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EARLY 20TH CENTURY LAKE SUPERIOR BASIN PRECIPITATION ESTIMATES

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EARLY 20TH CENTURY LAKE SUPERIOR BASIN PRECIPITATION ESTIMATES

Raymond A. Assel, David C. Norton, and Frank H. Quinn

Abstract. A method to provide improved estimates of the annual value of over-land areally weighted Lake Superior basin precipitation is described and compared with the traditional Thiessen method. The method consists of calculating the ratio of areally weighted precipitation to precipitation at individual grid cells in the basin during periods when station density is high. The ratios are used in conjunction with data collected during the late 19th and early 20th centuries to generate improved basin precipitation estimates. The “ratio method” provides precipitation estimates for that period that are more in agreement (relative to the Thiessen method) with trends in flow for the outlet of Lake Superior.

1. INTRODUCTION

The Laurentian Great Lakes are an important natural resource containing about 95% of the United States and 20% of the world’s fresh surface water supply; about one-eighth of the U.S. population and one-third of Canada’s population live within the Lakes drainage basin. Lake Superior, located between the 46th and 49th parallel and having a surface area of 82,100 km^2 and a mean depth of 149 m, is the largest, the farthest upstream, and the furthest north of the five Great Lakes (Figure 1). Long-term precipitation data are important in climate and water resources studies of the Great Lakes (Quinn, 1981) and in developing models that are useful tools for weighing regulation policy options (Croley, 1989). A historical review showed annual precipitation over the Canadian portion of the Lake Superior basin to be less than the precipitation over the U.S. portion during the first half of this century, and greater than the U.S. precipitation during the second half of this century (T. Bullock -personal communication, 1995, Environment Canada, Atmospheric Environment Service, Downsview, Ontario, Canada).This could have major significance for Great Lakes water resource studies. It is likely that gage undercatchment and low station density both contributed to the lower estimates of Canadian basin precipitation. The scope of this study, however, is limited to consideration of the problem of low station density.

An independent assessment of precipitation changes can be undertaken using the Lake Superior outflow through the St. Marys River. Three-year moving averages of Lake Superior’s overland basin precipitation and outflow are highly correlated between 1920 and 1990 (r = 0.81), but the correlation is much lower betewen 1880 and 1920 (r = 0.18). Prior to about 1910, over-land precipitation on the Lake Superior basin was consistently less than the outflow through the lake’s outlet, the St. Marys River (Figure 2). This relationship started to change between 1910 and 1920, at the same time the number of precipitation gages installed on the Canadian side of the basin were increasing, bringing into question whether the precipitation data prior to about 1920 are representative. It should be noted that the natural flow through the St. Marys River was altered by construction of navigation locks, hydropower diversion canals, and compensating works (gates controlling river flow) in the late 19th and early 20th centuries (Quinn, 1978). However, the effect of these modifications on the St. Marys River flow were not of sufficient magnitude to cause the observed change in the relationship between river outflow and over-land basin precipitation (Figure 2). The objective of this study is to provide improved estimates of over-land Lake Superior basin precipitation (Croley and Hunter, 1994) for the late 19th and the early 20th centuries by the development of improved estimates of basin precipitation when station density is low. Approximately 67 percent of the Lake Superior basin lies in Canada (Figure 3). Thus, estimates of areally weighted precipitation have been more dependent upon the location, number, and accuracy of the precipitation gages in Canada than on those in the U.S. Previous studies indicate that Canadian gages have underestimated precipitation (snowfall in particular) prior to 1940 (Metcalfe et al., 1997), and both U.S. and Canadian gages have underestimated precipitation in the first half of the 20th century (Groisman and Easterling, 1994). However, it was beyond the scope of this study to develop and apply correction factors to precipitation data. We believe that Thiessen weighting of sparse Canadian gage data during the late 19th and early 20th centuries (Figure 4) adversely affected estimates of total basin precipitation and contributed to the observed dichotomy of annual precipitation between U.S. and Canadian sub-basins (Figure 5) in the late 19th and early 20th centuries. A method was developed to estimate catchment precipitation that is independent of station locations. It is described and compared to the traditional Thiessen method (Croley and Hartman, 1985). Both methods are compared to Lake Superior outflows to evaluate the better estimate.

2. METHODOLOGY AND APPLICATION TO THE LAKE SUPERIOR BASIN

2.1 General Description

The method used to estimate areally weighted precipitation consists of the following steps: (1) a cartesian grid (described below) is applied to a lake basin, and precipitation is estimated for each grid cell from available (irregularly spaced) station data in contemporary years when the number of stations is much higher than it was in the early 20th century. The grid is necessary because some of the earlier stations were discontinued or moved, and we needed to relate precipitation at the discontinued station location with contemporary basin average precipitation; (2) a ratio of total basin precipitation to precipitation at every grid cell is calculated; (3) the ratios and available station data in prior years are used to calculate multiple basin precipitation estimates; (4) the median of the calculated basin precipitation estimates is selected (for reasons explained later) as the basin precipitation.

2.2 Data Sources and Gridding Method

Gridded estimates of monthly precipitation for the Lake Superior drainage basin were calculated from monthly precipitation data [sources include: Earth Info., 1996; Assel et al., 1995; Atmospheric Environment Service, 1994] using a software package called Surfer (Golden Software, Inc. 1995). The grid consists of a 760 x 516 matrix of 1-km x 1-km cells (Figure 3). Kriging, a relatively well-known interpolation methodology, has been used to estimate regional precipitation (Dingman et al., 1988). Kriging, employing a one component linear variogram with no drift (contained in the Surfer software package), was used to convert station data to grid cell data. Kriging generates a good overall interpretation of irregularly spaced data sets and is an exact interpolator, i.e., it does not smooth the input data. Monthly precipitation grids were generated for the 1961-1990 base period, a period when station spatial density was high. The 30-year gridded average annual precipitation spatial pattern (Figure 6) resembles the long-term (1931-1960) annual precipitation in Phillips and McCulloch (1972).

2.3 Calculating the Ratio for All Cells Within the Basin

The Lake Superior drainage basin was used as a mask to differentiate between cells inside and outside the basin (Figure 3). A spatial average for each month “j” and year “y” ($Avg._{jy}$) was calculated over all the cell values inside the basin. The ratio of the average basin precipitation to that at each cell “i” was then calculated for that month and year:

$R_{ijy} = Avg._{jy} / P_{ijy}$, where P_{ijy} is the precipitation at cell “i” for month “j”, and year “y”.

Not surprisingly, an average of the monthly ratios (Figure 7) was largest in the northwest and smallest in the southeast portion of the basin, i.e., the inverse of the precipitation spatial pattern shown in Figure 6. Monthly groupings of the thirty grids (e.g., all January grids for 1961 to 1990, all February grids for 1961-1990, etc.) were sorted (largest to smallest) for each cell (from the 760 x 516 cell matrix). The *median* ratio “m” for the years 1961-1990 at each cell “i” and month “j” ($_{ij}$) was selected and output as a grid, establishing 12 monthly median ratio grids. The median of the precipitation ratios was selected because it is a more robust estimator of centrality than the average in non-normally distributed populations. Since the frequency distribution of precipitation tends to be skewed toward higher values (Cong et al., 1993), the cell ratios derived from the precipitation cellular values will tend to reflect skew characteristics in corresponding (although opposite) distribution shapes.

2.4 Calculating the Basin Precipitation from the Ratios

To estimate basin precipitation (BP_{ijy}) for month “j” of year “y” using grid cell “i”, we multiply the total monthly precipitation in cell “i” (either station data or data estimated from Kriging) for that month and year, (P_{ijy}) with the median precipitation ratio for that month and grid cell:

$$BP_{ijy} = {}_{ij} \text{ x } P_{ijk}$$

The assemblage of basin precipitation estimates (for all grid cells with rain gage data) was then sorted, and the median value *(a second median)* was selected as the estimated monthly precipitation value. Annual basin precipitation values were calculated as the sum of the monthly values. Our preliminary analysis of these data indicated that using this second median rather than an average reduced the impact of any erroneous or otherwise non-representative station data. In using this method to estimate precipitation during the first half of the 20th century, it is implicitly assumed that spatial and seasonal precipitation patterns over the Lake Superior basin have not changed significantly from that of the 1961-1990 base period.

2.5 Evaluating Station Density in the Canadian Basin

In order to evaluate inaccuracies derived from low station density, the Canadian portion of the basin was isolated for examination. The examination focused on the 1961-1990 period data to obviate undercatchment uncertainties so as to explore only network and method differences. A representative assemblage of stations reporting around 1910 were identified and plotted (Figure 8) along with the closest stations with good records for the 1961-1990 period. The greater density and continuity among U.S. stations is notable. During the 1961-1990 period, four of the five Canadian stations closed in the early 1970’s, and new adjacent stations had to be used. Thiessen-weighted monthly precipitation was computed for the Canadian basin using all (18-34) reporting Canadian stations, and separately for the selected-station network. In Figure 9 it is evident that precipitation estimates from the selected-station network rather consistently underestimate the all-station network. Selected-station ratioed values were also calculated, and they spanned the all-station Thiessen values.

Using paired t-tests with a 5% confidence level, it was determined that the selected-station network Thiessen method yielded statistically different basin precipitation than the all-station Thiessen values and the selected-station ratioed values. However, the selected-station ratioed values were statistically the same (at the 5% confidence level) as the all-station Thiessen values. Therefore, in this evaluation, the ratio method proved to be superior to the Thiessen method when limited to a small station network representative of that which existed in the early part of this century.

Gridding using all Canadian station data yielded another estimate of Canadian basin precipitation. Although statistically different, these values are broadly comparable (Figure 10) to ratioed values computed using a combined selected Canadian and selected U.S. station network (Figure 8). The reasonable fit lends credence to the methodology used in this study, i.e. the utilization of precipitation from U.S. stations as proxy data (geographically external but climatically related) to aide in estimating Canadian Basin precipitation.

2.6 Error Analysis

The remaining analysis focuses on the entire Lake Superior drainage basin. The grid ratios used in this study were calculated from 30 years of data: 1961-1990; the root mean square error (RMSE) of annual precipitation using these ratios was 40 mm, and the standard deviation of the gridded data about its 30-year mean (819 mm) was 89 mm. The method of cross-validation (Ferguson, 1976) was used to obtain an unbiased estimate of the RMSE of annual precipitation for station networks from 1961 to 1990. In our application of cross-validation, we used gridded precipitation for the *even* years from 1961-1990 to calculate the ratios, and then used the station precipitation for the *odd* years (again between 1961 and 1990) and the even-year ratios to estimate annual precipitation. The process was then repeated using the odd years to calculate the ratios and the even years' station precipitation to calculate the annual catchment precipitation. The RMSEs increased by less than 18% over the independent data (47 mm and 46 mm, respectively). Thus, applying the ratios to independent data did not result in a large increase in its RMSE value. This lends credence to the RMSE of the ratio method using all years of data to derive the ratios. Precipitation values throughout the text have been rounded to the nearest millimeter.

Existing station networks (number and location of stations in the Lake Superior basin) from each year (1880-1960) were used to calculate annual precipitation for the 1961-1990 base period to evaluate the ratio method's utility to simulate basin precipitation when station networks had less stations and different spatial configurations. The station networks from 1880 to 1960 were used to select cell precipitation values from the gridded data and to calculate the annual precipitation for each year of the 30 years (1961-1990), using the ratio method. Results were compared to the actual gridded precipitation estimates using all available stations. The RMSE ranged from a minimum of 22 mm to a maximum of 68 mm, and the average RSME was 37 mm (median, 36 mm). These values lend further credence to the ratio method for calculating precipitation when the number of stations is much smaller and the distribution pattern is different (less evenly distributed) than the 1961-1990 network.

2.7 Ratio and Thiessen Precipitation Comparisons with St. Marys River Flow

During the contemporary period (1961-1990), the ratioed values compared well to the Thiessen values; the RMSE of the Thiessen estimated precipitation was virtually the same as that of the ratioed estimated precipitation (40 mm). Not surprisingly, contemporary estimates of basin precipitation from both methods tend to converge to the same value. A plot of the 3-year running mean of the ratioed data, plus and minus the RMSE for the 1880-1960 annual ratioed precipitation, provides an estimate of the uncertainty in estimated average basin precipitation in years with low station density (Figure 11). Note that the Thiessen values clearly fall outside the ratio error bounds during a majority of years prior to about 1910, and the values are also at or below the lower limit of the lower error bound most years between 1910 and 1930. A three-year moving average of Lake Superior's overland basin precipitation and outflow between 1880 and 1920 is much more highly correlated for the ratio-estimated precipitation (r = 0.57) than is a similar correlation for the Thiessen-estimated basin precipitation (r=0.18). This and a discussion on double mass curves given below provides evidence that the ratio method produces the more representative estimate of actual basin precipitation for the late decades of the 19th and early decades of the 20th century.

Double mass curves were generated for both the Thiessen and ratioed precipitation versus the St. Marys flow. The slopes between successive years were computed and then plotted as cumulative sums (Figure 12). Since the relationship (slope) between basin precipitation and outflow is assumed to be constant through time, deviations from the predominate slope indicate lower accuracy estimates. Because flows are accurately measured, these deviations can be attributed to precipitation estimate inaccuracy. The impact of anthropogenic flow changes is believed to be small enough to be ignored here. The slopes of the Thiessen and ratioed values remain constant from about 1930 onward. If a line is drawn through the recent Thiessen slope, that line continues and coincides with the ratioed slope from the 1920's back to the origin, indicating that the ratioed values are more correct than the Thiessen values during that period. Since there was an increase/change in the precipitation gage network around 1931, ratioed values are recommended from 1880-1930 and Thiessen values from 1931 onward.

A tabular summary of the 1880-1930 ratio-generated estimates of monthly and annual over-land precipitation for the Lake Superior basin is given in Table 1. Annual Thiessen estimates of precipitation (Croley and Hunter, 1994) are also provided (Table 1) for comparison with the ratio-generated annual values.

3. SUMMARY AND CONCLUSIONS

A ratio of precipitation at each grid cell to that over the entire Lake Superior basin was developed for a 30-year base period in order to define a relationship between precipitation at a point and precipitation over the entire Lake Superior basin. The ratios were calculated to estimate monthly Lake Superior basin precipitation in the first half of the 20th century. Prior to about 1930, differences in the ratio-estimated basin precipitation and St. Marys River outflow were smaller than similar differences for Thiessen precipitation estimates. A double mass curve analysis of basin precipitation and St. Marys River outflow demonstrated that prior to about 1930, ratio estimates of basin precipitation were more consistent with St. Marys River outflow than Thiessen estimates of basin precipitation. Therefore, we conclude that prior to about 1930, the ratio method produced better basin precipitation estimates relative to the Thiessen method. However, we should caution that the ratio method is not a panacea for producing better estimates of areally averaged precipitation. The assumptions about precipitation distribution patterns not changing significantly over time, errors in precipitation data associated with changes in precipitation gages, gage exposure, or gage accuracy, while beyond the scope of this study, are clearly important factors to be considered in a future study. It should be emphasized that when one is faced with a sparse rain-gage network, independent but related observations such as the St. Marys River flow data, are extremely helpful and perhaps even critical in evaluating the utility of different methods of calculating areal precipitation. If the downward trend in the number of precipitation stations for the Lake Superior basin that started about 1980 continues (Figure 4), the ratio method may be useful in the future to obtain more representative estimates of basin precipitation (relative to the Thiessen method). Finally, a discontinuity observed in the Canadian station data beginning in 1975 when new gages were installed, while not adversely affecting the historical ratio-estimated precipitation in this study, has implications for contemporary precipitation and is currently under study.

4. ACKNOWLEDGMENTS

T. Bullock of Environment Canada, Downsview, Ontario, participated in the early stages of this study by identifying the differences in precipitation between U.S. and Canadian sub-basins of Lake Superior. The Cooperative Institute for Limnology and Ecosystem Research Project “Great Lakes Ice, Precipitation, and Temperature Data Rescue” data were used in our analysis. This is GLERL contribution number 1048.

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Table 1. Total Over-Land Lake Superior Basin Precipitation (mm). Ratio Monthly and Annual Values for 1880-1930 with Reference Thiessen Annual [TH] .

Year	J	F	M	A	M	J	J	A	S	O	N	D	Ann	TH
1880	63	69	27	63	116	158	85	104	86	80	46	34	931	807
1881	32	53	30	23	88	68	63	84	265	95	93	18	912	764
1882	35	91	54	49	45	97	106	99	98	135	36	48	893	717
1883	47	32	13	34	68	126	137	52	55	73	75	58	770	653
1884	26	48	30	68	72	33	96	144	130	142	34	73	896	786
1885	37	22	33	25	47	92	93	65	61	32	63	37	607	574
1886	80	75	35	48	43	111	51	40	117	86	56	34	776	685
1887	33	36	15	51	39	63	115	33	54	90	54	45	628	622
1888	61	29	41	44	76	94	47	102	72	58	38	30	692	665
1889	49	49	31	59	63	49	113	78	92	32	30	79	724	724
1890	68	60	31	33	67	81	120	88	70	47	25	24	714	675
1891	39	55	51	41	17	37	101	81	70	65	54	62	673	608
1892	37	28	28	43	78	58	67	85	42	57	57	23	603	562
1893	41	57	37	65	49	71	88	46	55	72	36	68	685	637
1894	42	16	83	65	91	56	51	50	74	116	61	37	742	656
1895	59	31	18	33	85	89	56	54	137	36	39	53	690	661
1896	67	22	30	88	123	55	50	71	42	97	129	34	808	671
1897	88	46	44	30	56	73	143	72	47	70	37	37	743	640
1898	32	46	36	14	88	139	88	64	54	90	47	30	728	634
1899	42	30	38	47	119	132	72	108	97	84	16	61	846	656
1900	35	27	24	36	23	53	131	135	181	63	39	29	776	701
1901	30	21	65	28	42	122	139	65	71	73	51	42	749	674
1902	33	29	21	41	70	82	97	68	63	74	78	75	731	654
1903	36	36	55	43	102	36	146	102	91	101	55	50	853	716
1904	35	43	58	22	74	67	80	77	110	96	23	64	749	668
1905	38	22	45	41	84	120	99	68	123	87	77	28	832	730
1906	46	25	38	25	85	139	40	89	77	75	91	54	784	665
1907	68	29	45	49	71	37	77	98	108	42	42	26	692	678
Year	J	F	M	A	M	J	J	A	S	O	N	D	Ann	TH

Table 1. Cont.

Year	J	F	M	A	M	J	J	A	S	O	N	D	Ann	TH
1908	24	73	50	61	126	105	91	34	86	32	40	45	767	708
1909	36	68	31	53	59	35	147	82	65	59	90	77	802	702
1910	33	40	7	48	48	15	81	71	80	52	41	39	555	589
1911	36	53	37	21	86	71	154	81	89	54	83	65	830	847
1912	33	12	10	58	96	52	55	99	86	45	28	60	634	671
1913	29	40	71	40	74	88	142	58	92	89	47	8	778	734
1914	48	32	31	85	47	96	77	109	70	34	53	24	706	625
1915	48	37	15	28	78	151	74	63	112	85	96	51	838	777
1916	101	23	59	79	83	147	47	84	135	81	31	44	914	802
1917	25	28	79	36	34	86	59	76	56	92	16	51	638	618
1918	38	28	12	36	104	55	71	74	79	89	74	53	713	697
1919	30	57	28	57	47	67	66	70	75	87	118	32	734	675
1920	41	20	70	50	40	127	104	47	58	51	56	64	728	679
1921	26	30	62	61	67	46	129	57	99	37	40	54	708	701
1922	37	85	48	70	71	106	113	54	63	31	66	47	791	669
1923	57	29	50	27	35	82	111	57	59	46	28	42	623	598
1924	45	38	22	62	55	59	92	127	74	35	46	43	698	660
1925	25	37	25	25	41	98	65	62	98	51	34	40	601	612
1926	31	42	55	22	31	116	105	79	159	90	113	53	896	815
1927	32	44	38	41	108	73	113	41	73	59	82	79	783	728
1928	39	18	35	66	39	122	118	122	114	112	24	28	837	766
1929	83	23	47	40	57	70	74	41	115	77	43	55	725	687
1930	36	45	28	28	78	111	65	16	113	62	57	32	671	663
Year	J	F	M	A	M	J	J	A	S	O	N	D	Ann	TH

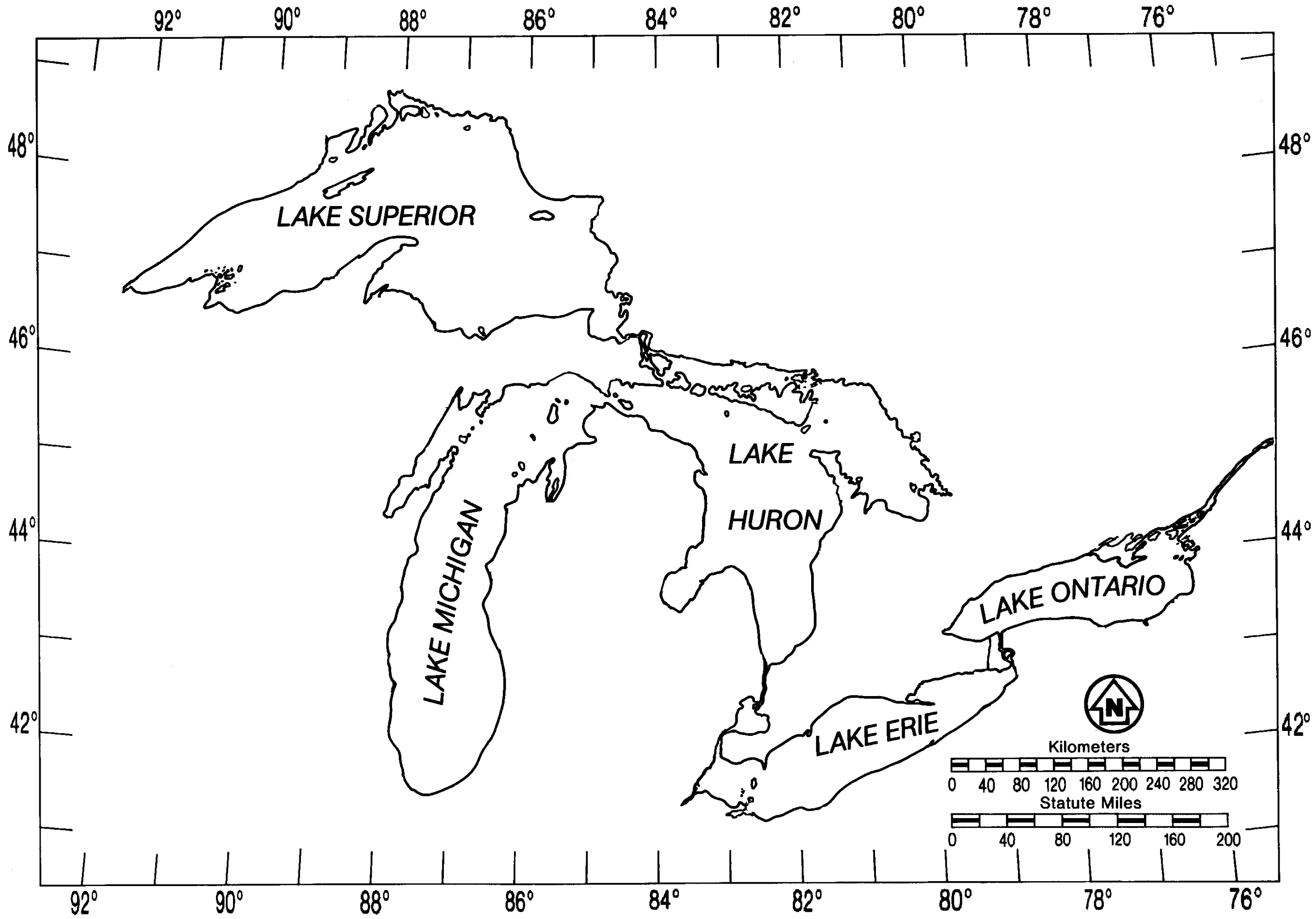

Figure 1. Location Map of the Great Lakes.

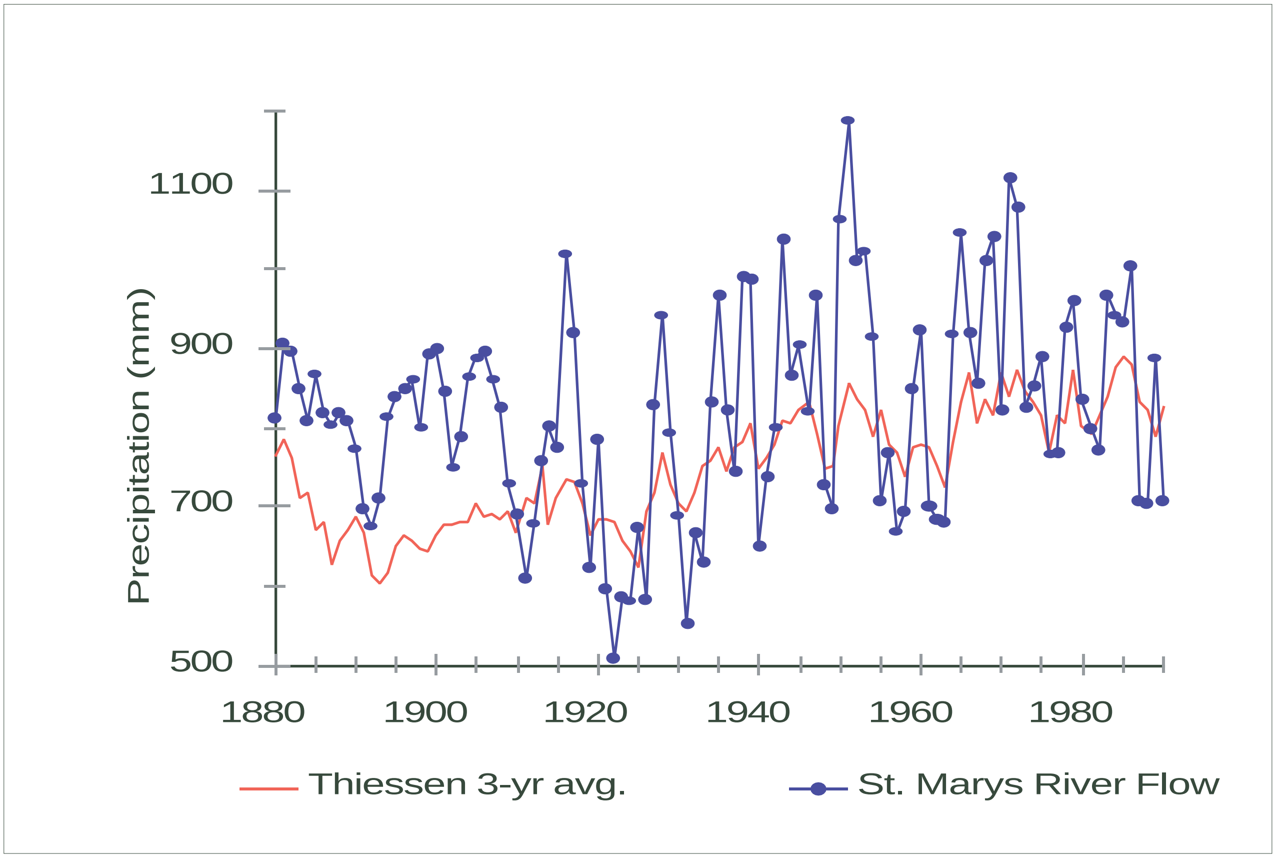

Figure 2. Three-year running average annual precipitation using the Thiessen method and St. Marys River flow per unit surface area of Lake Superior.

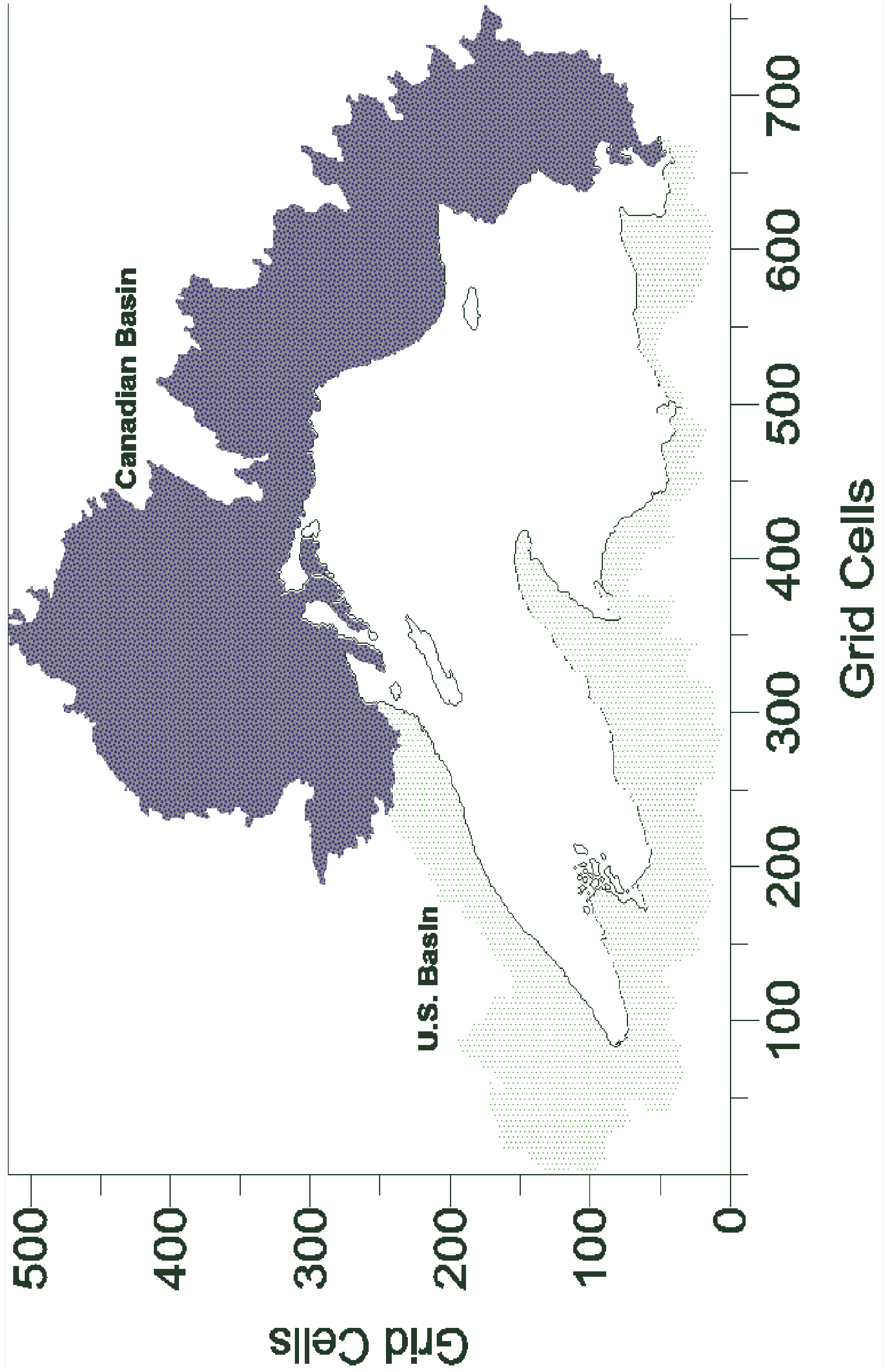

Figure 3. Map of Lake Superior hydrologic basin with 1 x 1 km grid cell indicated along the horizontal and vertical axes. The Canadian sub-basin has dark shading while the U.S. sub-basin has light shading. The western juncture of the sub-basins was defined along the nearest drainage basin to the international divide.

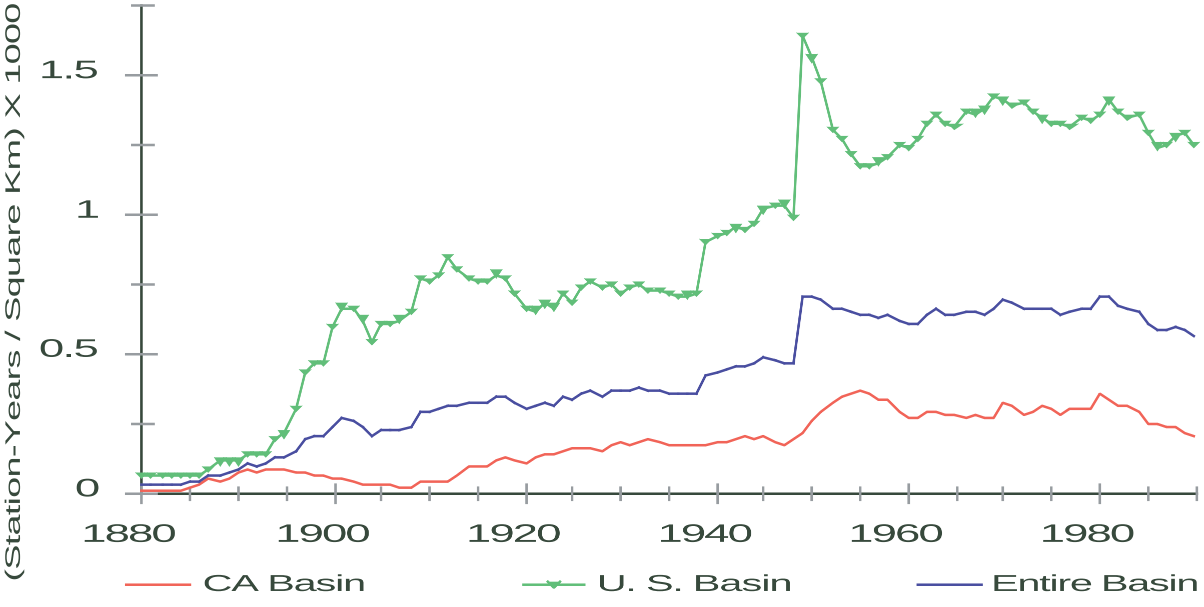

Figure 4. Station Density. The annual total number of station-months of data divided by 12 (months) per unit area (KM^2). The transitory increase and decrease in stations in the mid-to-late 1940s - early 1950s is attributed to temporary stations that were started following the end of the second World War.

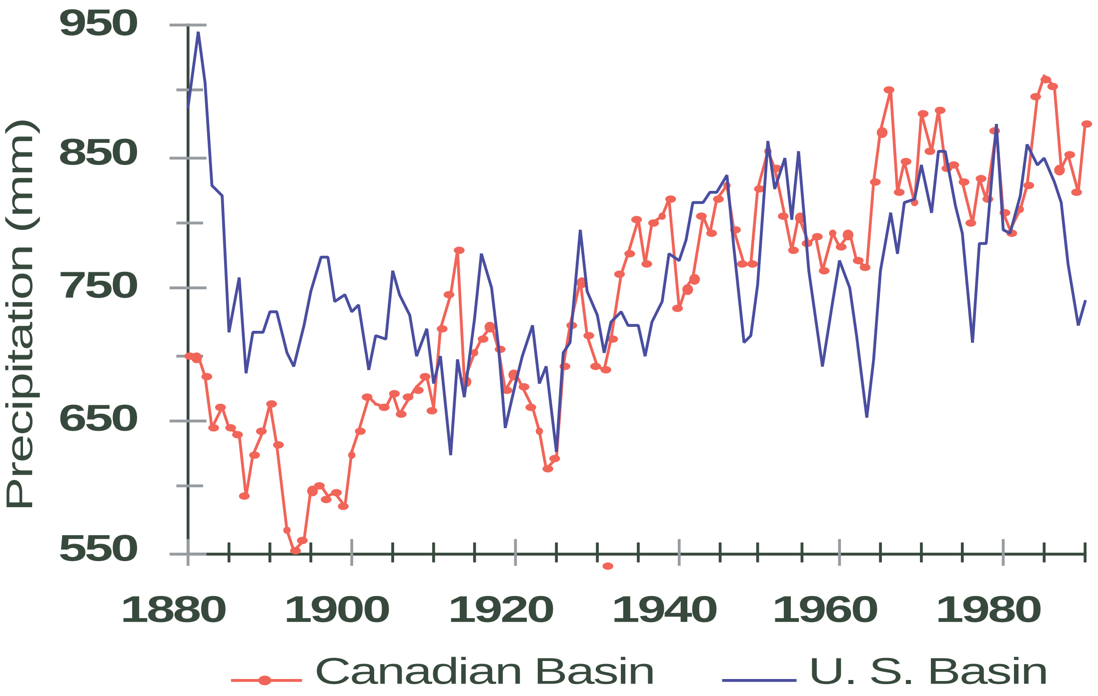

Figure 5. Annual precipitation for the overland areas of U.S. and Canadian portions of the Lake Superior basin, derived from the Thiessen polygon method to estimate catchment precipitation.

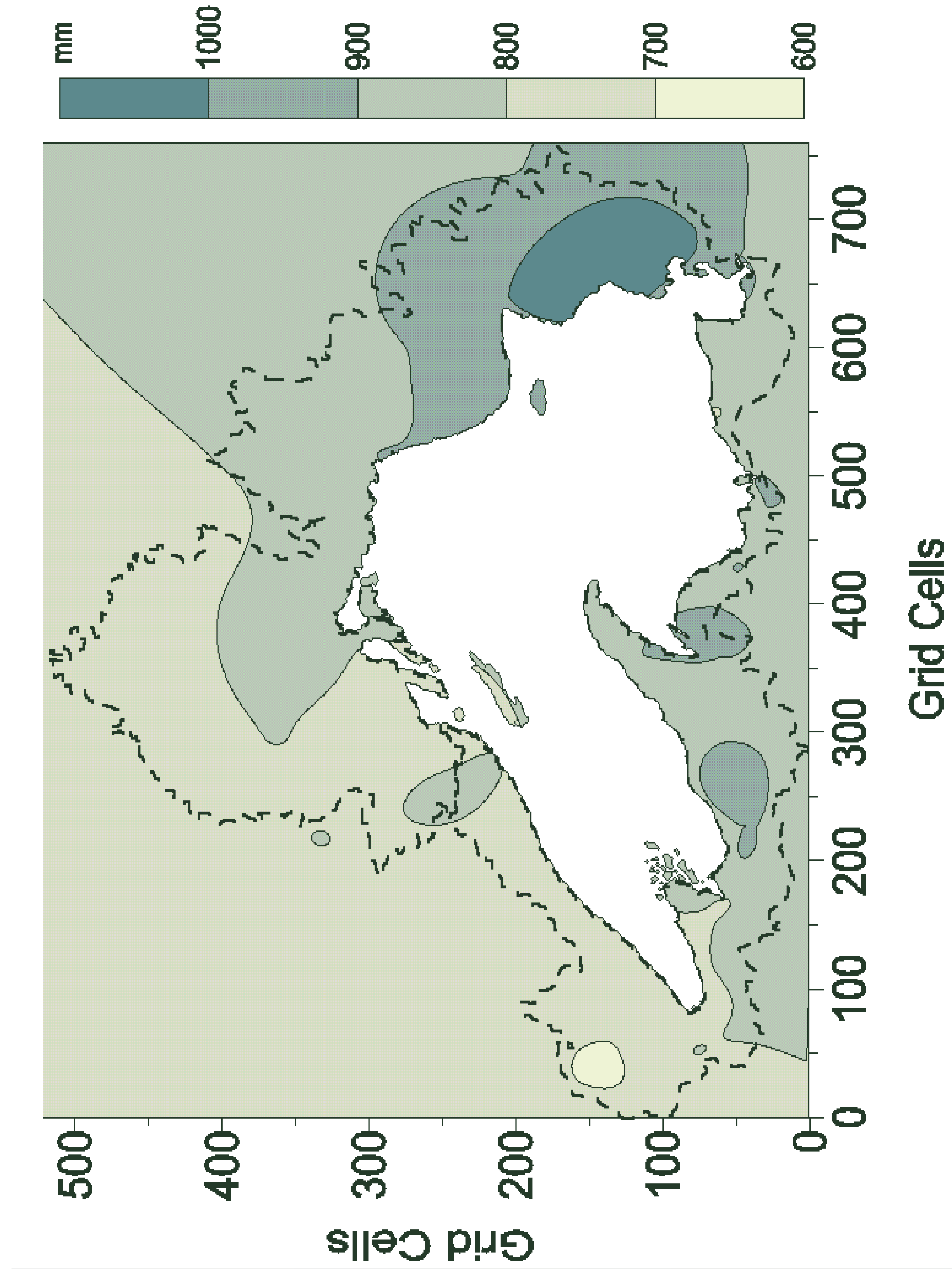

Figure 6. Average annual precipitation grid for the 1961-1990 period.

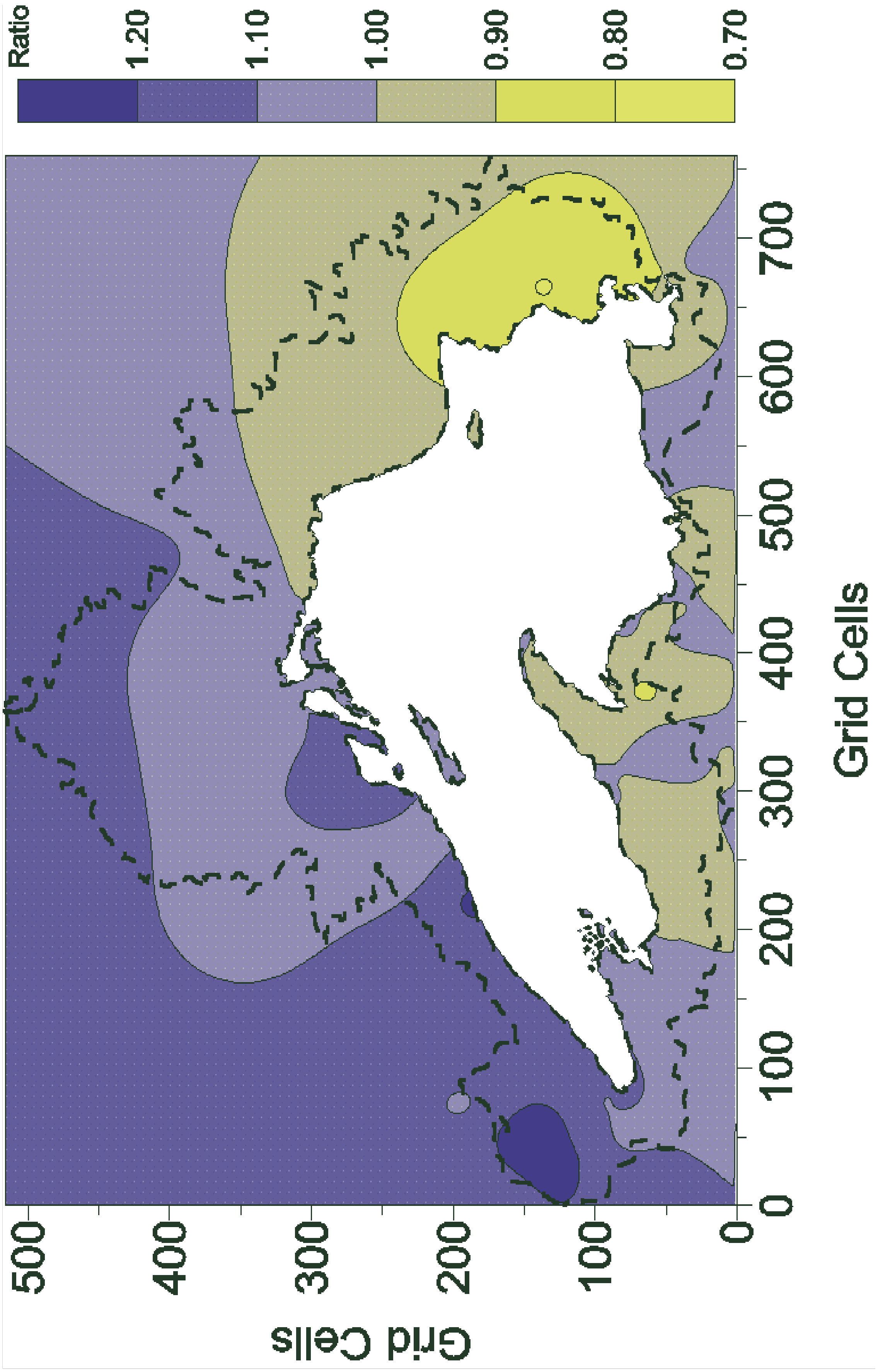

Figure 7. Average annual ratios grid(basin precipitation/cellular precipitation) for the 1961-1990 period.

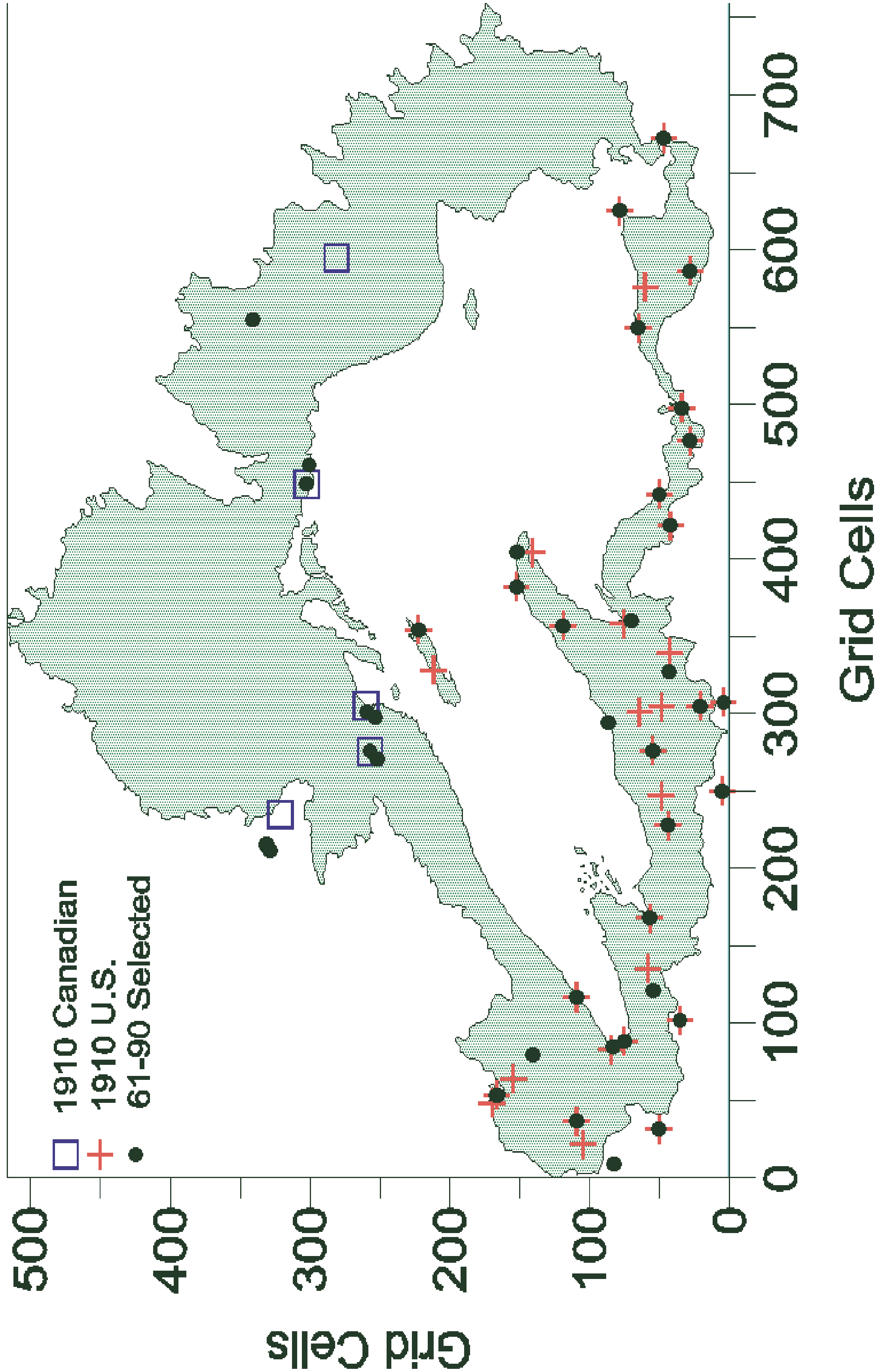

Figure 8. Locations of Canadian and U.S. precipitation stations representative of 1910 and selected (closest) reporting 1961-1990 stations.

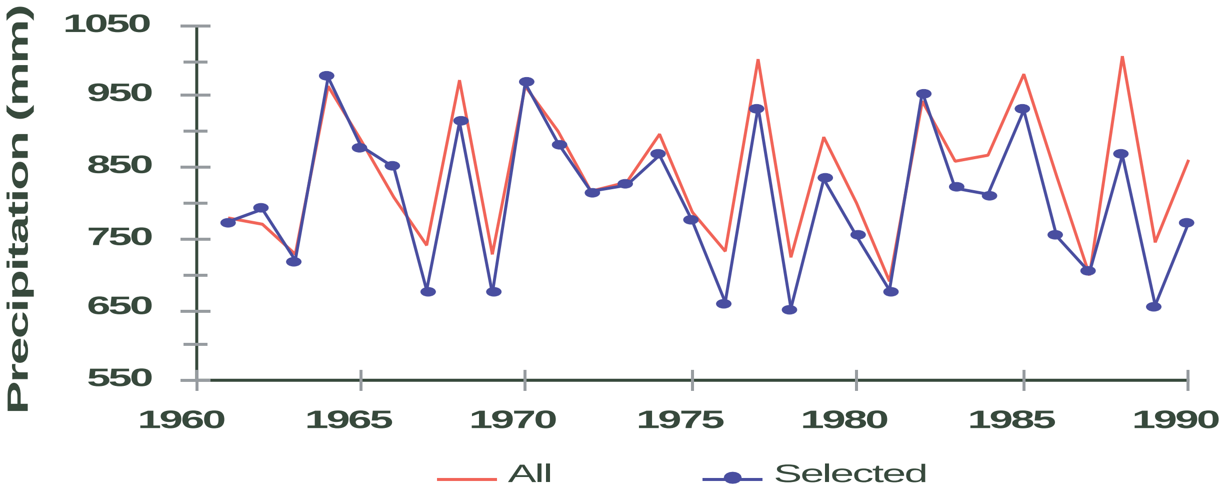

Figure 9. Precipitation over the Canadian portion of the Lake Superior drainage basin. Two Thiessen weighted estimates, one using all Canadian stations (All) and a second using the selected station network (Selected) composed of 5 stations (see Figure 8).

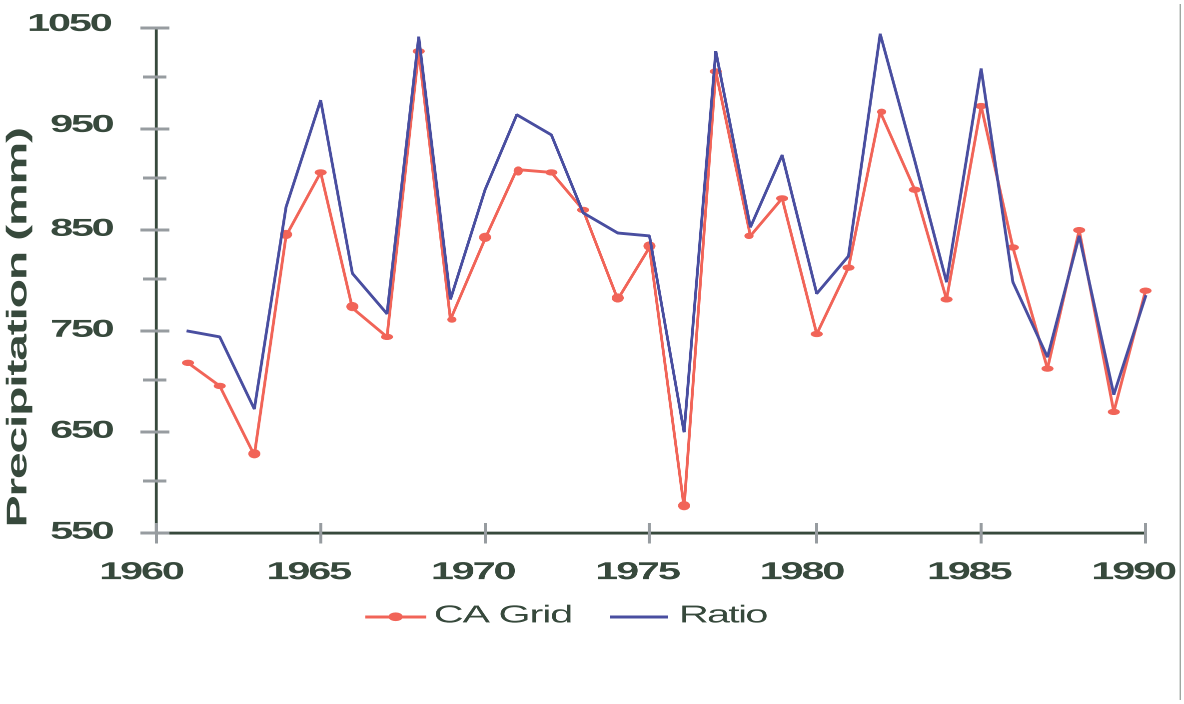

Figure 10. Precipitation over the Canadian portion of the Lake Superior drainage basin. Gridded estimates (Grid) using all Canadian stations, and ratioed estimates (Ratio) using the selected U.S. and Canadian stations given in Figure 8.

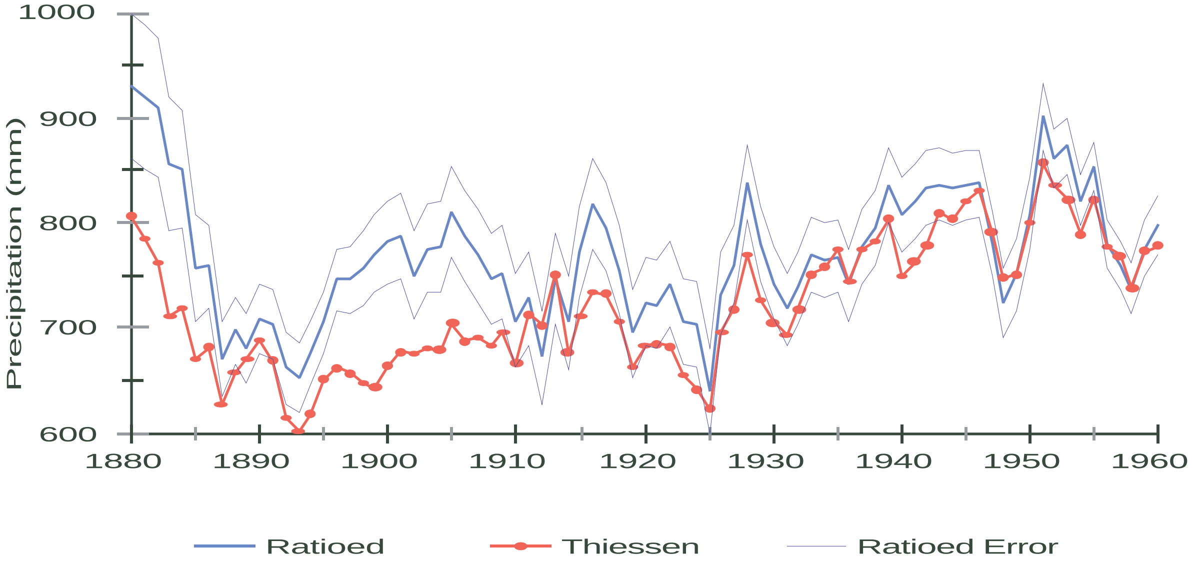

Figure 11. A comparison of 3-year running averages of annual precipitation estimates for the Lake Superior basin using the Thiessen method and the ratio method along with its error bars for the 1880-1960 period.

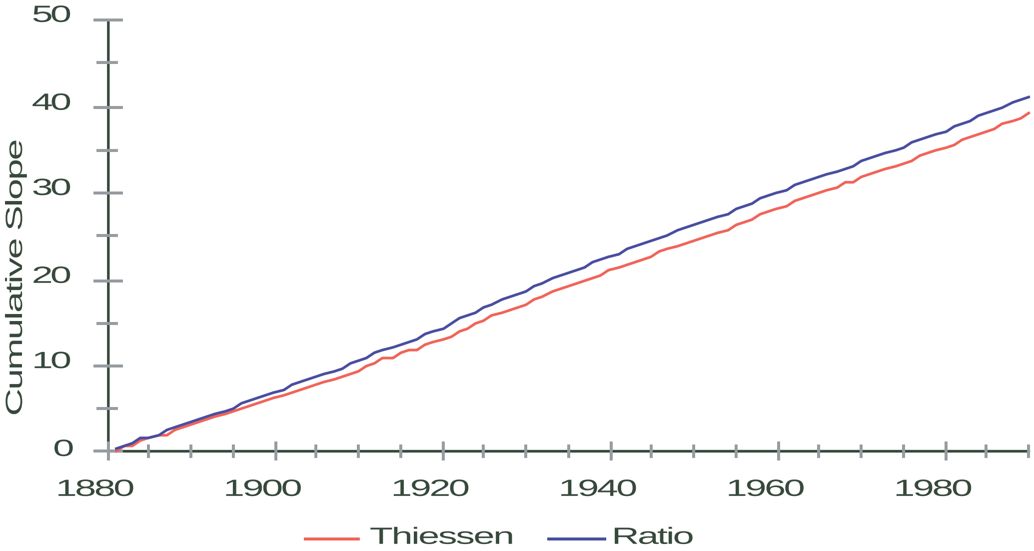

Figure 12. Cumulative annual successive year slopes from double mass curves (precipitation/flow) where precipitation in mm was computed by the Thiessen and ratio method using all available Canadian and U.S. stations and St. Marys River flow per unit surface area of Lake Superior.