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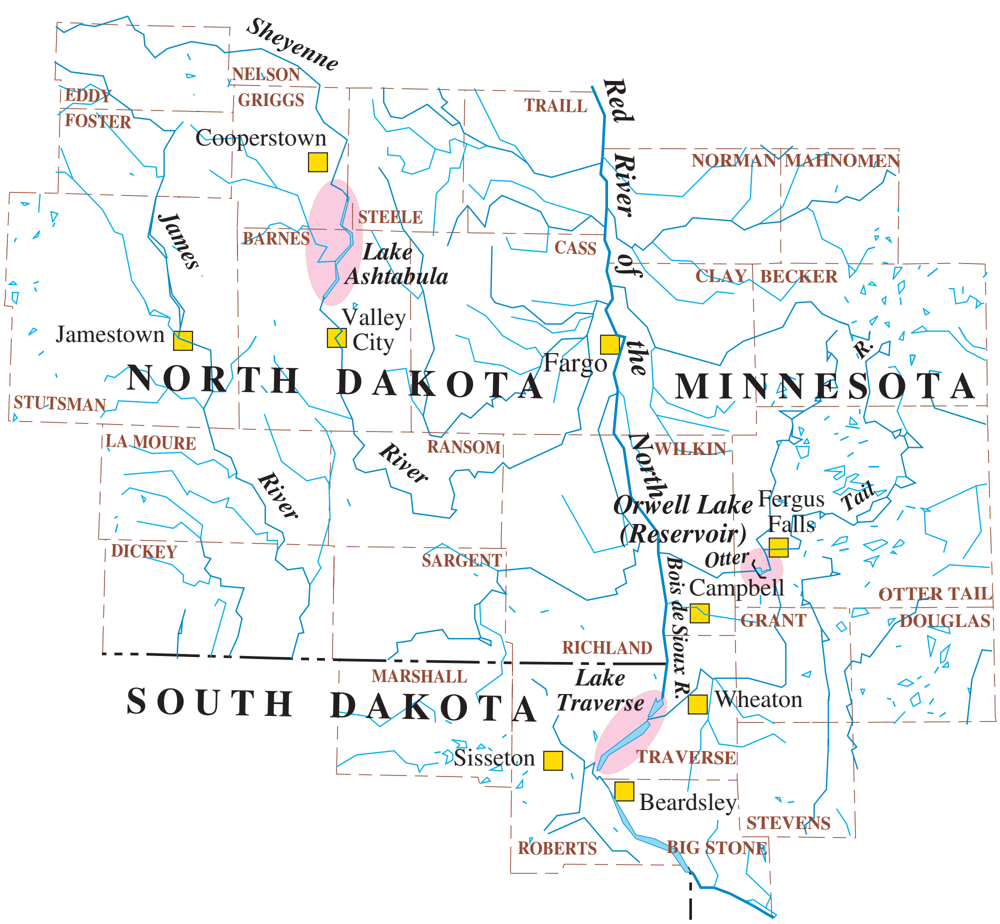
Estimation of Monthly Evaporation from Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota, 1931-2001

Water-Resources Investigations Report 03-4282



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Estimation of Monthly Evaporation from Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota, 1931-2001

By Kevin C. Vining

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In cooperation with the Bureau of Reclamation

Bismarck, North Dakota
2003

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Estimation of Monthly Evaporation from Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota, 1931-2001

By Kevin C. Vining

Abstract

Reservoirs on tributaries of the Red River of the North provide water for Fargo and Grand Forks, N. Dak., and other cities along the river. Adequate estimates of evaporative losses from the reservoirs are needed to determine the total water supply in the Basin. Many equations could be used to estimate lake or reservoir evaporation. However, in addition to measurements of air temperature, the equations require measurements of net radiation, wind speed, and relative humidity. Evaporation and air temperature data from energy budget evaporation sites at Wetland P1 in North Dakota and at Williams Lake in Minnesota are available. Air temperature data collected from climate stations near Lake Ashtabula in North Dakota, from Orwell Lake in Minnesota, and from Lake Traverse in Minnesota and South Dakota also are available. Therefore, the combined data sets were used to estimate monthly evaporation from Lake Ashtabula, Orwell Lake, and Lake Traverse. Averaged monthly mean air temperatures determined for each reservoir study site were used to calculate monthly evaporation data sets for 1931-2001. Results from the procedure that estimates reservoir evaporation indicate that slight downward trends in annual evaporation occurred from 1931-2001. The trends may have been caused by the selected time period of the study, which began with the drought conditions in the mid 1930's and ended with the more wet conditions in the late 1990's. Average annual evaporation values for each reservoir for 1931-2001 correspond well with published average annual lake evaporation values for 1946-55.

INTRODUCTION

Reliable water supplies are needed for population growth of cities in the Red River of the North Basin. Currently, reservoirs on tributaries of the Red River of the North provide water for Fargo and Grand Forks, N. Dak., and other cities along the river. The Dakota Water Resources Act was passed by the U.S. Congress on December 15, 2000 (Garrison Diversion Conservancy District and the Dakotas Area Office of the Bureau of Reclamation, [n.d.]). The Act authorized the Secretary of the Interior to conduct a comprehensive study of the future water-quantity and quality needs of the Red River of the North Basin in North Dakota and the possible options to meet those water needs. Adequate estimates of evaporative losses from the reservoirs in the Red River of the North Basin are needed to determine the total water supply in the Basin. To provide the needed evaporation data, the U.S. Geological Survey conducted a study in cooperation with the Bureau of Reclamation to review studies that evaluated evaporation estimation methods and to estimate monthly evaporation from selected reservoirs for 1931-2001. This report describes the results of the study. The reservoirs for which monthly evaporation was estimated are Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota (fig. 1).

METHODS OF ESTIMATING EVAPORATION

Pan evaporation data commonly are used to estimate evaporation from lakes and reservoirs; however, there are problems with using these data. Debris in the water, animal activity in and around the pan, size of the pan, materials used to construct the pan, exposure of the pan, strong winds, and the measurement of water depth in the pan can introduce errors in pan evaporation rates (Farnsworth and others, 1982; Rosenberg and others, 1983). Shallow free-water-surface evaporation atlases of the United States have been created by using pan evaporation data, but the values in the atlases cannot be used to estimate lake or reservoir evaporation unless heat storage changes and heat inflows and outflows from the lakes and reservoirs can be accounted for (Farnsworth and others, 1982).

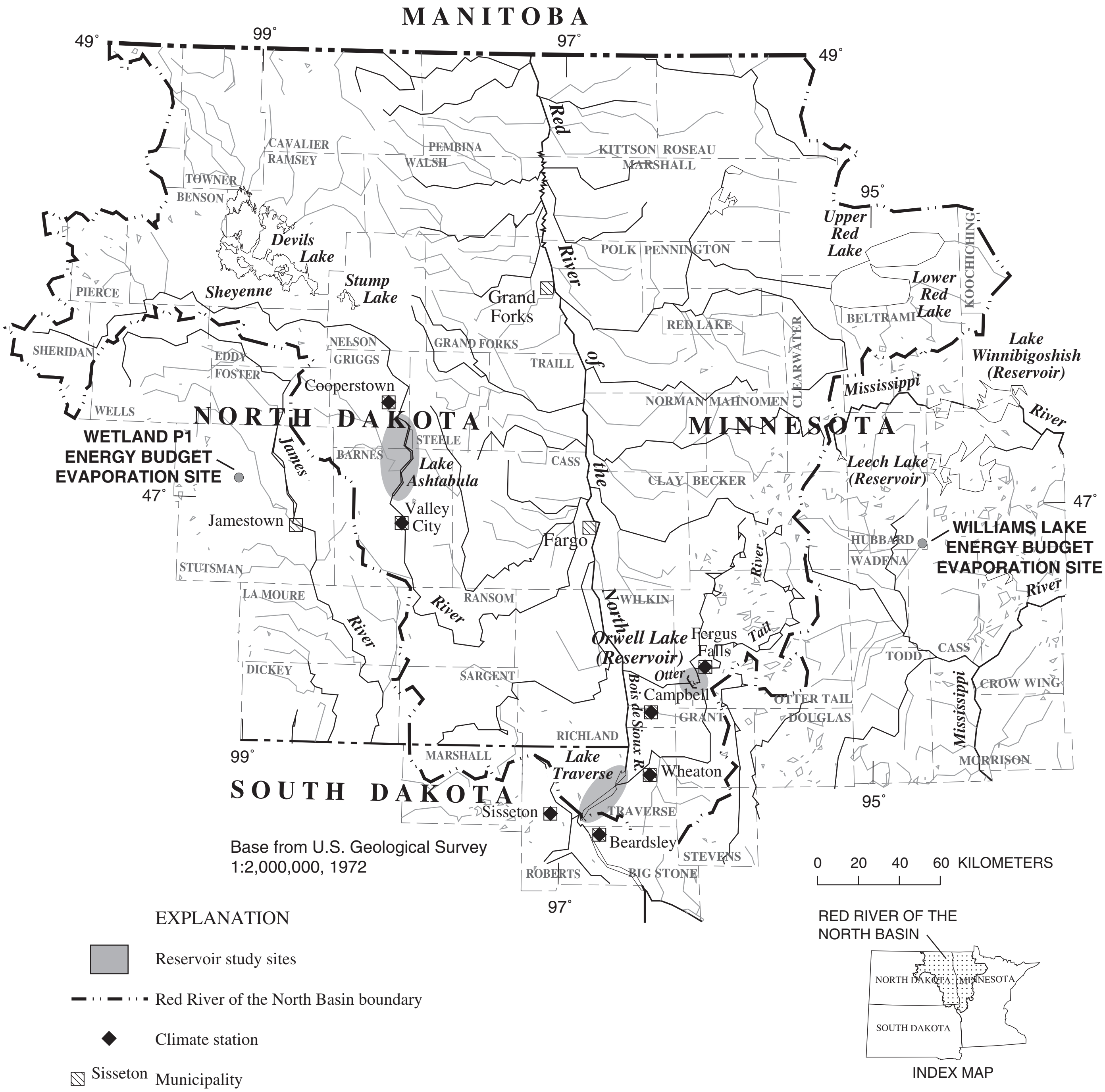

Figure 1. Location of the Lake Ashtabula, Orwell Lake, and Lake Traverse study sites, climate stations, and Wetland P1 and Williams Lake energy budget evaporation sites in North Dakota, Minnesota, and South Dakota.

The energy budget method was used to determine evaporation from a wetland in North Dakota, Wetland P1, and from a lake in Minnesota, Williams Lake (Rosenberry and others, 1993; Parkhurst and others, 1998). The energy budget method relies on the optimum placement of sensors in and around a lake or reservoir to provide a rigorous estimate of evaporation (Rosenberry and others, 1993). In another study, the energy budget method was compared to 11 other evaporation equations in order to determine monthly evaporation from Williams Lake (Winter and others, 1995). Of the 11 equations evaluated, a modified DeBruin-Keijman equation, the Priestley-Taylor equation, and a modified Penman equation produced results that corresponded well with the energy budget method. However, in addition to measurements of air temperature, the equations require measurements of net radiation, wind speed, and relative humidity. Because net radiation, wind speed, and relative humidity are not measured routinely at most climate stations, the equations cannot be used for most lake or reservoir evaporation studies.

The most routinely measured variables at most climate stations are precipitation and air temperature. Because evaporation is directly related to air temperature, many evaporation estimation procedures use air temperature as a significant variable (Rosenberg and others, 1983). In Guenthner and others (1990), monthly pan evaporation data for Fargo, N. Dak., was regressed against monthly mean maximum and minimum air temperatures for Fargo for 1963-80. The resultant regression equation had a positive coefficient for the monthly mean maximum air temperature and a negative coefficient for the monthly mean minimum air temperature. As a result, the regression equation could produce an increase in monthly evaporation for a decrease in monthly mean minimum air temperature. In addition, the regression equation would produce the same monthly evaporation from a wide combination of monthly mean maximum and minimum air temperatures that could include below-freezing temperatures. A more reliable regression equation would relate monthly evaporation directly to only one monthly air temperature variable. The evaporation and air temperature data from the energy budget evaporation sites at Wetland P1 and Williams Lake are available, and the air temperature data collected from climate stations near Lake Ashtabula, Orwell Lake, and Lake Traverse also are available. Therefore, the combined data sets were used to estimate monthly evaporation from Lake Ashtabula, Orwell Lake, and Lake Traverse.

DATA ACQUISITION

Monthly mean air temperature data for 1931-2001 were measured at climate data stations located near the reservoir study sites. The data were obtained from the High Plains Regional Climate Center (2003) and from the Minnesota Climatology Working Group (2003). The climate data stations used near Lake Ashtabula were Cooperstown and Valley City, N. Dak.; the climate stations used near Orwell Lake were Campbell and Fergus Falls, Minn.; and the climate stations used near Lake Traverse were Beardsley and Wheaton, Minn., and Sisseton, S. Dak. (fig. 1). All of the climate data stations had occasional missing data during 1931-2001. Average monthly mean air temperatures for 1931-2001 were determined for each reservoir study site using a simple arithmetic average of the monthly mean air temperature data from the stations near each reservoir study site. Averaging the monthly values reduced the influence from a single station on the calculation of evaporation for each reservoir study site.

Energy budget data were obtained for Wetland P1 in North Dakota and for Williams Lake in Minnesota (fig. 1) (D.O. Rosenberry, U.S. Geological Survey, oral commun., 2003). Data included calculated monthly evaporation and measured monthly mean air temperatures. Data from the two sites were recorded during May through September and occasionally during October for 1982-85 and 1987 at Wetland P1 and for 1982-86 at Williams Lake. Plots of monthly evaporation in relation to monthly mean air temperature for Wetland P1 and Williams Lake are shown in figures 2 and 3, respectively.

ESTIMATION OF RESERVOIR EVAPORATION

Monthly evaporation data sets were calculated for each reservoir study site by using regression equations of monthly evaporation and monthly mean air temperature for Wetland P1 and Williams Lake. Monthly evaporation data for Wetland P1 was regressed against the measured monthly mean air temperature data for Wetland P1, and monthly evaporation data for Williams Lake was regressed against the measured monthly mean air temperature data for Williams Lake. The regression equation for Wetland P1 was

$$E_{P1} = 0.625T_{P1} + 1.218 \text{ (20 observations)} \qquad (1)$$

and the regression equation for Williams Lake was

$$E_{WL} = 0.518T_{WL} - 0.008 \text{ (22 observations)} \qquad (2)$$

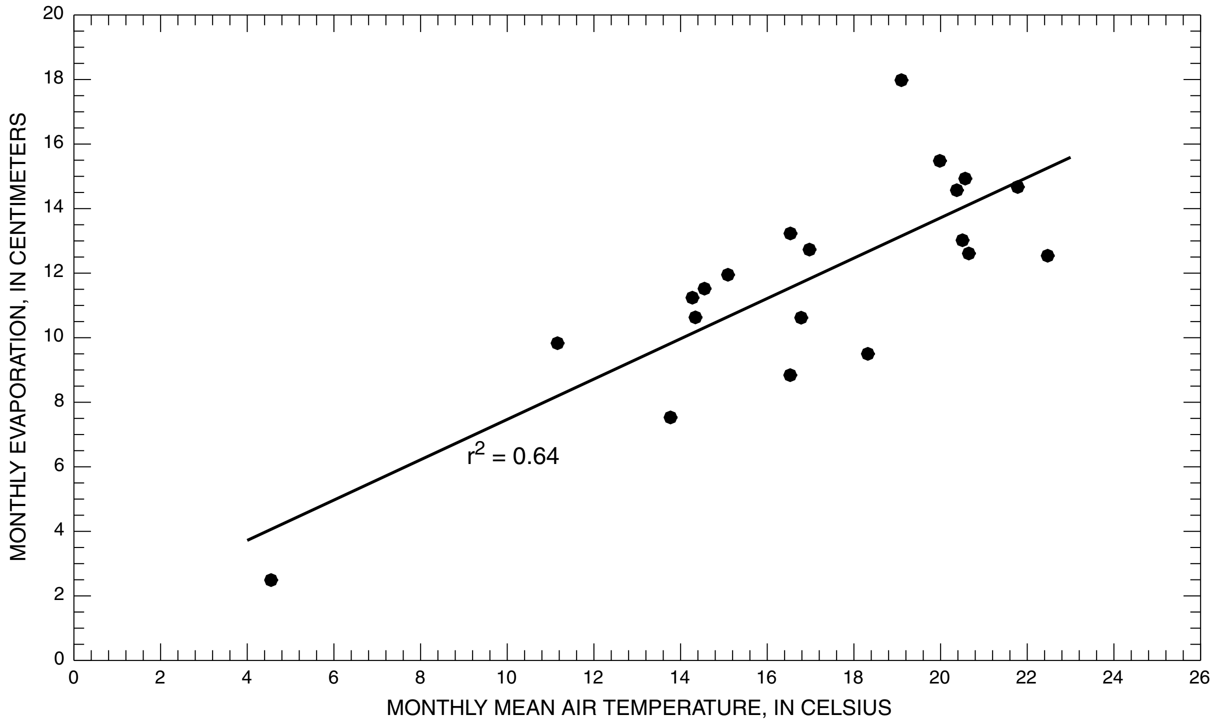

Figure 2. Monthly evaporation in relation to monthly mean air temperature determined from the energy budget evaporation site at Wetland P1 in North Dakota, 1982-85 and 1987.

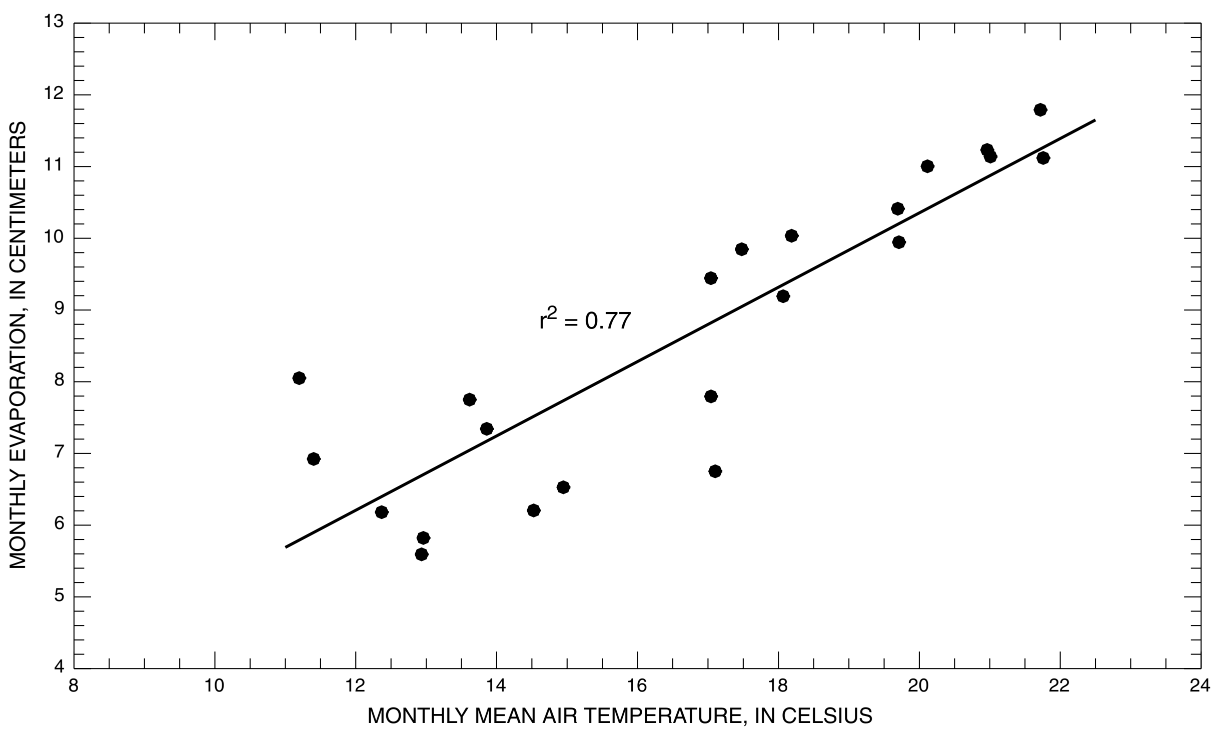

Figure 3. Monthly evaporation in relation to monthly mean air temperature determined from the energy budget evaporation site at Williams Lake in Minnesota, 1982-86.

where

E_{P1} is the monthly evaporation in centimeters at Wetland P1,
E_{WL} is the monthly evaporation in centimeters at Williams Lake,
T_{P1} is the monthly mean air temperature in degrees Celsius at Wetland P1, and
T_{WL} is the monthly mean air temperature in degrees Celsius at Williams Lake.

For Wetland P1, the correlation coefficient was 0.80 and the root mean square error was 2.0 centimeters. For Williams Lake, the correlation coefficient was 0.88 and the root mean square error was 1.0 centimeters.

The average monthly mean air temperatures determined for each reservoir study site for 1931-2001 from nearby climate data stations were used in place of T_{P1} and T_{WL} in equations 1 and 2 to calculate two monthly evaporation data sets for each reservoir study site for 1931-2001. An inverse distance weighting scheme was used to determine the fractional contribution of each of the two monthly evaporation data sets from the energy budget evaporation sites to the estimated monthly evaporation data set for each reservoir study site (table 1). For example, the total distance of Lake Ashtabula from Wetland P1 and Williams Lake is (85 + 255) = 340 kilometers. The fractional contribution of Wetland P1 monthly evaporation to Lake Ashtabula monthly evaporation is (340 - 85)/340 = 0.75 and the fractional contribution of Williams Lake monthly evaporation to Lake Ashtabula monthly evaporation is (340 - 255)/340 = 0.25. The two monthly evaporation data sets for each reservoir study site were multiplied by their appropriate fractional contributions and the results were summed to produce one weighted monthly evaporation data set for each reservoir study site. Monthly evaporation data during the winter period October through April often were not available for Wetland P1 and Williams Lake. Therefore, evaporation values for each winter month (m) and each reservoir study site (r) were estimated by using information presented by the Soil Conservation Service in the Hydrology Manual for North Dakota (U. S. Department of Agriculture, [n.d.]). Winter monthly evaporation values for each reservoir study site $(E_{m,r})$ were determined from the average monthly mean air temperatures at each reservoir study site $(T_{m,r})$ by using the equation

$$E_{m,r} = E_m \frac{(T_{m,r} + 273)}{(Mean_{m,r} + 273)} \qquad (3)$$

where

E_m is the Soil Conservation Service estimated winter monthly evaporation value, and
$Mean_{m,r}$ is the 1971-2000 normal monthly air temperature for each reservoir study site.

Temperatures in equation 3 were converted to degrees Kelvin to avoid zeros and negative values. Estimated monthly evaporation from Lake Ashtabula, Orwell Lake, and Lake Traverse for 1931-2001 are presented in tables 2, 3, and 4, respectively.

Table 1. Distances from reservoir study sites to Wetland P1 in North Dakota and to Williams Lake in Minnesota and fractional contributions applied to the evaporation data sets from Wetland P1 and Williams Lake to obtain estimated monthly evaporation from Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota

Reservoir site	Distances (kilometers)		Fractional contributions	
	Wetland P1	Williams Lake	Wetland P1	Williams Lake
Lake Ashtabula	85	255	0.75	0.25
Orwell Lake	248	124	.35	.65
Lake Traverse	238	196	.45	.55

Table 2. Estimated monthly evaporation, in centimeters, from Lake Ashtabula in North Dakota, 1931-2001

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1931	0.60	0.76	1.81	5.07	8.11	13.13	14.23	12.65	11.23	6.77	2.39	0.82	77.57
1932	.59	.74	1.78	4.61	9.03	13.00	13.85	13.39	9.38	6.66	2.36	.81	76.20
1933	.59	.73	1.81	4.60	8.59	14.25	14.02	13.10	11.21	6.68	2.37	.80	78.75
1934	.59	.75	1.81	5.01	11.73	12.36	14.57	12.77	8.25	6.77	2.40	.80	77.81
1935	.58	.76	1.80	4.57	6.82	10.75	15.13	12.69	9.24	6.71	2.32	.80	72.17
1936	.56	.70	1.80	4.56	10.71	12.45	16.96	13.98	10.34	6.68	2.37	.81	81.92
1937	.56	.73	1.79	4.58	9.26	11.13	13.95	14.56	9.67	6.69	2.36	.80	76.08
1938	.58	.73	2.12	5.28	7.48	11.12	12.89	13.38	9.94	6.83	2.35	.81	73.51
1939	.59	.71	1.79	4.60	10.56	10.93	14.46	13.52	9.77	6.67	2.40	.83	76.83
1940	.58	.74	1.78	4.58	8.51	11.30	14.41	12.59	11.23	7.13	2.35	.81	76.01
1941	.58	.73	1.79	5.53	9.89	11.86	13.94	12.99	9.38	6.72	2.38	.82	76.61
1942	.60	.74	1.82	5.57	7.28	10.59	12.59	12.35	8.10	6.73	2.39	.80	69.56
1943	.57	.75	1.78	5.70	7.54	11.20	14.30	13.24	9.08	6.77	2.38	.82	74.13
1944	.60	.74	1.78	4.60	9.95	11.98	13.23	12.62	9.46	6.76	2.39	.81	74.92
1945	.59	.74	2.14	4.59	6.51	10.01	12.91	12.79	8.80	6.73	2.36	.79	68.96
1946	.58	.73	2.38	6.27	7.45	11.69	13.39	12.11	8.98	6.68	2.37	.81	73.44
1947	.59	.74	1.80	4.60	7.03	10.46	13.41	14.73	9.30	7.82	2.35	.80	73.63
1948	.58	.73	1.77	4.59	8.66	11.44	13.89	13.43	11.67	6.74	2.38	.80	76.68
1949	.58	.73	1.79	6.23	9.31	12.10	13.86	13.76	8.95	6.73	2.41	.80	77.25
1950	.56	.73	1.79	4.53	7.19	12.01	12.57	11.39	9.67	6.72	2.33	.79	70.28
1951	.57	.74	1.76	4.59	9.72	9.72	12.98	11.79	8.21	6.69	2.34	.79	69.90
1952	.58	.75	1.79	6.41	8.99	12.64	13.55	13.01	11.07	6.70	2.39	.81	78.69
1953	.59	.75	1.81	4.57	8.23	11.68	13.30	14.07	9.73	8.11	2.41	.81	76.06
1954	.57	.77	1.80	4.61	7.18	11.46	13.98	12.74	9.18	6.72	2.41	.82	72.24
1955	.59	.73	1.78	7.06	10.22	11.56	14.66	14.31	9.62	6.76	2.33	.79	80.41
1956	.58	.73	1.78	4.55	8.39	13.49	12.58	12.72	8.58	7.11	2.39	.81	73.71
1957	.58	.74	1.81	4.61	8.75	10.90	14.77	12.68	8.54	6.72	2.38	.82	73.30
1958	.60	.74	1.82	4.98	9.38	9.88	12.19	12.92	9.84	6.74	2.37	.80	72.26
1959	.58	.73	1.83	4.61	7.86	12.37	13.58	13.82	9.35	6.63	2.34	.83	74.53
1960	.58	.74	1.77	4.60	8.80	10.87	13.64	13.41	10.06	6.74	2.38	.80	74.39
1961	.59	.75	1.83	4.57	7.81	12.68	12.76	14.37	8.52	6.74	2.38	.80	73.80
1962	.58	.73	1.79	4.59	8.45	11.82	12.68	13.60	8.81	6.77	2.40	.81	73.03
1963	.58	.74	1.83	4.74	8.34	13.05	14.13	13.34	10.74	8.93	2.40	.80	79.62
1964	.59	.75	1.78	4.87	9.61	11.30	14.11	11.84	8.55	6.73	2.37	.79	73.29
1965	.57	.73	1.77	4.60	8.25	11.20	12.88	12.11	5.81	6.75	2.37	.82	67.86
1966	.57	.73	1.82	4.57	7.67	11.82	14.56	12.07	9.68	6.73	2.35	.80	73.37
1967	.59	.73	1.81	4.57	7.12	11.16	13.02	12.61	10.21	6.70	2.38	.81	71.71
1968	.58	.74	1.83	4.81	7.53	11.32	12.92	12.21	9.39	6.73	2.39	.80	71.25
1969	.57	.74	1.77	4.86	9.13	9.53	13.03	14.49	9.89	6.64	2.39	.81	73.85
1970	.57	.74	1.77	4.58	7.64	12.75	14.12	13.55	9.78	6.71	2.36	.80	75.37
1971	.57	.74	1.80	5.12	8.12	12.46	12.01	13.38	9.43	6.73	2.37	.80	73.53
1972	.58	.73	1.79	4.58	9.52	11.98	12.11	12.87	8.49	6.67	2.37	.79	72.48
1973	.59	.75	1.82	4.60	8.41	11.75	13.15	13.81	8.45	6.77	2.35	.80	73.25
1974	.57	.74	1.78	4.59	7.04	11.52	14.47	11.38	7.99	6.73	2.38	.82	70.01
1975	.59	.74	1.78	4.52	8.52	11.31	14.15	12.16	8.31	6.74	2.39	.81	72.02
1976	.58	.75	1.79	5.27	8.58	12.33	13.25	13.59	9.74	6.63	2.35	.80	75.66
1977	.57	.75	1.82	6.48	11.77	12.06	13.33	10.27	8.70	6.73	2.36	.79	75.63
1978	.57	.73	1.80	4.60	9.70	11.59	13.29	12.80	11.11	6.73	2.35	.79	76.06
1979	.57	.72	1.78	4.53	6.27	11.37	13.56	11.96	10.32	6.69	2.36	.82	70.95
1980	.58	.74	1.78	6.29	10.05	11.64	13.52	11.79	8.74	6.68	2.40	.81	75.02

Table 2. Estimated monthly evaporation, in centimeters, from Lake Ashtabula in North Dakota, 1931-2001—Continued

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1981	0.59	0.75	1.83	5.31	8.04	10.53	13.23	13.06	8.99	6.70	2.41	0.80	72.24
1982	.56	.73	1.79	4.58	8.76	9.77	13.21	12.43	8.81	6.71	2.35	.82	70.52
1983	.60	.75	1.81	4.58	7.10	11.44	14.47	14.66	9.10	6.70	2.39	.78	74.38
1984	.59	.76	1.79	4.69	7.88	11.71	13.27	13.96	7.83	6.72	2.37	.80	72.37
1985	.58	.74	1.83	5.62	10.03	9.93	13.10	11.27	7.86	6.68	2.31	.79	70.74
1986	.59	.74	1.83	4.61	8.94	12.23	13.34	11.44	8.16	6.71	2.34	.82	71.75
1987	.60	.76	1.81	6.81	10.11	12.82	13.87	11.77	9.57	6.68	2.40	.82	78.02
1988	.58	.73	1.81	4.72	10.74	14.19	14.31	13.31	9.15	6.68	2.37	.81	79.40
1989	.59	.73	1.78	4.61	8.95	11.11	14.73	13.32	9.52	6.72	2.36	.79	75.21
1990	.60	.75	1.82	4.61	8.11	11.88	12.85	12.98	10.46	6.70	2.39	.80	73.95
1991	.58	.76	1.82	5.49	9.72	12.74	13.04	13.68	9.36	6.67	2.34	.81	77.01
1992	.59	.76	1.83	4.59	9.63	10.56	10.98	11.33	8.68	6.69	2.36	.80	68.80
1993	.58	.73	1.80	4.60	8.36	10.08	11.65	12.37	7.96	6.67	2.36	.81	67.97
1994	.57	.72	1.81	4.59	9.52	12.11	12.10	11.79	10.09	6.75	2.39	.81	73.25
1995	.58	.74	1.80	4.56	7.70	12.92	12.81	13.34	9.22	6.69	2.34	.80	73.50
1996	.57	.74	1.77	4.55	7.49	12.19	12.64	13.12	9.47	6.69	2.31	.79	72.33
1997	.57	.74	1.78	4.54	7.33	12.70	13.09	12.06	10.12	6.72	2.35	.82	72.82
1998	.58	.76	1.80	5.71	9.72	10.64	13.26	13.34	10.64	6.72	2.37	.81	76.35
1999	.58	.75	1.81	4.61	8.72	11.41	13.25	12.35	8.30	6.68	2.41	.82	71.69
2000	.58	.75	1.83	4.60	8.71	10.55	13.11	12.58	8.80	6.73	2.36	.78	71.38
2001	.59	.73	1.80	4.61	9.04	11.33	13.51	13.38	9.32	6.67	2.85	.81	74.64

Table 3. Estimated monthly evaporation, in centimeters, from Orwell Lake in Minnesota, 1931-2001

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1931	0.57	0.72	1.70	4.49	6.96	12.09	13.10	11.35	10.45	6.36	2.22	0.76	70.77
1932	.56	.70	1.67	4.43	8.49	11.87	12.73	11.99	8.28	6.27	2.19	.75	69.93
1933	.56	.69	1.70	4.29	7.80	12.96	13.37	11.57	9.93	6.27	2.18	.75	72.07
1934	.56	.70	1.69	4.30	10.81	11.56	12.97	11.39	7.18	6.37	2.23	.75	70.51
1935	.55	.71	1.70	4.27	6.50	9.66	14.03	11.92	8.63	6.29	2.16	.75	67.17
1936	.54	.67	1.69	4.25	9.69	10.98	15.24	12.86	9.81	6.28	2.18	.76	74.95
1937	.54	.69	1.68	4.29	8.43	10.42	13.00	13.62	9.02	6.29	2.19	.75	70.92
1938	.55	.70	1.73	4.31	6.90	10.64	12.35	13.08	9.47	6.78	2.19	.76	69.46
1939	.56	.68	1.69	4.28	9.83	10.88	12.91	12.14	9.19	6.29	2.23	.77	71.45
1940	.55	.70	1.68	4.28	7.64	10.40	12.90	11.34	10.23	6.54	2.18	.76	69.20
1941	.56	.70	1.70	5.93	9.29	11.18	13.07	12.22	8.84	6.34	2.22	.77	72.82
1942	.56	.70	1.72	5.57	6.92	10.09	11.75	11.68	7.50	6.34	2.21	.75	65.79
1943	.54	.70	1.67	4.31	6.70	10.67	13.06	11.89	8.27	6.36	2.21	.77	67.15
1944	.57	.70	1.68	4.28	8.75	11.27	11.87	12.16	9.38	6.38	2.23	.76	70.03
1945	.56	.70	1.72	4.27	5.78	9.01	11.67	11.71	8.11	6.31	2.20	.74	62.78
1946	.55	.69	1.73	5.55	6.78	10.74	12.40	11.01	8.22	6.30	2.20	.75	66.92
1947	.56	.69	1.69	4.27	6.16	9.62	12.42	13.46	8.73	7.26	2.18	.75	67.79
1948	.55	.69	1.67	4.35	7.93	10.19	12.63	11.93	10.44	6.34	2.21	.75	69.68
1949	.55	.69	1.69	4.66	8.58	11.04	12.55	12.84	7.75	6.35	2.23	.75	69.68
1950	.54	.69	1.67	4.22	6.38	10.90	11.17	10.54	9.05	6.35	2.18	.74	64.43
1951	.54	.70	1.65	4.27	8.64	9.28	11.65	10.70	7.26	6.30	2.17	.74	63.90
1952	.55	.70	1.67	4.71	8.06	11.34	12.28	11.53	9.50	6.27	2.22	.76	69.59
1953	.56	.70	1.70	4.27	7.60	11.01	12.22	12.59	8.78	7.05	2.23	.75	69.46
1954	.54	.72	1.69	4.29	6.21	10.84	12.59	11.55	8.19	6.32	2.23	.76	65.93
1955	.56	.69	1.67	6.48	9.54	10.79	13.50	12.91	8.68	6.35	2.17	.74	74.08
1956	.55	.69	1.68	4.25	7.64	12.21	11.52	11.65	7.86	6.70	2.21	.76	67.72
1957	.55	.70	1.70	4.30	7.53	10.15	13.64	11.67	8.04	6.32	2.21	.76	67.57
1958	.56	.70	1.70	4.59	8.86	8.88	11.21	11.92	9.08	6.35	2.21	.75	66.81
1959	.55	.69	1.71	4.31	8.24	11.70	12.70	13.06	9.03	6.25	2.17	.77	71.18
1960	.55	.70	1.66	4.29	8.00	10.13	12.70	12.46	9.41	6.34	2.21	.75	69.20
1961	.55	.71	1.72	4.25	6.77	11.51	12.02	12.86	8.48	6.34	2.21	.75	68.17
1962	.55	.69	1.68	4.27	8.11	10.55	11.37	11.78	7.73	6.37	2.23	.76	66.09
1963	.54	.70	1.71	4.54	7.43	11.55	12.73	11.71	9.52	7.96	2.23	.74	71.36
1964	.56	.71	1.67	4.31	9.08	10.94	13.13	10.78	7.73	6.32	2.21	.74	68.18
1965	.54	.69	1.66	4.29	7.97	10.56	11.86	11.19	5.63	6.34	2.20	.77	63.70
1966	.54	.69	1.71	4.26	6.82	10.90	13.51	11.06	8.79	6.30	2.18	.75	67.51
1967	.55	.69	1.70	4.30	6.25	10.26	11.51	11.15	9.02	6.30	2.21	.76	64.70
1968	.55	.69	1.72	4.38	6.61	10.56	11.97	11.57	8.68	6.32	2.21	.75	66.01
1969	.54	.70	1.66	4.31	7.97	8.48	11.65	12.73	9.09	6.27	2.21	.76	66.37
1970	.54	.70	1.67	4.28	7.39	11.57	13.07	12.50	9.15	6.33	2.20	.75	70.15
1971	.54	.70	1.69	4.30	7.18	11.69	10.84	11.75	8.91	6.35	2.21	.75	66.91
1972	.54	.69	1.69	4.29	8.82	11.00	11.51	11.95	7.90	6.28	2.20	.74	67.61
1973	.56	.71	2.07	4.30	7.69	11.19	12.23	12.99	8.36	6.74	2.21	.75	69.80
1974	.55	.70	1.69	4.31	6.72	10.75	13.62	10.91	7.48	6.35	2.21	.77	66.06
1975	.56	.69	1.67	4.24	8.38	10.79	13.37	11.89	7.78	6.36	2.22	.76	68.71
1976	.55	.71	1.69	5.65	7.94	12.14	13.06	13.39	9.22	6.24	2.18	.74	73.51
1977	.54	.70	1.71	5.48	10.74	10.77	12.36	9.59	8.17	6.30	2.18	.74	69.28
1978	.54	.68	1.68	4.27	8.39	10.40	11.84	11.84	10.16	6.32	2.19	.74	69.05
1979	.54	.68	1.67	4.23	6.28	10.60	12.09	10.71	9.55	6.30	2.20	.77	65.62
1980	.55	.70	1.68	5.59	9.44	10.84	12.56	11.55	8.44	6.29	2.23	.75	70.62

Table 3. Estimated monthly evaporation, in centimeters, from Orwell Lake in Minnesota, 1931-2001—Continued

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1981	0.56	0.71	1.72	4.92	7.80	10.10	12.35	11.60	8.58	6.30	2.24	0.75	67.63
1982	.54	.69	1.68	4.28	8.72	9.08	12.43	11.69	8.07	6.31	2.19	.76	66.44
1983	.56	.71	1.71	4.28	6.69	10.52	13.27	13.24	8.61	6.29	2.22	.73	68.83
1984	.55	.72	1.68	4.60	7.02	10.69	12.26	12.64	7.07	6.34	2.21	.75	66.53
1985	.55	.69	1.72	5.13	9.36	9.17	11.88	10.40	7.70	6.30	2.15	.74	65.79
1986	.56	.69	1.70	4.31	8.07	11.36	12.34	10.47	7.81	6.32	2.18	.76	66.57
1987	.56	.72	1.71	6.43	9.35	11.80	12.75	11.14	8.92	6.27	2.23	.76	72.64
1988	.55	.69	1.70	4.31	10.19	13.10	13.61	12.72	8.82	6.27	2.20	.75	74.91
1989	.56	.68	1.67	4.29	8.20	10.37	13.61	11.96	8.69	6.33	2.18	.74	69.28
1990	.57	.70	1.71	4.31	7.18	10.92	11.84	11.88	9.62	6.30	2.22	.75	68.00
1991	.55	.71	1.70	5.02	9.24	12.04	12.02	12.54	8.22	6.28	2.17	.76	71.25
1992	.56	.71	1.71	4.27	8.78	9.89	10.01	10.30	8.05	6.30	2.19	.75	63.52
1993	.55	.69	1.68	4.29	7.72	9.51	11.02	11.58	6.86	6.28	2.18	.75	63.11
1994	.54	.68	1.70	4.30	8.82	11.39	11.38	10.85	9.56	6.35	2.22	.76	68.55
1995	.55	.70	1.69	4.26	7.29	12.05	12.05	12.31	8.61	6.30	2.17	.76	68.74
1996	.54	.70	1.66	4.26	7.18	11.48	11.92	12.36	9.05	6.33	2.16	.74	68.38
1997	.55	.70	1.68	4.27	6.61	12.09	11.75	11.01	9.57	6.34	2.18	.77	67.52
1998	.56	.72	1.69	5.27	9.17	9.48	12.01	12.36	10.56	6.34	2.21	.76	71.13
1999	.55	.71	1.71	4.31	8.52	10.90	12.55	12.01	8.14	6.30	2.66	.77	69.13
2000	.55	.71	1.87	4.30	8.54	10.06	12.42	12.09	8.75	6.35	2.19	.73	68.56
2001	.56	.68	1.68	4.30	8.80	11.06	12.91	12.63	8.71	6.30	3.41	.76	71.80

Table 4. Estimated monthly evaporation, in centimeters, from Lake Traverse in Minnesota and South Dakota, 1931-2001

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1931	0.61	0.77	1.81	5.53	7.86	13.21	14.30	12.35	11.80	6.92	2.41	0.82	78.39
1932	.59	.75	1.78	4.69	9.09	12.42	13.61	13.01	9.35	6.67	2.37	.81	75.14
1933	.60	.74	1.81	4.40	8.64	14.33	14.63	12.80	11.39	6.70	2.38	.81	79.23
1934	.60	.75	1.80	5.03	11.82	12.61	13.90	12.18	8.11	6.99	2.41	.81	77.01
1935	.59	.77	1.82	4.05	6.92	10.36	14.56	12.75	9.53	6.70	2.35	.81	71.21
1936	.57	.71	1.81	4.05	10.56	11.97	16.11	13.75	10.88	6.68	2.37	.82	80.28
1937	.58	.74	1.80	4.07	9.23	11.02	13.57	14.56	10.07	6.69	2.37	.81	75.51
1938	.59	.75	1.83	5.27	7.69	11.58	13.05	14.12	10.35	7.82	2.37	.82	76.24
1939	.60	.73	1.81	4.07	10.77	11.79	13.53	12.87	10.53	6.69	2.42	.83	76.64
1940	.58	.75	1.79	4.06	8.51	11.56	14.34	11.95	11.10	7.44	2.36	.82	75.26
1941	.60	.75	1.81	6.09	10.40	11.83	13.79	12.87	10.04	6.72	2.40	.82	78.12
1942	.60	.75	1.83	6.38	7.42	10.67	12.43	12.52	8.32	6.73	2.39	.80	70.84
1943	.58	.75	1.78	5.38	7.32	11.24	13.78	12.83	8.75	6.74	2.38	.82	72.35
1944	.61	.75	1.79	4.06	9.44	11.78	12.76	12.40	9.48	6.76	2.40	.82	73.05
1945	.60	.75	2.64	4.07	6.98	9.82	12.65	12.75	9.12	6.72	2.37	.80	69.27
1946	.59	.74	2.45	6.52	7.70	11.87	13.34	12.19	9.22	6.71	2.39	.81	74.53
1947	.61	.74	1.80	4.06	7.30	10.64	13.39	14.83	10.26	8.30	2.36	.81	75.10
1948	.59	.74	1.78	5.62	8.71	11.13	13.47	12.85	11.49	6.74	2.39	.81	76.32
1949	.59	.74	1.80	5.63	9.64	12.02	13.46	13.98	8.86	6.74	2.43	.81	76.70
1950	.58	.74	1.79	4.01	7.28	11.88	12.37	11.29	9.68	6.75	2.36	.80	69.53
1951	.58	.75	1.76	4.06	9.32	9.93	12.56	11.55	8.16	6.70	2.36	.80	68.53
1952	.59	.75	1.78	5.51	8.59	12.38	13.37	12.83	10.88	6.69	2.40	.82	76.59
1953	.60	.75	1.81	4.05	8.04	11.84	12.77	13.20	9.88	8.15	2.42	.82	74.33
1954	.58	.77	1.80	4.58	6.75	11.38	13.41	12.46	9.15	6.70	2.47	.82	70.87
1955	.59	.74	1.79	7.31	10.44	11.30	14.35	13.84	9.77	6.76	2.34	.80	80.03
1956	.59	.74	1.79	4.04	8.47	12.98	12.14	12.34	9.07	7.76	2.39	.82	73.13
1957	.59	.75	1.81	4.69	8.01	10.99	14.43	12.42	9.04	6.72	2.39	.83	72.67
1958	.60	.75	1.81	5.18	9.68	10.02	12.53	13.51	10.56	6.97	2.40	.81	74.82
1959	.59	.74	1.83	5.06	8.98	12.85	13.68	14.06	10.17	6.65	2.35	.83	77.79
1960	.59	.75	1.77	4.43	8.75	10.74	13.67	13.32	10.42	6.75	2.40	.81	74.40
1961	.59	.76	2.02	4.05	7.76	12.68	12.63	13.90	9.07	6.75	2.39	.80	73.40
1962	.59	.74	1.79	4.07	9.06	11.35	12.02	12.81	8.91	6.99	2.41	.82	71.56
1963	.58	.75	1.83	5.37	8.38	12.40	13.26	12.61	10.51	8.95	2.41	.80	77.85
1964	.60	.76	1.79	5.18	9.83	12.02	14.20	12.01	8.90	6.75	2.39	.80	75.23
1965	.58	.74	1.77	4.31	8.86	11.40	12.87	12.35	6.50	7.01	2.39	.83	69.61
1966	.58	.74	1.83	4.05	7.57	11.52	14.74	11.80	9.55	6.73	2.36	.81	72.28
1967	.59	.74	1.82	4.30	6.92	11.05	12.47	12.03	10.01	6.71	2.39	.82	69.85
1968	.59	.74	3.22	5.26	7.36	11.41	12.94	12.69	9.64	6.73	2.40	.81	73.79
1969	.58	.75	1.77	5.13	8.95	9.51	12.68	13.91	10.19	6.66	2.40	.82	73.35
1970	.58	.75	1.79	4.07	8.54	12.44	13.87	13.23	10.25	6.73	2.38	.81	75.44
1971	.58	.75	1.81	5.62	8.13	12.47	11.99	12.96	9.93	6.75	2.39	.81	74.19
1972	.59	.74	1.80	4.07	9.52	11.73	12.64	13.11	9.30	6.68	2.38	.80	73.36
1973	.60	.76	2.65	4.71	8.47	12.20	13.07	13.90	9.08	7.61	2.38	.81	76.24
1974	.59	.75	1.80	4.78	7.65	11.50	14.73	12.06	8.85	6.80	2.40	.82	72.73
1975	.60	.74	1.78	4.02	9.17	11.58	14.60	12.65	8.72	6.77	2.40	.81	73.84
1976	.59	.77	1.81	6.36	8.64	12.92	14.24	14.41	10.46	6.67	2.37	.81	80.05
1977	.58	.76	1.83	7.16	11.33	11.95	13.77	11.17	9.43	6.73	2.37	.80	77.88
1978	.58	.74	1.80	4.07	9.38	11.58	13.03	13.12	11.53	6.74	2.37	.81	75.75
1979	.58	.73	1.79	4.03	7.03	11.37	12.82	11.80	10.57	6.70	2.38	.83	70.63
1980	.59	.74	1.79	6.28	10.05	11.52	13.45	12.18	9.53	6.70	2.41	.81	76.05

Table 4. Estimated monthly evaporation, in centimeters, from Lake Traverse in Minnesota and South Dakota, 1931-2001—Continued

Year	January	February	March	April	May	June	July	August	September	October	November	December	Total
1981	0.60	0.76	2.16	6.35	8.69	10.95	13.13	12.71	9.74	6.71	2.46	0.81	75.07
1982	.57	.74	1.80	4.07	9.14	10.07	13.82	12.90	9.29	6.72	2.37	.82	72.31
1983	.60	.76	1.81	4.06	7.84	11.68	14.72	14.62	10.04	6.72	2.39	.79	76.03
1984	.60	.77	1.79	5.00	8.54	11.82	13.41	13.85	8.36	6.74	2.40	.81	74.09
1985	.59	.75	1.83	6.60	10.32	10.50	13.41	11.53	8.52	6.71	2.33	.80	73.89
1986	.60	.74	1.83	5.10	9.11	12.31	13.62	11.55	8.78	6.73	2.37	.83	73.57
1987	.61	.77	1.83	7.41	10.20	12.61	14.19	12.26	10.11	6.68	2.41	.82	79.90
1988	.59	.74	1.82	5.47	10.89	13.94	14.71	13.54	9.74	6.68	2.38	.82	81.32
1989	.60	.73	1.79	4.48	9.05	11.21	14.09	12.57	9.65	6.73	2.37	.80	74.07
1990	.61	.76	1.83	5.00	8.07	11.87	12.51	12.58	10.59	6.71	2.41	.81	73.75
1991	.59	.76	1.82	5.91	9.69	12.57	12.90	13.27	9.57	6.70	2.35	.82	76.95
1992	.61	.77	1.83	4.07	9.72	10.62	10.87	11.28	9.44	6.71	2.37	.81	69.10
1993	.59	.74	1.80	4.24	8.49	10.16	11.82	12.31	8.20	6.71	2.37	.81	68.24
1994	.58	.74	1.82	5.18	9.77	12.28	12.18	11.62	10.46	6.76	2.41	.82	74.62
1995	.59	.75	1.81	4.04	8.08	12.49	12.89	13.45	9.33	6.69	2.36	.81	73.29
1996	.58	.75	1.78	4.05	7.53	12.08	12.49	12.76	9.37	6.72	2.33	.80	71.24
1997	.58	.75	1.79	4.05	7.71	12.54	12.91	12.21	10.73	6.75	2.37	.83	73.22
1998	.59	.77	1.80	6.05	10.20	10.91	13.42	13.39	11.35	6.75	2.40	.82	78.45
1999	.59	.77	1.83	5.12	9.13	11.65	13.90	12.78	8.98	6.71	3.40	.83	75.69
2000	.59	.76	2.67	4.70	9.32	11.21	13.05	12.98	9.81	6.75	2.37	.79	75.00
2001	.60	.74	1.79	4.53	9.38	12.02	14.00	13.42	9.70	6.71	4.15	.82	77.86

Results from the procedure that estimates reservoir evaporation indicate that either Lake Ashtabula or Lake Traverse had the most evaporation per year, whereas Orwell Lake had somewhat less (fig. 4). Regression analyses indicate that slight downward trends in annual evaporation (about -0.05 centimeters per year) occurred from 1931-2001 at all three reservoir study sites. The trends may have been caused by the selected time period of the study, which began with the drought conditions in the mid 1930’s and ended with the more wet conditions in the late 1990’s. Average annual evaporation for each reservoir for 1931-2001 was about 74.0 centimeters from Lake Ashtabula, about 68.2 centimeters from Orwell Lake, and about 74.6 centimeters from Lake Traverse. These values correspond well with average annual lake evaporation values for 1946-55 (Kohler and others, 1959).

METHOD CONSIDERATIONS AND LIMITATIONS

The data used in this report were obtained from rigorous methods and established climate stations; however, the data still only represent conditions at a point or small area. It is possible that physical and atmospheric conditions at the reservoir study sites and at the energy budget evaporation sites may have been inadequately represented by the data. The use of monthly values can improve representation of conditions by integrating and smoothing point and daily information into a single value.

Regression equations usually cannot be used to indicate cause and effect. However, because the data from the two energy budget evaporation sites were determined from a rigorous energy budget method, and because air temperature directly influences evaporation from open-water surfaces, the results from the regression equations could be considered cause and effect. A limitation of the method is that the evaporation data from the two energy budget evaporation sites in North Dakota and Minnesota covered a time period that did not include the most recent dry episode in the late 1980’s and early 1990’s. Data from the dry episode may have indicated whether the relation between monthly evaporation and monthly mean air temperature was different than the linear function used in the regressions. In addition, the monthly evaporation corrections used for the winter months October through April were general corrections from other published material and were not based on specific factors associated with each reservoir.

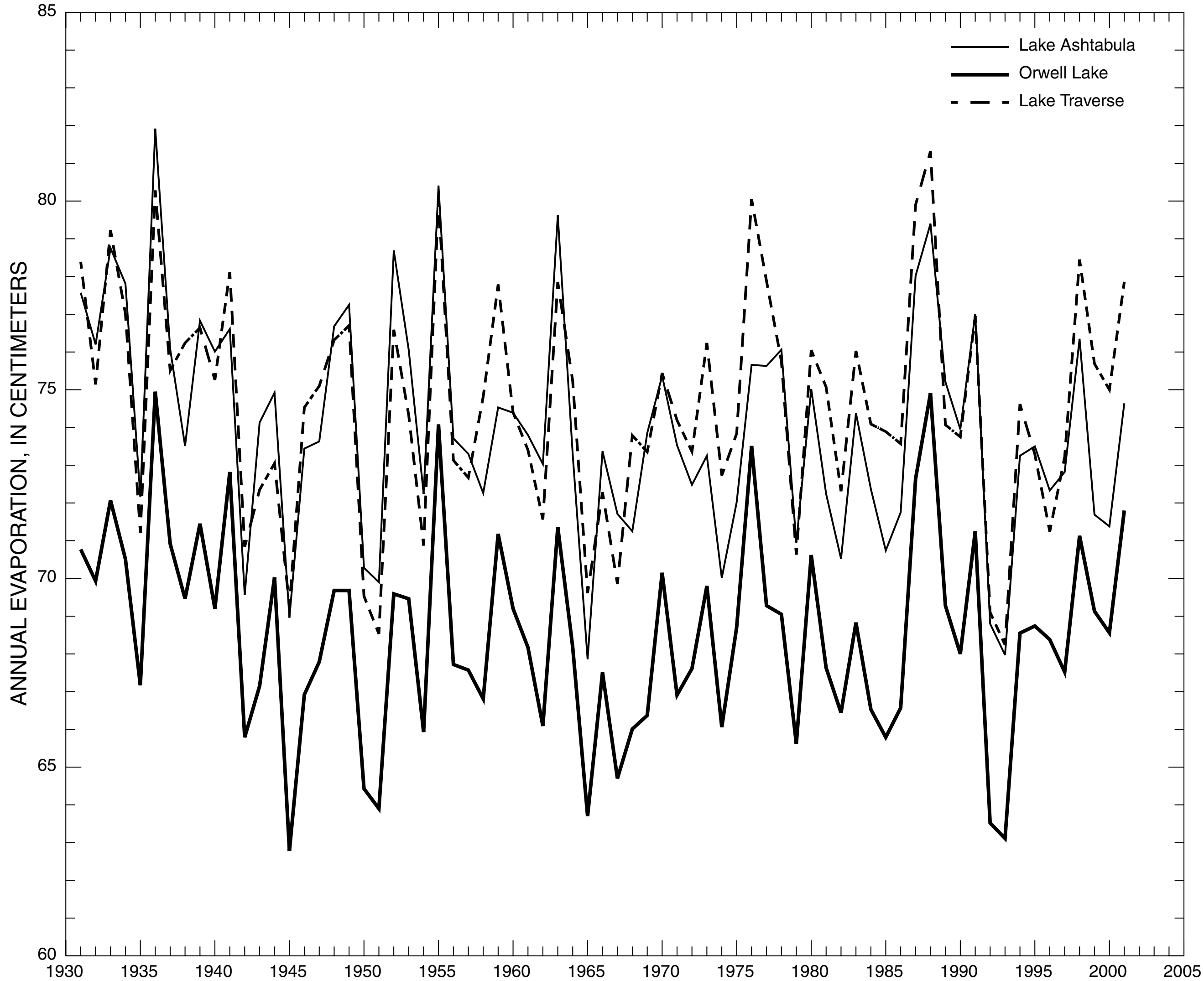

Figure 4. Annual evaporation determined from the regression equation for Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota, 1931-2001.

SUMMARY

Reliable water supplies are needed for population growth of cities in the Red River of the North Basin. Currently, reservoirs on tributaries of the Red River of the North provide water for Fargo and Grand Forks, N. Dak., and other cities along the river. The Dakota Water Resources Act, passed by the U. S. Congress on December 15, 2000, authorized the Secretary of the Interior to conduct a comprehensive study of the future water-quantity and quality needs of the Red River of the North Basin in North Dakota and the possible options to meet those water needs. Adequate estimates of evaporative losses from reservoirs in the Red River of the North Basin are needed to determine the total water supply in the Basin. A study was conducted by the U.S. Geological Survey in cooperation with the Bureau of Reclamation to review studies that evaluated evaporation estimation methods and to estimate monthly evaporation from Lake Ashtabula in North Dakota, Orwell Lake in Minnesota, and Lake Traverse in Minnesota and South Dakota for 1931-2001.

Pan evaporation data commonly are used to estimate evaporation from lakes and reservoirs; however, there are problems with using these data. Debris in the water, animal activity in and around the pan, size of the pan, materials used to construct the pan, exposure of the pan, strong winds, and measurement of water depth in the pan can introduce errors in pan evaporation rates. The energy budget method was used to determine evaporation from a wetland in North Dakota, Wetland P1, and from a lake in Minnesota, Williams Lake. The energy budget method relies on the optimum placement of sensors in and around the lake or reservoir to provide a rigorous estimate of evaporation. The energy budget method was

compared to 11 other evaporation equations. Of the 11 equations evaluated, 3 equations produced results that corresponded well with the energy budget method. However, in addition to measurements of air temperature, the equations require measurements of net radiation, wind speed, and relative humidity. The evaporation and air temperature data from the energy budget evaporation sites at Wetland P1 and Williams Lake are available, and the air temperature data collected from climate stations near Lake Ashtabula, Orwell Lake, and Lake Traverse also are available. Therefore, the combined data sets were used to estimate monthly evaporation from Lake Ashtabula, Orwell Lake, and Lake Traverse.

Monthly mean air temperature data for 1931-2001 were collected from climate data stations located near the reservoir study sites. Energy budget data were obtained for Wetland P1 and Williams Lake. Monthly evaporation data for Wetland P1 was regressed against the measured monthly mean air temperature data for Wetland P1, and monthly evaporation data for Williams Lake was regressed against the measured monthly mean air temperature data for Williams Lake. Averaged monthly mean air temperatures determined for each reservoir study site for 1931-2001 from nearby climate data stations were used in the Wetland P1 and Williams Lake equations to calculate two monthly evaporation data sets for each reservoir study site for 1931-2001. An inverse distance weighting scheme was used to determine the fractional contribution of each of the two monthly evaporation data sets from the energy budget evaporation sites to the estimated monthly evaporation data set for each reservoir study site. The two monthly evaporation data sets for each reservoir study site were multiplied by their appropriate fractional contributions and the results were summed to produce one weighted monthly evaporation data set for each reservoir study site.

Results from the procedure that estimates reservoir evaporation indicate that slight downward trends in annual evaporation occurred from 1931-2001. The trends may have been caused by the selected time period of the study, which began with the drought conditions in the mid 1930's and ended with the more wet conditions in the late 1990's. Average annual evaporation values for each reservoir for 1931-2001 correspond well with published average annual lake evaporation values for 1946-55.

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