last two the period changes to 15 and 13 years. The final two, though not at 14 years, are one year different from the significant 14 year period length.

5.4 Analysis of the Variability in Annual Precipitation

As briefly mentioned earlier there exist discernable patterns in the data that shows precipitation between successive years can be highly variable to relatively consistent. The maximum variation of 309.7 mm between 1976 and 1977 is in sharp contrast to the minimum variation of 5 mm for 1921 and 1922. This section will analyze the data set for patterns associated with variability. An examination of the change in precipitation amounts between successive years by using the difference between observed departure and the mean. The decadal characteristics of annual precipitation contained in Table 5.4 were also investigated.

Table 5.4 Annual precipitation characteristics per decade (mm)

Decade	Average Precipitation	Average Change	Standard Deviation	Coefficient Variation (%)
1900-09	694.73	50.4	43.47	6.26
1910-19	700.17	123.1	81.46	11.63
1920-29	713.66	76.7	74.74	10.47
1930-39	758.18	71.4	57.96	7.64
1940-49	787.50	75.5	54.19	6.88
1950-59	804.26	70.3	46.86	6.83
1960-69	800.61	116.6	97.76	14.56
1970-79	842.70	101.9	98.57	11.70

The average change in the amount of annual precipitation between successive years; average precipitation, standard deviation and the coefficient of variation were calculated for eight decades from 1900 to 1979. The decadal scale was used as a definable measure of time. It may be inferred that the decades which have high variation experienced more and to a greater extent transitions between below and above normal precipitation. The periods of less variation may be considered periods in which precipitation was more consistent at a certain precipitation level.

The nature of decade variation is similar to that of the original data, in which the values depart significantly from the mean change value of 85.74 mm. The decadal precipitation showed a nearly constant increase from 694.73 mm to 842.70 mm. The values show that there has been relative abrupt increase (72.7 mm) from the first decade to the second after which there was a sharp decrease (46.4 mm). The decrease was followed by a somewhat consistent period in which the average change per decade remained within the 70 mm category. The change returns to over the 100 mm amount (116.6 mm) with a 46.3 mm increase between the sixth and seventh decade. The four decades with the greatest change experience variations over 10% with the highest being 14.56% from 1960-1969. The first decade has the least change and the least variation.

Table 5.4 indicates that average precipitation and variation had an inverse relationship for decades two through seven. In general, mean annual precipitation appears to be increasing throughout the periods with variability decreasing during the first six decades while increasing in final two decades. The greater precipitation from 1960-79 was accompanied by a greater degree of variability. From 1950-59 the precipitation averaged over 800 mm/yr but the 46.86 mm standard deviation was only 6.83% of the mean indicating that the amount of precipitation was relatively consistent and above average. The last two decades must have had annual precipitation amounts that were highly variable from year to year. Only recently, from 1960 to the present, has there been a tendency towards greater annual precipitation variability in which there has been large changes in precipitation between successive years.

5.5 Analysis of Annual Departures from the Mean for Possible Cycles

To further understand the nature of variability in annual precipitation an analysis into the change in precipitation amounts between successive years was performed. The data set was plotted as the difference from the observed change in precipitation between successive years and the mean expected departure, 85.74 mm. There was an apparent reduction in departure amounts near the middle of the plot (1940-1960), much like the precipitation scattergram, but it is not certain. Also of uncertainty was the occurrence of any significant cycles.

To see whether there were any significant cycles contained in the annual departures from the mean variance (Fig. 5.7), an autocorrelation analysis was performed in the same context as used previously. As shown by the autocorrelogram (Fig. 5.8) the distinct coefficients were -0.2050 at lag 6 and 0.2238 for lag 15. With Z-values of -1.76 and -1.74 respectively, lags 6 and 7 are significant. Lag 15 is also significant as indicated by the Z-value of 1.80. There is, on average, a 6 to 7 year time period between a peak positive departure and a 'pit' negative departure. Lag 15 represents that peak positive departures occurred on average every 15 years. The periods show that precipitation between successive years becomes more stable every six to seven years whereas the change between years reaches a maximum every 15 years.

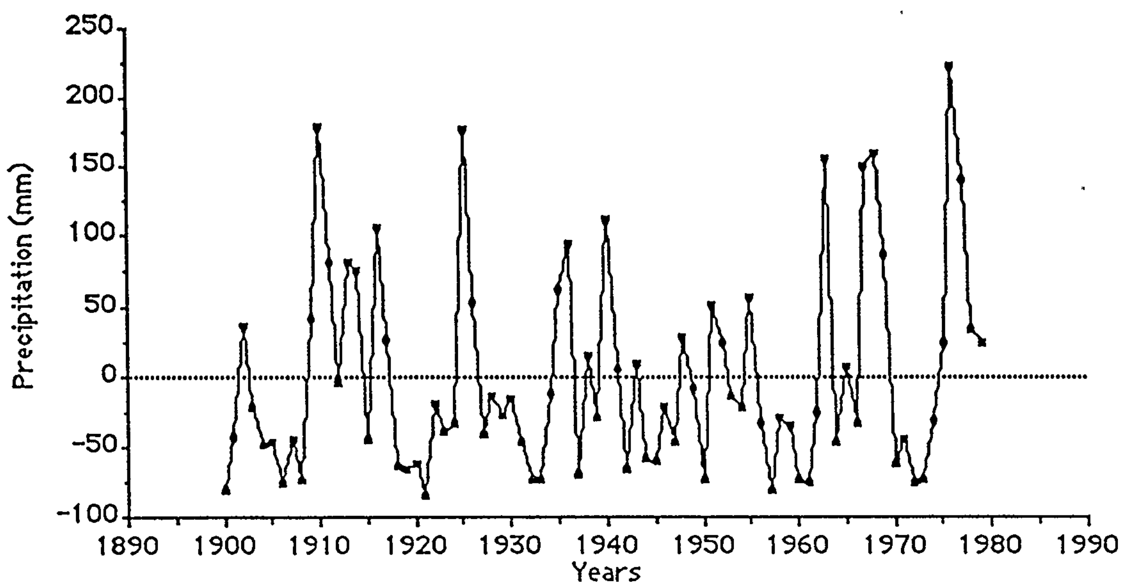


Figure 5.7 Precipitation change for successive years as departures from the mean

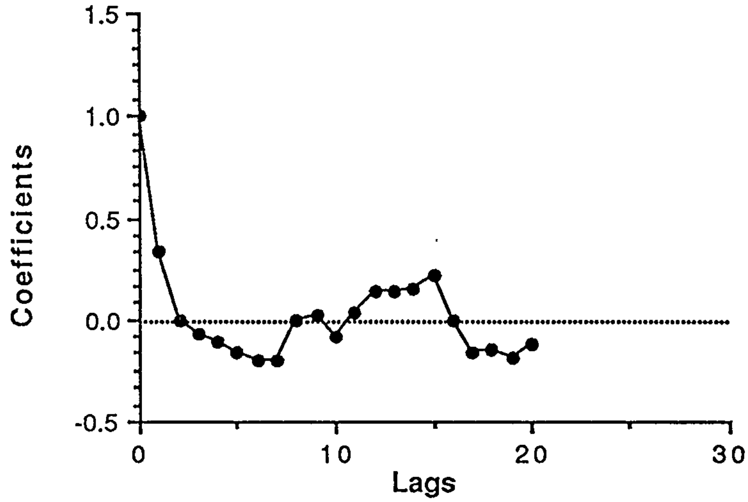


Figure 5.8 Autocorrelogram for annual departures shown in Figure 5.7

The significant 15 year cycle can be depicted clearly on the residual plot and by Table 5.5. The first complete cycle was from 1910 (179.20 mm) to 1925 (177.5 mm). During that period there were nine instances (60%) of negative departures versus the six (40%) positive. The second cycle phase continued to 1940 (113.10 mm). Once again there was a greater number of negative departures with 10 (67%) compared to the five (33%) positive. At 56.66 mm, the 1955 third peak was roughly half the amount of the first two. However, when compared to the surrounding values, it was the greatest positive departure during a 23 year period.

Table 5.5 Fifteen year cycle between peak departures (mm)

Year	Value	to	Year	Value
1910	179.20		1925	172.50
1940	113.10		1955	56.66
1955	56.66		1968	159.68

After a 45 year stretch corresponding to the 15 year expected cycle the data set, the slightly deviates from the pattern. The time between the next peaks decreases to 13 years from 1955 to 159.6 mm in 1968. As experienced during the previous cycles there was a far greater number of negative (9) departures than positive (4). There was another 13 year between peaks period which overlapped the previous one. Even though there would appear to be an indication of a 13 year cycle, the coefficient value of 0.1423 had a calculated significance value (1.19) well below critical.

In regards to the 'half' cycles for lag years six and seven, they appeared to be better camouflaged by the plot. After a detailed investigation there appeared to be a pattern with two negative departures sharing a positive peak between six and seven years away. There were three distinct and two probable occurrences of two 'twinned' negative departures sharing a positive peak departure. As an indication to how close the negative departure values were, the greatest difference between pairs was 3.2 mm for 1918 and 1919. Through close inspection, the six and seven year half lags were clearly indicated in the data set (Table 5.6).

Table 5.6 Six and seven year pattern from negative to positive departures

Twin Pits Value (mm)	Peaks Value (mm)
1904 (-47.5) & 1905 (-46.0)	1910 (179.2) & 1911 (80.8)
1918 (-62.7) & 1919 (-65.9)	1925 (177.5)
1932 (-74.0) & 1933 (-73.0)	1940 (113.1)
1944 (-57.0) & 1945 (-59.2)	1951 (51.36
1960 (-72.7) & 1961 (-74.7)	1967 (150.5) &1968 (159.6)

5.6 Summary of results

In summary, average annual basin precipitation as well as the degree of variation between successive years is increasing. The basin is experiencing an increase in the amount of precipitation while having a tendency towards greater variation between years where the amount of precipitation for a given year is far greater or less than a neighboring year. The Lake Superior Basin experienced statistically significant 2.12 mm/yr increase in annual precipitation depth. Contained in this increase were three periods of varying length and each having a different rate of decrease in annual precipitation. While showing decreases, the means of the three gave indication to the overall increase in precipitation. Both the 80 year increase as well as each secondary decrease was shown to have impacted the water level of Lake Superior. The first decreasing period contributed to the lowest water levels on record for Lake Superior during this century. The second decrease can be associated with the lowest lake level since 1926. The third is associated with a below normal level in 1977. There were no trends showing a substantial increase during the periods surrounding the decreases.

There were no indication of significant complete cycles contained in annual precipitation. One, lag 15, was 0.01 from being significant. The only coefficient to be proven significant was -0.2334 at lag 14. There was five instances contained in the data set that were used to exemplify the 'half' cycle. With such a period, it may be expected to experience a reduction in annual precipitation with a 'pit' occurring 14 years, on average, from a wet peak year. A hindrance to the analysis was the relative short data set and the limitation of the autocorrelation program to one-quarter that data set length. A cycle may exist at a period greater than the 20 year lag examined. Any cycle over 20 years may provide some useful insight into the occurrence of the two decreasing trends contained in the data set.

About the variability of annual precipitation, in the first 40 years there were 26 (65%) occurrences in which there were departures from the mean less than the average of

85.74 mm. The final 40 had 24 (60%) below average. For the data set 63% (50) of the values had precipitation departures below the expected. While there was a higher frequency of negative departures, the fewer positive ones made up for the lack in numbers by greater overall departures. From 1940 to 1960 there were 14 below average departures indicating a tendency for annual precipitation to become more similar in nature for successive years. The second, third, seventh and eighth decades of this century had a higher degree of variation in annual precipitation with coefficients exceeding 10%. The remaining decades had variations less than 8%.

There is a significant pattern with a period of 6 and 7 years separating precipitation that shows large changes from year to year to years with below normal changes. The series contains a 15 year cycle indicating above normal differences in successive annual precipitation amounts occur in 15 year intervals.

CHAPTER 6

SEASONAL ANALYSIS OF MONTHLY PRECIPITATION

6.1 Introduction to Monthly Precipitation

The investigation into seasonal precipitation characteristics and possible variation, was undertaken in order to get a more detailed look on a shorter time period at precipitation characteristics in the Lake Superior Basin. An investigation into the seasonal precipitation may provide insight for the 2.12 mm/yr statistically significant increasing trend in annual basin precipitation data. The main purpose was to derive a seasonal classification for monthly precipitation which can be related to Lake Superior. Secondly, investigate the characteristics of seasonal precipitation for any unique and/or distinct change or pattern. The main data set consisted of monthly precipitation for the Lake Superior Basin, 1900-1980, compiled by Quinn and Kelley (1983) of the GLERL.

There have been conflicting statements concerning the seasonality of precipitation in the Lake Superior Basin. Derecki (1980) stated that precipitation varies seasonally, with winter lows and summer highs, while Phillips (1978) indicated that annual precipitation totals are quite similar for each season, with a slight summer maximum. The difference may result from the distribution of precipitation throughout the year in any one area. The areas in Upper Michigan and Ontario influenced by lake effect snow would show little variation in precipitation throughout a year. Individual snow belt areas may experience equal to greater precipitation amounts in a given winter than in any other season. For most areas yearly precipitation amounts can be related to the seasons.

Table 6.1 contains the distribution of average monthly precipitation. The percentages represent the proportion each monthly value is of average annual precipitation. The monthly values indicate June and September are normally the wettest months September is the primary monthly precipitation peak accounting for an average 12% of yearly precipitation while June contributes 11%. February is normally the driest month, contributing five percent, 35.0 mm, of the annual precipitation. The summer months of June, July, August and September account for 343.1 mm (45%) of the total annual precipitation while the winter months December, January, February and March average total contribution is 23% or 173.4 mm. The remaining months provide 246.4 mm (32%) to the total yearly precipitation.

Table 6.1 Monthly distribution and percentage of annual precipitation (mm)

Month	Precipitation	Month	Precipitation
Jan.	46.1 (6%)	July	84.7(11%)
Feb.	35.8 (5%)	Aug.	83.3(11%)
Mar.	44.0 (6%)	Sep.	89.5(12%)
Apr.	59.5 (6%)	Oct.	66.6 (9%)
May	69.1 (9%)	Nov.	61.2 (8%)
June	85.6(11%)	Dec.	47.5 (6%)

Figure 6.1 shows the normal monthly precipitation distribution with months generally thought as 'warm', May - September, experiencing greater amounts of precipitation than the 'cool' months, October - April. The graph reveals a peak-valley pattern, with the yearly maximum of 89.5 mm in September and a subsequent minimum of 35.8 mm in February. The monthly distribution of precipitation, in which the 'warm' months are expected to have greater precipitation and the 'cold' months the least, can also be shown by the frequency each month receives the greatest amount of precipitation for a seasonal year (Fig. 6.2). The second wettest month, June, had the highest frequency of seasonal peaks with 20. June has a 25% chance of being the wettest month in a given year.

The remaining 'warm' months of July (16), August (13) and September (17) have the majority of peaks. They make up 82% of the wettest months.

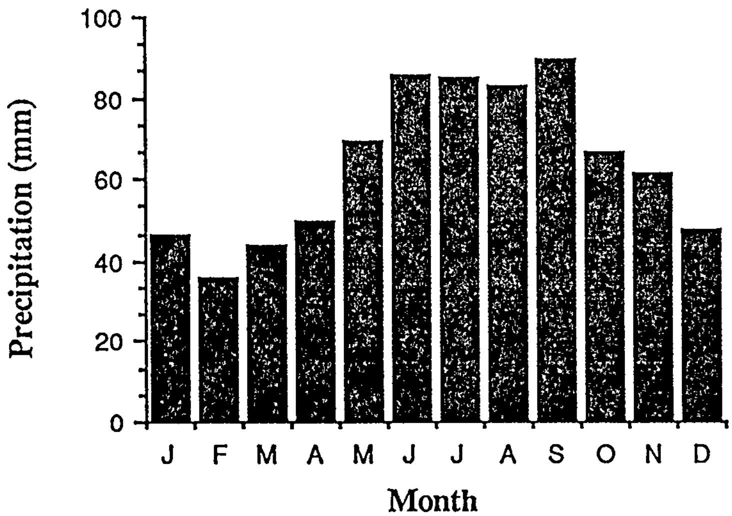


Figure 6.1 Average monthly precipitation, 1900-1980

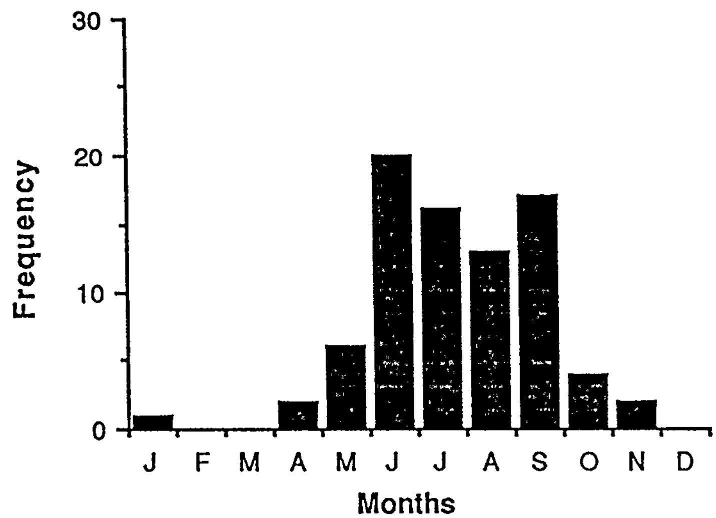


Figure 6.2 Frequency each month attains the greatest precipitation in a year

The distribution of precipitation peaks per month was quite similar in nature to monthly precipitation distribution except the peaks are reversed. The months which may be considered to be in winter, December to March, had one peak. The lone peak in January may be unique when neither December or February has one. It occurred in 1936 at 88.5 mm. This is more than double the January average of 43.9 mm.

6.2 Definition of Season

Phillips (1978) used the four seasons of the solar calendar to show the percentage of annual precipitation each season received on average. He determined that summer had a high of 30%, with 28% in autumn, 23% for spring and a low 19% in winter. The use of the four seasons may, at times be appropriate since the climate in the Lake Superior Basin is characterized by four distinct seasons. So it could be assumed that there would be a similar distribution of monthly precipitation to follow that of the solar seasons. For this study there was need to define a useable seasonal classification for the Lake Superior Basin which would be better suited for the precipitation characteristics than the four seasons (spring, summer, fall and winter) comprising the solar calender. As well as one that can be incorporated with the yearly change in the lake level of Lake Superior. The objective was to derive a two season year directly related to a component of Lake Superior.

It has been proven the surface water temperature of Lake Superior influences precipitation within the basin. Deviation from the normal march of lake temperature may influence the monthly distribution of precipitation. This combined with annual variations in storm frequency may be considered the main influences on seasonal precipitation variation. The impact the lake has on the areal distribution of precipitation was a main reason to use EUD precipitation for the analysis. It would absorb the variations in monthly precipitation depths found between regions.

6.2.1 Classification of Seasons Using a Water Budget Method

For defining a basin year containing two seasons, a method was used which incorporates a variable directly associated with the surface water temperature of Lake

Superior. The variable was evaporation from the surface of Lake Superior. A water budget method was picked with the difference between precipitation and lake evaporation acting as the determinant for season classification (Table 6.2).

Table 6.2. Classification of seasons using a water budget method (mm)

Month	Precipitation (P) Lake	Precipitation (P) Land	Evaporation (E)	P - E Lake	P - E Land
Jan.	34	46	78	-44	-32
Feb.	23	36	50	-27	-15
Mar.	56	44	24	32	20
Apr.	43	50	19	24	31
May	94	69	-03	97	72
Jun.	84	86	-10	94	96
Jul.	76	85	-02	78	87
Aug.	103	83	08	95	76
Sep.	75	89	69	06	20
Oct.	57	67	67	-10	00
Nov.	58	61	92	-34	-31
Dec.	46	47	105	-59	-58

The first season consists of the wet months having surplus water resulting from greater precipitation than evaporation. The second season contains the dry months when the evaporation amount exceeds the precipitation resulting in a water deficit. A water budget method was employed by Schertzer (1978) and Derecki (1980) to determine the evaporation from open water on Lake Superior through calculating the difference between the water supply entering the lake and that leaving as outflow. Both overlake and overland precipitation values were used to double check the seasonal classification.

Negative evaporation values for May, June and July represent periods when more water is added to Lake Superior from low level condensation than lost through evaporation. With the reduction in evaporation, the precipitation falling upon the lake surface has a direct, immediate impact on the water level greater during these months than months with higher evaporation values. Water surplus occurs in warm months with June having the greatest at 94 (lake) and 96 (land) mm. The deficit season has a low in December at 57 mm (land) and 59 mm (lake). The great deficit can result from the reduction in precipitation combined with the greatest evaporation amount at 105 mm. The seasonal year as defined runs from March through February. The first seven months represent the surplus season and the remaining five the deficit season (Fig 6.3).

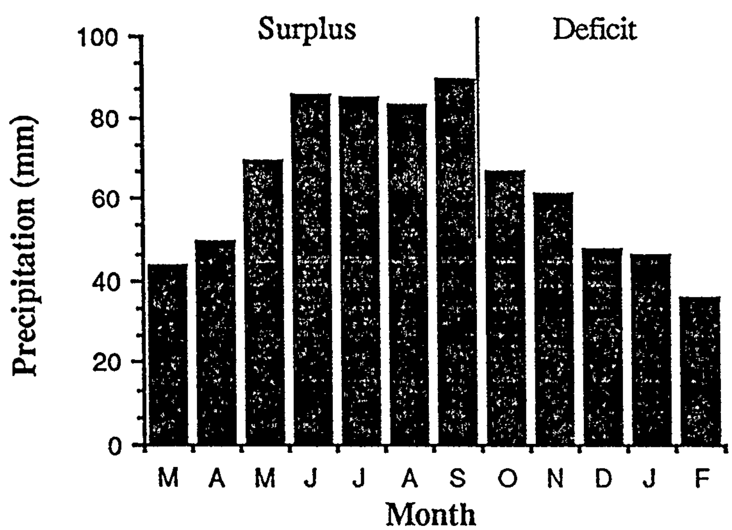


Figure 6.3 Seasonal distribution and classification of average monthly precipitation

From the calculations the months are divided into a surplus season containing seven wet months (March, April, May, June, July, August and September) and a deficit season of five dry months (October, November, December, January and February). Though

October indicates an equilibrium between precipitation and evaporation, in reality it experiences an average deficit of 0.4 mm. Statistics for each season are contained in Table 6.3

Table 6.3 Statistics for the two seasons (mm)

Statistic	Surplus	Deficit
Mean	504.9	257.0
Maximum	687.8	387.4
Minimum	374.1	178.8
Range	313.7	208.6
Stan. Dev.	68.1	47.4
Coef. of Var.(%)	13.5	18.4

The importance of this classification type is related to the degree of impact each season has on water level. During the deficit season, the level of Lake Superior is more susceptible to water loss from evaporation. Normally the lake level is decreasing during the period of greatest evaporation. The drop in lake level may be enhanced by a reduction in precipitation during the deficit season. Since the dry months correspond to the cold season much of the precipitation that falls on the basin is frozen and held in storage. On the other hand the decline in lake level may be subdued if there were to be large quantities of direct snowfall onto the lake surface.

The surplus season corresponds to seasonal increase in lake levels. During this time stable conditions exists over the lake. Low level condensation is at maximum adding water to Lake Superior. A reduction in the amount of precipitation may result in the suppression of the rate at which the water level increases. It may or may not have the impact as in the dry season due to the importance of spring runoff of the snowfall from the prior winter. With that, the two seasons are related in that the moisture that fell during the winter is stored as snow until the warmer spring. Given an abnormally wet surplus season, the combination of spring runoff and rainfall would increase the level at a much higher rate.

6.3 Surplus Season Characteristics

The surplus season appears to share certain characteristics exhibited in the annual precipitation data. Precipitation amounts are shown to be variable from season to season (Fig. 6.4). The precipitation value increases or decreases at a substantial amount. There were 19 occurrences having a seasonal difference over 100 mm. While at other times the changes have been less distinct. The amount of precipitation between 12 neighboring seasons was less than 25 mm. The data may be labeled as variable with periods of consistency.

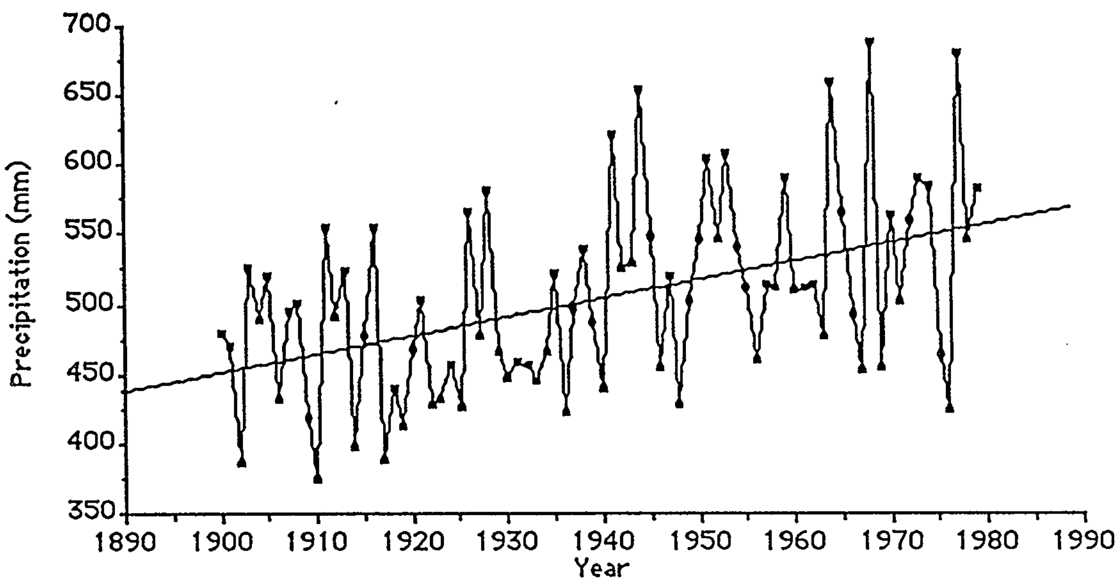


Figure 6.4 Plot and trend of the surplus season

The surplus season has a mean of 504.9 mm which is 66% of the average annual total. Contained in the data is a maximum of 687.8 mm in 1965, a minimum in 1910 of 374.1 mm for a seasonal range of 313.70 mm. The data has a greater degree of relative variation compared to the annual data. The standard deviation value, 68.1 mm, is 13.5% of the seasonal mean. The relationship is moderate as indicated by the correlation coefficient of 0.46. Further indication of the variability contained in the plot is shown by having 21% of the surplus season plot explained with increase in time.

6.3.1 Trends

The plot of the surplus season gives indication to an increase in precipitation during wet months. To quantify the apparent increase regression analysis was applied to the data in order to derive a trend. The tendency of surplus seasons through time can be shown by the equation:

$$P_S = 1.34t - 2100.59 \tag{6.1}$$

where P_S is the expected precipitation for a surplus season in year t. The relationship is statistically significant at the 99% confidence level. With 1 regression and 79 residual degrees of freedom the F-calculated value, 20.78, is greater than the 7.33 F-critical value. There has been a significant 1.34 mm increase per season in the amount of precipitation received during the surplus season. Contained in the primary trend were two periods showing greater rates of increase in surplus season precipitation. The increases were proven to be significant at the 99% confidence level. Table 6.4 contains the trends and their statistics.

Table 6.4 Primary and secondary trends of the surplus season

Period	r^2	Trend	F-cal	F-crit	Df
1900-1980	.46	1.34	20.78	7.33	1,79
1917-1944	.32	4.38	12.12	7.22	1,26
1930-1944	.48	10.34	11.85	9.07	1,13

From 1917 to 1944 precipitation during the surplus season increased at 4.38 mm/season which can be shown by the equation:

$$P_S = 4.38t - 7976.51 \tag{6.2}$$

where P_S is the expected surplus season precipitation in year t. This increase contains a period where seasonal precipitation increased at still a greater rate. Expected surplus season precipitation from 1930 to 1944 increased an average 10.34 mm/season. The increase is shown by the equation:

$$P_S = 10.34t - 19516.93 \tag{6.3}$$

where P_S is the expected surplus season precipitation in year t. There were no other significant periods showing either an increase or decrease in precipitation. The plots of annual precipitation and lake levels were not distinctly affected by the secondary trends, other than contributing to the general increases. The two trends are depicted in Figures 6.5 and 6.6.

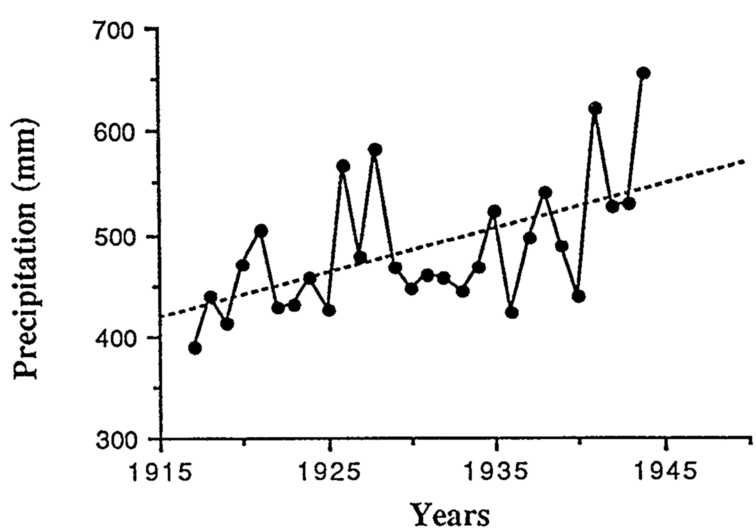


Figure 6.5 Surplus season trend, 1917-1944

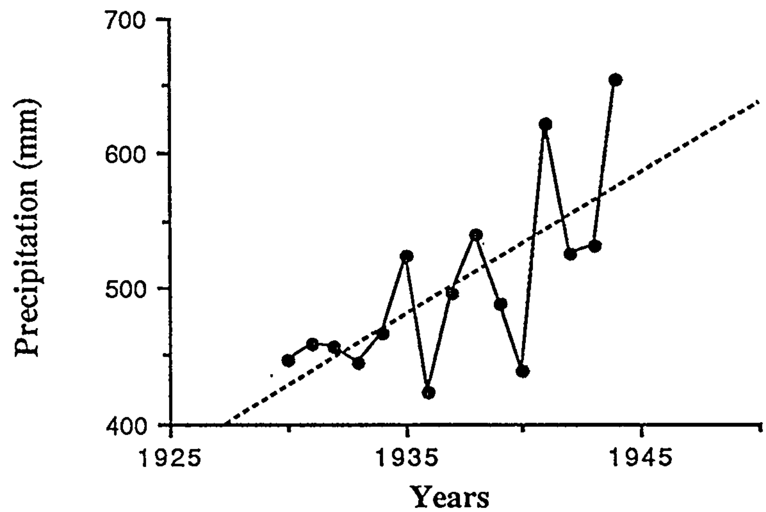


Figure 6.6 Surplus season trend, 1930-1944

6.3.2 Cycles

Residual precipitation values from the surplus season underwent autocorrelation analysis for determining the possible existence and length of cycles. A autocorrelogram was constructed from the correlation coefficients (Fig. 6.7). The autocorrelogram shows three distinct peaks at lags 9 (0.2145), 13 (0.1879) and 15 (0.2242). Distinctive negative correlation coefficients were lags 5 (-0.1059), 14 (-0.1268) and 19 (-0.1199). A two tailed Z-test was used for determining whether the coefficients were significant. With a Z-critical value of +/- 1.64 only lags 9 and 15 were significant with Z-values of 1.81. Therefore two cycles exist in the surplus season. The first of nine years indicates precipitation during a surplus season would experience a peak every nine years. The second cycle entails surplus seasons to show peaks every 15 years. This and the cycle of nine years can be found on the plot of the residuals (Fig. 6.8).

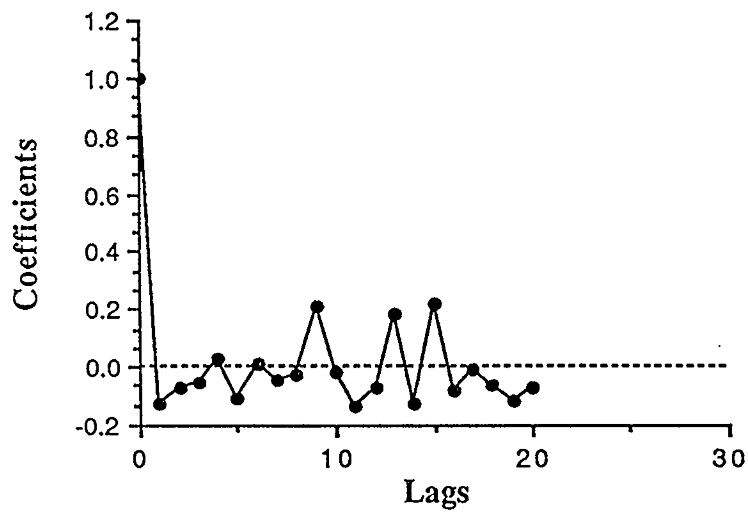


Figure 6.7 Autocorrelogram for surplus season residuals shown in Figure 6.8

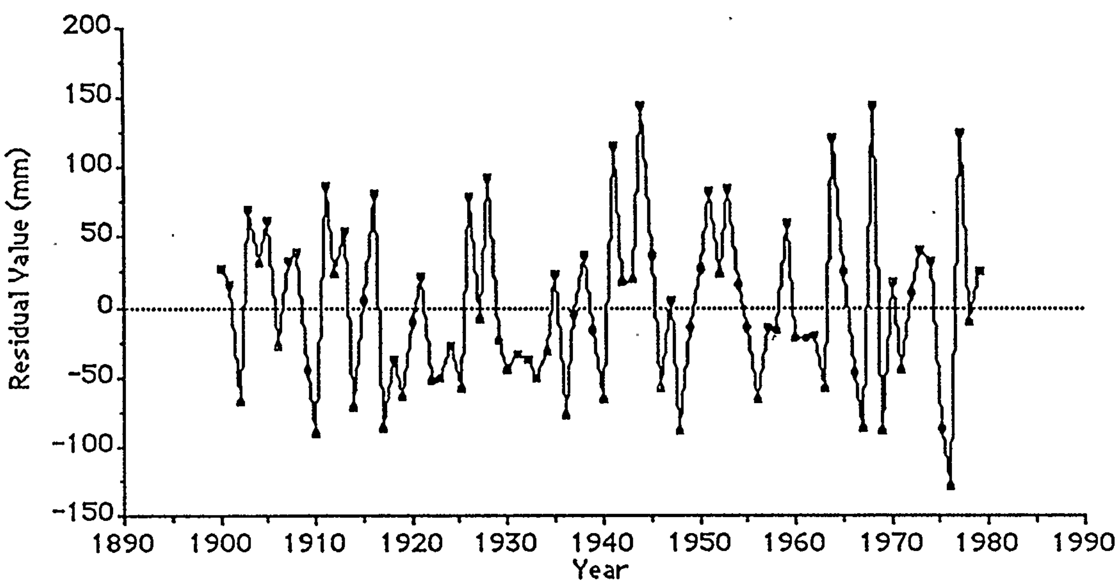


Figure 6.8 Residual values for the surplus season

Given two cycles any intertwining of them may have contributed to the pattern of cycles being broken or disrupted after 1940. Both patterns begin with the calculated periods between high precipitation 'peaks'. The cycle of 9 years becomes discontinuous past 1953 only to be reinstated by a new cycle with origins in 1941. This second cyclic pattern continues to 1977. The original 15 year cycle starts in 1911 and ends in 1941. A second cyclic pattern begins 1928 and continues the near perfect 15 year period between peak precipitation occurrences until 1974. The disruption of the cycles may be one cause to the reduction of variability found during the mid-century. The values from the plot are contained in Tables 6.5 and 6.6.

Table 6.5 Nine year cycle for the surplus season

Year	Value (mm)	Year	Value (mm)
1926	79.3	1941	115.3
1935	24.1	1950	28.4
1944	143.7	1959	60.4
1953	85.3	1968	144.6
		1977	125.4

Table 6.6 Fifteen year cycle for the surplus season

Year	Value (mm)	Year	Value (mm)
1911	87.2	1928	92.0
1926	79.3	1944	143.7
1941	115.3	1959	60.4
		1974	34.1

The cycles have a common multiple of 45 years. At this time interval it would be expected that their wave crests would meet to produce a precipitation amount that would be far greater than what is expected. That year may be classed as an extreme occurrence. Such exists with the high residual values for 1944 (143.7 mm) and 1968 (144.6 mm).

6.4 Deficit Season Characteristics

The scattergram containing the values for the deficit season continues the pattern found in the surplus and annual plots. There appears to be a general increase in precipitation during the deficit season. This season may contain a greater degree of variability with more distinct differences in precipitation amounts between years. During a seven year period from 1931 to 1938 the values show a tendency to be more consistent. A trend towards decreasing precipitation may exist in the first third of the data from approximately 1915 to 1925. Other periods of increasing and decreasing tendency are found throughout the plot (Fig. 6.9).

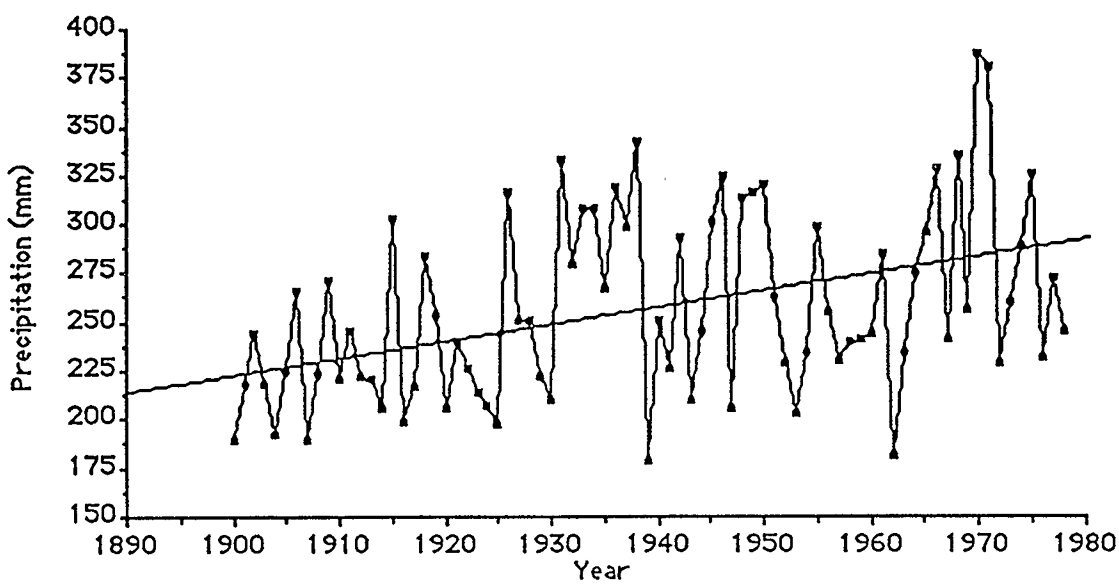


Figure 6.9 Plot and trend for deficit season

The average precipitation for the deficit season is 257.0 mm which is 34% of the average annual mean. The seasons have a range of 208.6 mm resulting from a minimum of 178.8 mm in 1939 and a 387.4 mm in 1970 maximum. The data has the highest proportion of variability of the examined data sets with a 47.7 mm standard deviation at 18.4% of the mean. In response, the relationship is weaker with a correlation coefficient of 0.39 resulting in 15% of the variation shown by the plot to be explained.

6.4.1 Trends

Analysis of Figure 6.9 gives preliminary indication that precipitation for the deficit season has increased during this century. The tendency for the deficit season during this century can be shown by the regression equation:

$$P_d = 0.80t - 1295.82 \qquad (6.4)$$

where P_d is the expected deficit season precipitation for year t. Precipitation during the deficit season has increased at 0.80 mm per season. The significance is shown by the F-value of 13.63 being greater than the F-critical value 7.33 at the 99% confidence level with 1 regression and 77 residual degrees of freedom. From further examination of the plot additional patterns were found. The five secondary trends can be shown by the following regression equations:

$$P_d = 2.24t - 4056.76 \qquad (6.5)$$

$$P_d = 19036.53 - 9.79t \qquad (6.6)$$

$$P_d = 9.56t - 18331.31 \qquad (6.7)$$

$$P_d = 6.33t - 12143.13 \qquad (6.8)$$

$$P_d = 16.98t - 33092.07 \qquad (6.9)$$

where P_d is the expected deficit season precipitation in year t. Contained in the first secondary trend of 2.24 mm/season was a seven year decrease in expected deficit season precipitation at an average 9.79 mm/season. This decrease had a substantial impact on both annual precipitation as well as the water level of Lake Superior. This decrease is comparable with the decreases shown in Figures 1.1 and 5.1. Table 6.7 contains the primary trend and five secondary trends with their explained variance (r^2), the trend, F-test calculated (F-cal) and critical values (F-crit), with the degrees of freedom (Df) and at what confidence level.

Table 6.7 Primary and secondary trends in the deficit season

Period	r^2	trend	F-cal	F-crit	Df	Conf. Level (%)
1900-1980	.60	0.80	3.63	7.35	1,77	99.0
1900-1938	.35	2.24	19.57	7.40	1,37	99.0
1918-1925	.67	-9.79	12.41	8.81	1,6	97.5
1939-1950	.43	9.56	7.65	6.94	1,10	97.5
1953-1971	.41	6.33	11.80	8.40	1,17	99.0
1962-1971	.60	16.98	11.81	11.26	1,8	99.0

At the end of the first decrease in 1938 at 342.0 mm the next secondary trend begins in 1939 with the driest deficit season in the data set at 178.8 mm. This establishes a pattern in which each of the two remaining secondary trends begin with the two lowest values, 202.6 mm in 1953 and 181.1 mm in 1962. The large increase in expected deficit season precipitation from 1962 to 1971 at 16.98 mm/season may have provided a substantial impact on the water level of Lake Superior. The lake level shows an increase for the same time period. Graphic examples of the five secondary trends are contained in the following plots (Figs 6.10, 6.11, 6.12, 6.13 & 6.14).

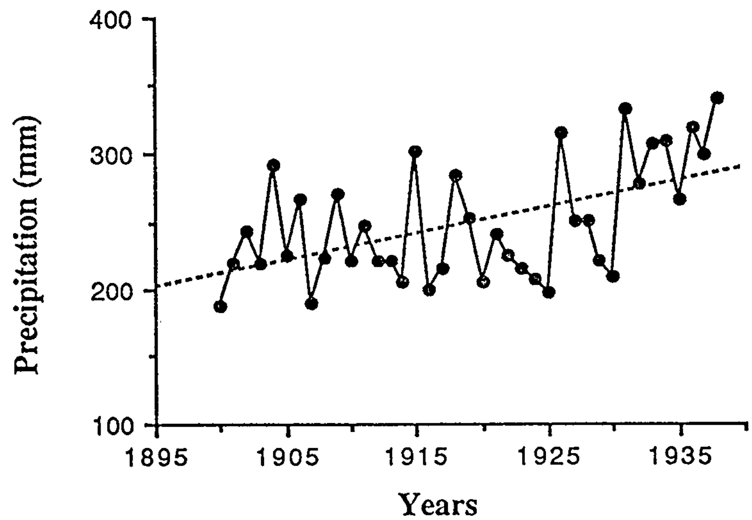


Figure 6.10 Deficit season trend, 1900-1938

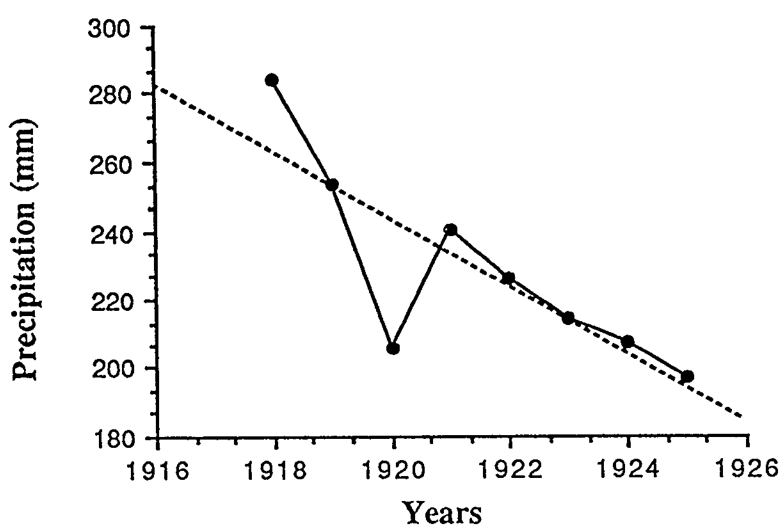


Figure 6.11 Deficit season trend, 1918-1925

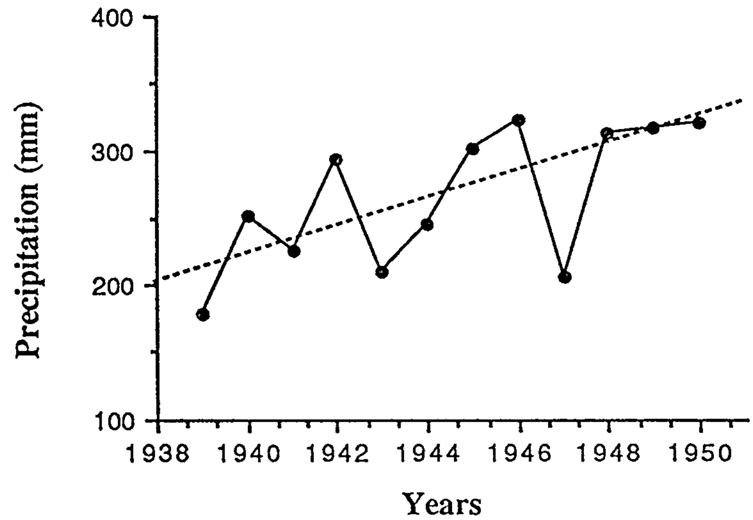


Figure 6.12 Deficit season trend, 1939-1950

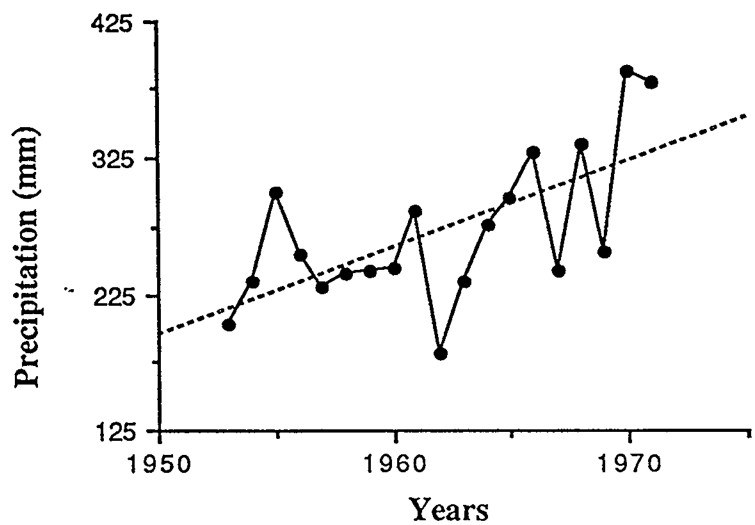


Figure 6.13 Deficit season trend, 1953-1971

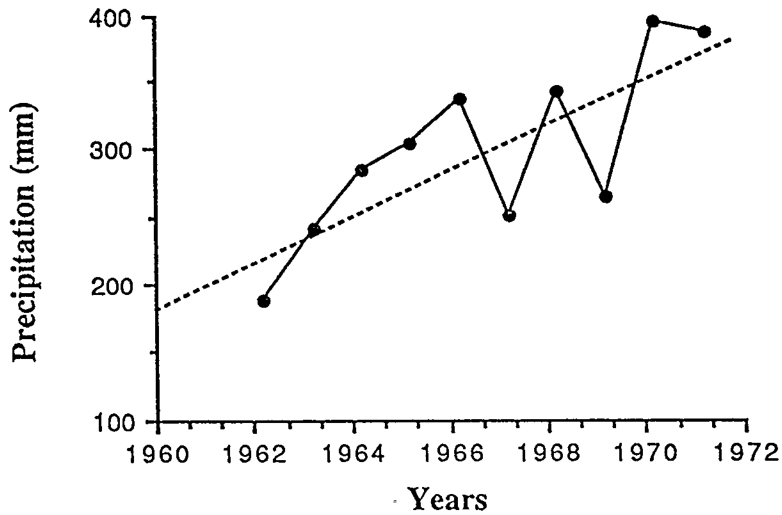


Figure 6.14 Deficit season trend, 1962-1971

6.4.2 Cycles

Autocorrelation analysis on the residual values of the deficit season precipitation was used to determine the existence and length of possible cycles. The autocorrelation coefficients are contained in the autocorrelogram (Fig. 6.15). Distinct coefficients are 0.1773 and -0.2709 for lags 4 and 8 respectively. The remaining coefficient values are situated between lag 5 at 0.1105 and -0.0882 for lag 12. A Z-test was used to determine the significance of the coefficients. At the +/- 1.64 significance value lag 8 is significant at 2.28 while lag 4 with 1.54 lacks significance. No complete cycle exists for the deficit season. However, a pattern consisting of a period of eight years between years of above and below normal precipitation does exist and is of significance. By examining the residual plot (Fig. 6.16) numerous occurrences were found that corresponded to the significant eight year pattern. Table 6.8 contains the years and corresponding values that defines the pattern of eight years.

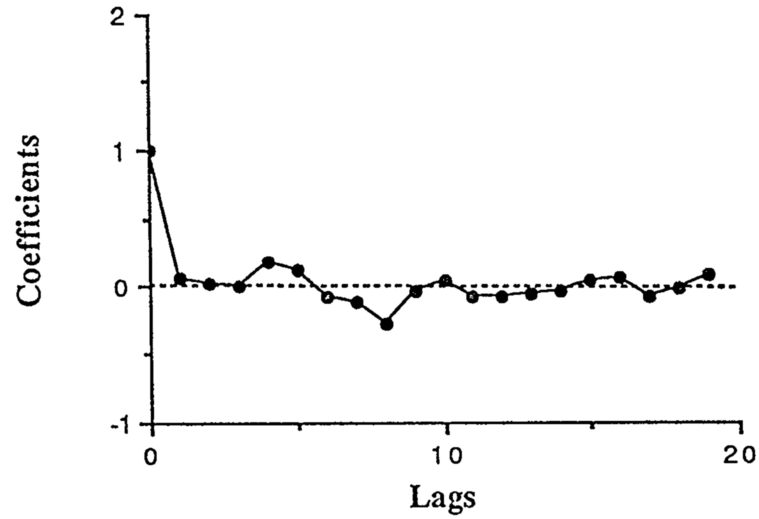


Figure 6.15 Autocorrelogram for deficit season residuals shown in Figure 6.16

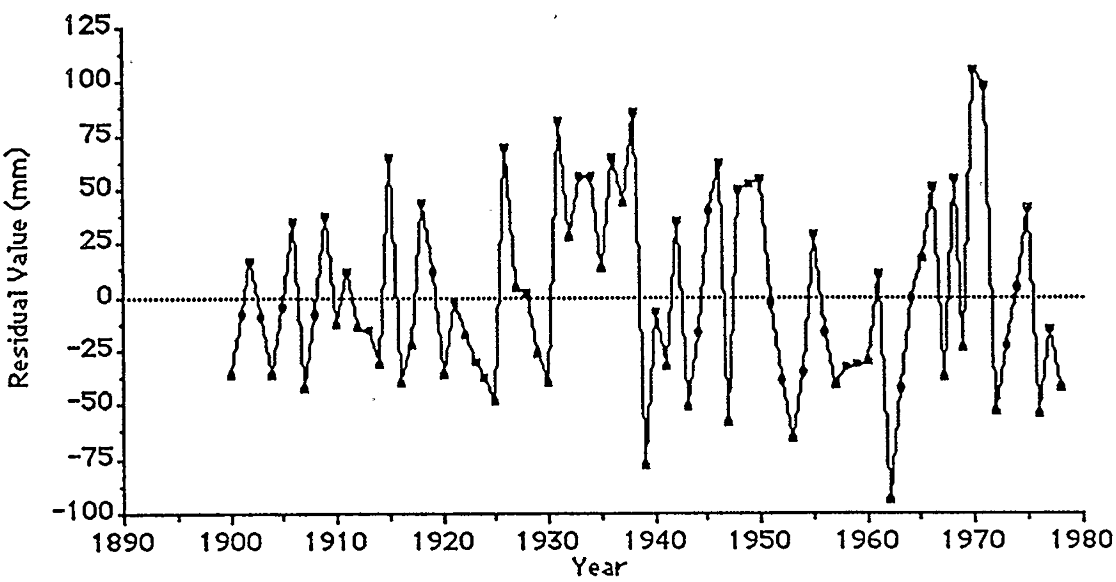


Figure 6.16 Residual plot for the deficit season

Table 6.8 Eight year 'half cycle' pattern for deficit season

Year	Value (mm)	to	Year	Value (mm)
1907	-41.7		1915	64.7
1931	81.9		1939	-78.2
1947	-57.8		1955	29.0
1962	-94.4		1970	105.5

6.5 Summary of Results

Using a water budget method the monthly precipitation was divided into surplus and deficit seasons. This seasonal classification relates to the period when Lake Superior gains water during the seven month surplus season resulting from precipitation input exceeding evaporation loss. The deficit season is a five month period when losses from evaporation are greater than the precipitation amount. Both seasons have experienced a statistically significant increase in their precipitation amounts during this century. Combined the surplus season increase of 1.34 mm and 0.80 mm increase for the deficit. The two seasons have differing patterns contained in them. While the surplus season has two significant cycles, the deficit contains no cycles only a eight year pattern between precipitation extremes.

The seasons appear to be independent of each other as shown by their tendency to act in opposition to one another. With a total of seven secondary trends between the seasons there was no indication of correlation only partial overlaps. The lack of correlation shows up in the plot of annual precipitation. Another example would be when the surplus season has experienced consecutive years of precipitation increase the deficit season would receive reduced amounts. This can be seen in the residual pattern. Over half (54%) of the seasonal residuals were opposite.

CHAPTER 7

CONCLUSION

7.1 Summary

This chapter will summarize the results from the analysis of precipitation climatology in the Lake Superior Basin. It is felt that the thesis has accomplished the objectives set forth in the introduction. The precipitation climatology of the Lake Superior Basin has been analyzed to the extent necessary to provide a basis for further research into areas that utilize precipitation. Most important would be continuing towards further understanding of the relationship between water level change in Lake Superior and how precipitation influences the degree of change.

7.2 Discussion

The increase in annual precipitation has been closely matched by an increase in the water level of Lake Superior. A continuation of the trend in annual precipitation would increase runoff volumes and direct precipitation creating above normal lake levels. Higher lake levels are deemed positive by interests associated with water borne commerce and hydroelectric power generation. Property owners along the lake shore look upon high water levels negatively. Lake induced erosion would worsen as levels increase. The impact of the increased volume of Lake Superior would be felt in other Great Lakes. This can be implied through using the values from Botts and Krushelniki (1987) outflow from Lake Superior, at an average 22 cms, is 43% of the total water supply entering Lake Huron. The increased variability found during the last two decades may restrict the accuracy of any predictions towards the future behavior of both basin precipitation as well as lake level.

The 'Greenhouse Effect' may play an important role with future precipitation tendencies. The past and present impact on the Lake Superior basin is uncertain, but nevertheless it may be partially responsible for the greater variability. The largest change in between successive years occurred recently between 1976 (681.4 mm) and 1977 (991.1 mm). The 309.7 mm change is associated with the wettest year of the data set and the driest since 1940. More recently, according to the US Corps of Engineers (1988), the first six months of 1988 were the driest in 100 years, while record precipitation amounts fell during two of the remaining months.

Prior to being concerned about the 'Greenhouse Effect' and the possible effects of a warmer planet there has been talk about a climate change towards the opposite in the Great Lakes Basin. A change in climate towards wetter and cooler.may have begun around 1970. This is shown with only the precipitation for 1976 below normal. The change to a wetter and cooler climate may be short lived as a result of an increase in atmospheric temperature.

A model showing the possible results on the Great Lakes Basin from an increase in Carbon Dioxide of twice the pre-industrial amount was examined by Environment Canada (1987). The main points are an average increase in annual temperature of approximately 4.5°C., with an accompanying 8% increase in annual precipitation. For the Lake Superior basin the increases would result in an average annual precipitation 61.03 mm greater than present at 823.93 mm. The basin would have an expected annual temperature around 8.2°C.. The increases are not to be considered certainties but more like possibilities. The lake may be able to buffer any abrupt changes in climate.

7.3 Conclusions

The research has produced the following conclusions:

1. The meteorological station network used for the study was adequate for providing relevant information concerning precipitation characteristics in the Lake Superior

Basin. Though not optimum, the stations give the best estimate possible given the inherent limitations.

2. Nearly three-fifths (59%) of the precipitation falling on the basin is influenced by the surface water temperature of Lake Superior. For the station network used, the amount decreases to 42%. The degree of influence increases from southwest to northeast.

3. A significant relationship exists stating that for every degree Celsius increase in the surface temperature of Lake Superior precipitation is expected to increase by 3.81 mm. This relationship implies precipitation is greater during the late summer to early fall when the water temperature is warmest.

4. Longitudinal location was determined to be the most important factor in explaining the amount of annual precipitation received throughout the basin, the degree of influence on the precipitation provided by Lake Superior and the amount of relative variation exhibited by precipitation. Longitudinal location accounted for roughly 48% of the distribution of annual precipitation and the degree of influence by Lake Superior.

5. The month with the greatest average precipitation, September, correlates to the warmest lake surface temperature.

6. Travelling west to east annual precipitation is expected to increase 26.44 mm for every degree of longitude.

7. Annual precipitation has increased 2.12 mm/yr during this century. The increase has not been constant with three periods showing decreases in annual precipitation ranging between 7.57 mm/yr and 31.03 mm/yr for periods of 7 to 15 years. All four trends were shown to be important in the behavior of the water levels of Lake Superior, with the primary trend corresponding closely to the 2.10 mm/yr increase in lake level.

8. There exists a significant pattern containing a 14 year period between annual precipitation amounts which are excessively above the expected value and those 'pits' well below the expected amount.

9. With precipitation increasing constantly through the century, during the first 60 years variation decreased. Recently, however, variability along with precipitation has increased from variations less than 8% to over 11% .

10. Annual departures contained a significant cycle having a period of 15 years between peak positive departures. It is expected to have two years with opposite, one above and the other below normal, precipitation amounts every 15 years. In addition a significant pattern exists in which two years of similar precipitation are situated six to seven years from a peak departure.

11. The data was divided successfully into a year containing two seasons. The surplus season shows an increase of 1.34 mm per season while the deficit increase is 0.80 mm.

12. With 54% of the seasonal residuals opposites and no secondary trends in direct correlation, the seasons appear to be independent of each other.

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