Ground-Water Baseflow to the Upper Mississippi River Upstream of the Minneapolis-St. Paul Area, Minnesota During July 1988

By G.A. Payne

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Conversion Factors

Multiply	By	To obtain
cubic foot per square mile (ft^3/mi^2)	0.01093	cubic meter per square mile
cubic foot per second (ft^3/s)	.02832	cubic meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Ground-Water Baseflow to the Upper Mississippi River Upstream of the Minneapolis-St. Paul Area, Minnesota During July 1988

By Gregory A. Payne

Abstract

Ground-water baseflow to six subreaches of the Upper Mississippi River were estimated for July 1988, a period of drought. Ground-water baseflow to each subreach was estimated on the basis of streamflow gains determined from records of daily discharge at gaging stations. Streamflow gains were adjusted for estimated inflow from tributaries, municipal and industrial discharges, withdrawals, and evaporation. Low-flow frequency characteristics were computed for the Mississippi River near Anoka, Minnesota and the Mississippi River at St. Paul, Minnesota.

Introduction

The Mississippi River supplies water for the Minneapolis-St. Paul area of Minnesota (fig. 1). A drought in 1988 raised concern about the need for supplemental releases of water from reservoirs in the Mississippi River headwaters. The U.S. Army Corps of Engineers (USCOE) and the Minnesota Environmental Quality Board (EQB) have undertaken a study to develop a methodology that can be used to estimate the timing and volume of releases from the Headwaters Reservoirs necessary to support minimum flows of the Mississippi River in the Minneapolis-St. Paul area. One of the needs identified by the USCOE-EQB is quantification of ground-water contribution to the Upper Mississippi River during periods of baseflow. The U.S. Geological Survey (USGS) was requested to assist the USCOE-EQB study by (1) estimating the ground-water baseflow by subreach to the Mississippi River during July 1988, and (2) computing updated low-flow frequency statistics for the Mississippi River near Anoka and the Mississippi River at St. Paul.

Purpose and Scope

This report presents the results of estimates of ground-water gains and losses in six subreaches of the Mississippi River from the headwaters reservoirs to Anoka, Minnesota during July 1988 and lists low-flow statistics for the Mississippi River near Anoka for 1933-93 and Mississippi River at St. Paul, Minnesota for 1895, 1897, 1901-05, and 1907-93.

Approach and Methods

The scope of work for this investigation identified two primary objectives (1) determination of baseflow discharge to the Mississippi River, and (2) computation of low-flow frequency characteristics for the Mississippi River near the Minneapolis-St. Paul area. An approach and method was developed to address each of the objectives.

Ground-water baseflow

The study reach, which extends from the Mississippi River headwaters reservoirs downstream to Anoka in the Minneapolis-St. Paul area, was divided into six subreaches (fig. 1). A USGS continuous-record streamflow gaging station is located at the upstream and downstream end of each subreach. Distance in river miles for each subreach was determined from data published in the USCOE users manual for the River Emergency Management Model (U.S. Army Corps of Engineers, 1993). Daily stream discharge records for the gaging stations during July 1988 were used to determine the gain or loss of discharge within each subreach. Inflows from tributary streams and municipal and industrial discharges, both gaged and ungaged, were subtracted from the gain in each reach. Municipal and industrial withdrawals from the Mississippi River and estimated evaporative losses were added to the gain in each reach. The resulting stream discharge was considered to be the ground-water baseflow to the Mississippi River main channel within each subreach.

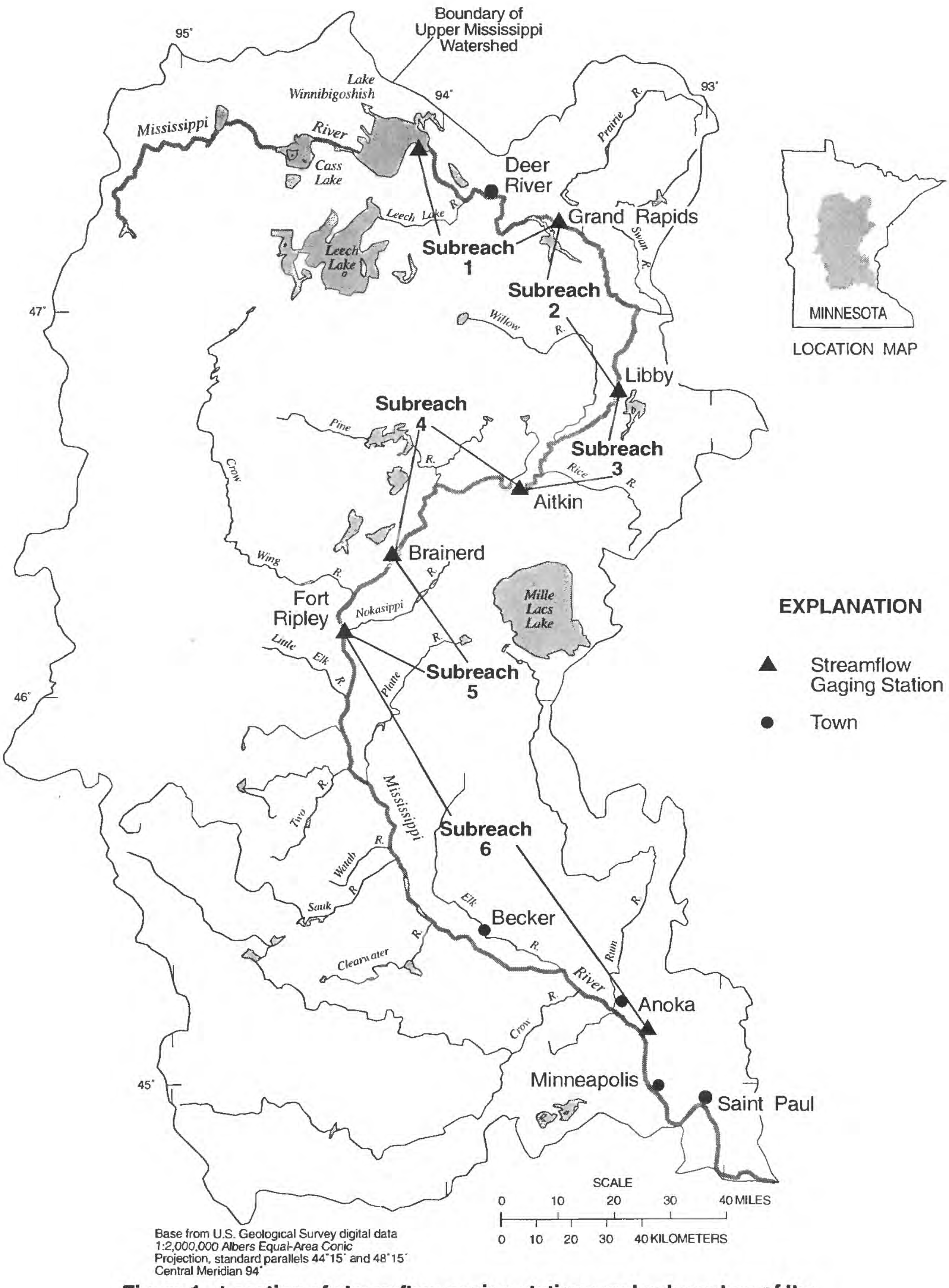

Figure 1.--Location of streamflow gaging stations and subreaches of the Upper Mississippi River watershed.

The following equation shows the calculation procedure:

(DSGAGE - USGAGE) - (INFLOWS) + (WITHDRAWALS) + (EVAP) = (GRNDWTR)

where,

DSGAGE = Discharge of the Mississippi River at gaging station at downstream end of subreach.

USGAGE = Discharge of the Mississippi River at gaging station at upstream end of subreach.

INFLOWS = Discharges for tributary, municipal, and industrial inflows in subreach.

WITHDRAWALS = Municipal and industrial withdrawals in subreach.

EVAP = Water evaporated from the surface of the Mississippi River.

GRNDWTR= Ground-water baseflow to the main channel of the Mississippi River.

Daily stream discharges for gaged tributaries were obtained from USGS records (Gunard and others 1990). Daily stream discharges for ungaged tributaries were estimated from periodic current-meter measurements made in ungaged tributary streams during May through August 1988. Characteristics of stream discharge during two previous low-flow periods (1976 and 1980) were also used for estimating discharge at some of the ungaged tributaries (U.S. Geological Survey 1977 and 1981). Stream discharges from the current-meter measurements were plotted by date on semi-log scale graphs and a smooth recession curve was drawn through the plotted points. Discharges for each day in July were determined from the curve. Each daily discharge was divided by the drainage area of the stream to obtain a cubic feet per square mile (ft^3/mi^2) daily discharge value. Drainage areas were obtained from USGS files, listings of drainage areas provided by the Minnesota Department of Natural Resources (MDNR) (Dana Dostert, Minnesota Department of Natural Resources, written communication, 1994), and by planimetering watershed boundaries drawn on USGS 7.5-minute topographic maps. Some of the periodic discharge measurements were made at locations other than the point where the tributary is confluent with the Mississippi River. The discharge at the mouth of those tributaries was estimated by using the ft^3/mi^2 values. Total drainage area at the mouth of those tributaries was multiplied by the daily ft^3/mi^2 value to obtain a daily discharge at the mouth. Discharges for ungaged tributaries for which no current-meter measurements had been obtained during May through August were estimated by using the daily ft^3/mi^2 values from a tributary in an adjacent or nearby watershed. The procedures used to estimate daily discharges at the mouth of each ungaged tributary are described in appendix A.

Municipal and industrial discharges were determined from data reported by the U.S. Army Corps of Engineers (1990). Evaporation from surface waters was estimated from evaporation rates measured at Williams Lake near Akeley, Minnesota (Sturrock and others, 1992) and from pan-evaporation measurements made by MDNR at Becker, Minnesota (Mark Rodney, U.S. Army Corps of Engineers, oral commun., 1994)

Low-flow frequency analysis

Low-flow frequency characteristics for the Mississippi River near Anoka and the Mississippi River at St. Paul were computed from continuous-record streamflow data maintained in the USGS Water-Data Storage and Retrieval System (WATSTORE; Hutchinson, 1975). Frequency characteristics were determined using a Log-Pearson type III frequency-distribution computation program in WATSTORE. The 1, 7, 14, and 30 day low-flow series were computed based on climatic years (April 1-March 31). Streamflow data from 1933 through 93 were analyzed for the Mississippi River near Anoka. Streamflow data from 1895, 1897, 1901-05, and 1907-93 were analyzed for the Mississippi River at St. Paul. Flow-duration data were computed based on water years (October 1-September 30) 1932-93 for the Mississippi River near Anoka, and 1895, 1897, 1901-05, and 1907-93 for the Mississippi River at St. Paul.

Results of Study

The approach and methods used to investigate ground-water baseflow resulted in a determination of tributary discharge, ground-water baseflow, evaporation, withdrawals, and net streamflow increase, by subreach, to the Mississippi River upstream of the Minneapolis-St. Paul area.

The application of the USGS WATSTORE computation program to continuous-record streamflow data resulted in calculation of low-flow frequency, flow duration, and climatic-year ranking information.

Ground-Water Baseflow

Estimated ground-water baseflow to each subreach is shown in table 1. Table 1 also shows the length of each subreach and the quantity of ground-water baseflow per river mile for each subreach. Discharges for tributaries,

Table 1.--Tributary discharges, ground-water baseflow, evaporation losses, and withdrawals, by subreach, Upper Mississippi River, July 1988
[ft^3/s, cubic feet per second]

	Length of subreach (river miles)	Discharge from tributaries[1] (ft^3/s)	Ground-water baseflow ft^3/s)	Evaporation from Mississ-ippi River (ft^3/s)	With-drawals from Mississippi River (ft^3/s)	Net streamflow increase (ft^3/s)	Net streamflow increase per river mile (ft^3/s)	Ground-water baseflow per river mile (ft^3/s)
[2]Subreach 1	67.4	206	28	107	36	91	1.35	0.42
[3]Subreach 2	74.9	93	41	16	0	118	1.58	.55
[4]Subreach 3	49.7	55	0	10	0	45	.91	.0
[5]Subreach 4	52.2	41	56	25	0	72	1.38	1.07
[6]Subreach 5	21.2	210	84	7.9	0	286	13.5	3.96
[7]Subreach 6	117.7	178	305	98	52	333	2.83	2.59
Total	383.1	783	514	264	88	945		

[1] Includes municipal wastewater discharges.
[2] Mississippi River from U.S. Geological Survey (USGS) gaging station at Lake Winnibigoshish Dam to USGS gaging station at Grand Rapids, Minnesota.
[3] Mississippi River from USGS gaging station in Grand Rapids to USGS gaging station near Libby, Minnesota.
[4] Mississippi River from USGS gaging station near Libby to USGS gaging station at Aitkin, Minnesota.
[5] Mississippi River from USGS gaging station at Aitkin to USGS gaging station at Brainerd, Minnesota.
[6] Mississippi River from USGS gaging station at Brainerd to USGS gaging station near Ft. Ripley, Minnesota.
[7] Mississippi River from USGS gaging station near Ft. Ripley to USGS gaging station near Anoka, Minnesota.

municipalities, and industries are listed in appendix B. Average discharges in the Upper Mississippi River at USGS gaging stations during July 1988 are shown in table 2. Net streamflow increases shown in table 1 are not consistent with data in table 2 because the data used to compute discharges for table 1 included discharges for June 28, 29, and 30, where necessary, to take into consideration travel times within subreaches.

Low-Flow Frequency Characteristics

Low-flow frequency data for the Mississippi River near Anoka and Mississippi River at St. Paul, Minnesota are shown in table 3. Flow-duration information is shown in table 4. Rankings by climatic year of lowest mean discharges for selected consecutive-day periods are shown in tables 5a and 5b.

Table 2.--Average discharge at U.S. Geological Survey gaging stations, Upper Mississippi River, July 1988

Gaging station	Discharge (cubic feet per second)
Mississippi River at Winnibigoshish Dam near Deer River, Minnesota	101
Mississippi River at Grand Rapids, Minnesota	192
Mississippi River below Sandy River, near Libby, Minnesota	313
Mississippi River at Aitkin, Minnesota	365
Mississippi River at Brainerd, Minnesota	442
Mississippi River near Fort Ripley, Minnesota	729
Mississippi River near Anoka, Minnesota	1090

Table 3.--Low-flow frequency characteristics for Mississippi River near Anoka, Minnesota and Mississippi River at St. Paul, climatic years (April 1 - March 31)

	Annual low flow for indicated recurrence interval in years, in cubic feet per second					
	Mississippi River near Anoka, 1933-93					
Period (consecutive days)	2 year	5 year	10 year	20 year	50 year	100 year
1 day	2110	1310	1010	808	622	519
3 day	2350	1470	1120	889	674	556
7 day	2610	1610	1210	941	697	564
14 day	2820	1720	1280	989	724	581
30 day	3030	1850	1380	1060	775	620
	Mississippi River at St. Paul, 1895, 1897, 1901-05, and 1907-93					
1 day	2550	1580	1220	984	765	645
3 day	2710	1720	1340	1090	862	734
7 day	2920	1840	1430	1160	911	772
14 day	3070	1940	1510	1220	960	813
30 day	3230	2070	1620	1320	1040	890

Table 4.--Flow-duration data for Mississippi River near Anoka and Mississippi River at St. Paul, Minnesota

Percent of time discharge equaled or exceeded	Discharge (cubic feet per second)
Mississippi River near Anoka, 1933-93	
95	1440
90	2040
85	2540
80	2980
75	3380
70	3780
65	4190
60	4580
55	4960
50	5430
45	5940
40	6580
35	7410
30	8460
25	9760
20	11500
15	14000
10	17500
5	23600
Mississippi River at St. Paul, 1895,1897, 1901-05, and 1907-93	
95	1910
90	2580
85	3110
80	3560
75	3970
70	4420
65	4910
60	5440
55	6030
50	6710
45	7590
40	8590
35	9750
30	11400
25	13600
20	16500
15	20300
10	26100
5	36500

Table 5a.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River near Anoka, Minnesota

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1933	877	6	913	6	981	6	1020	6	1060	6	1080	4	1140	3	1290	5	1260	4
1934	761	4	840	3	880	3	939	3	968	3	1140	5	1180	5	1260	4	1280	5
1935	602	1	610	1	646	1	690	1	710	1	752	1	852	1	933	1	1010	1
1936	1050	7	1350	10	1400	10	1430	10	1470	9	1580	8	1680	7	1730	7	1870	7
1937	686	2	693	2	722	2	755	2	963	2	1040	2	1070	2	1090	2	1110	2
1938	1220	11	1410	11	1570	11	1610	11	1640	10	1670	9	1690	8	1750	8	1910	8
1939	1960	29	2140	27	2230	22	2840	29	2970	29	3170	27	3250	26	3300	26	3400	20
1940	1070	8	1110	7	1120	7	1140	7	1170	7	1230	6	1310	6	1450	6	1830	6
1941	1220	12	1470	12	1590	12	1680	13	1800	14	1910	13	1930	12	2320	13	2680	14
1942	1660	20	2170	28	2930	34	3630	41	3820	40	4130	38	4200	36	4370	36	5980	45
1943	3120	49	3440	49	3490	45	3940	48	4460	49	4570	47	4670	43	4660	40	5450	40
1944	2850	43	3090	44	3610	48	4140	51	4710	51	5040	50	5150	48	5170	44	5220	38
1945	3600	52	3930	53	4170	53	4420	52	4720	52	5180	51	5400	49	5790	49	6280	46
1946	2800	39	3200	45	3460	43	3530	40	3650	38	3850	36	3990	34	4290	34	5230	39
1947	3310	50	3560	51	3810	50	3910	47	4050	42	4510	46	5050	47	5200	45	6520	49
1948	2800	40	2930	39	3110	39	3270	37	3390	35	3520	34	3620	30	3730	29	3970	27
1949	1800	25	2070	25	2230	23	2360	23	2700	23	2800	22	2930	23	2970	21	3020	16
1950	2520	36	2700	36	3030	35	3260	36	3370	34	3490	33	3580	29	3700	28	4120	29
1951	1900	28	2030	23	2560	29	3160	34	3820	41	4140	40	4300	39	4380	37	4750	35
1952	5500	60	5830	60	6060	59	6290	59	6430	59	6600	59	7020	58	7780	58	9080	58
1953	2520	37	2730	37	3260	41	4060	50	4400	47	4450	43	4640	42	4650	39	4940	36
1954	4050	57	4270	57	4950	57	4970	54	5450	57	5700	54	5720	53	6000	51	6300	47

Table 5a.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River near Anoka, Minnesota--Continued

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1955	3050	47	3080	42	3090	36	3150	33	3240	33	3420	32	3700	31	3860	31	4360	32
1956	1870	27	2140	26	2620	31	2790	27	2830	25	2910	23	3080	24	3250	24	3510	22
1957	2240	33	2300	31	2310	24	2350	22	2410	19	2510	18	2710	18	2860	19	3140	17
1958	3500	51	3550	50	3570	47	3700	42	4070	44	4280	42	4590	40	4830	42	5850	44
1959	1480	17	1570	14	1600	13	1610	12	1650	11	1750	11	1860	11	2020	10	2430	11
1960	1700	21	1780	18	2120	19	2250	19	2530	21	2710	21	2880	21	2970	22	3260	18
1961	1480	18	1580	15	1680	14	1760	15	1860	15	1920	14	2020	13	2150	12	2320	10
1962	1070	9	1110	8	1180	8	1220	8	1300	8	1670	10	1840	10	1970	9	2150	9
1963	1700	22	1890	20	2450	26	3120	32	3180	31	3230	28	3450	28	3740	30	4410	33
1964	1750	24	1940	21	2170	21	2340	21	2460	20	2530	19	2550	17	2620	15	2780	15
1965	1820	26	2030	24	2150	20	2250	20	2590	22	3150	26	3220	25	3250	25	3790	26
1966	3710	53	3930	52	4290	54	5150	57	5210	54	5900	56	7180	59	8670	61	9500	59
1967	2200	31	2570	34	3090	37	3750	43	4350	46	4500	45	4620	41	4770	41	5100	37
1968	1400	15	1580	16	1950	17	2090	17	2240	17	2380	15	2430	15	2500	14	2580	12
1969	2480	35	2560	33	2750	32	2880	31	3100	30	4220	41	5490	51	6300	52	7250	50
1970	2220	32	2270	29	2380	25	2550	24	2750	24	3230	29	3760	32	3990	32	4140	30
1971	1480	19	1670	17	1720	15	1750	14	1790	13	1910	12	2300	14	2810	18	4000	28
1972	2600	38	2660	35	2820	33	2870	30	3240	32	3290	30	4080	35	5270	46	7860	53
1973	4000	56	4200	56	4880	55	5040	55	5340	56	5910	57	6220	55	7160	56	8360	56
1974	3090	48	3260	48	3490	44	3780	45	4560	50	5510	53	5800	54	5940	50	7970	54
1975	1370	13	2350	32	2460	27	2620	25	2910	27	3400	31	4210	37	4540	38	4680	34
1976	3900	55	4130	55	4890	56	5110	56	5250	55	5340	52	5610	52	5720	48	5780	42

Table 5a.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River near Anoka, Minnesota--Continued

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1977	728	3	908	5	959	5	977	4	1040	4	1080	3	1160	4	1200	3	1240	3
1978	1150	10	1220	9	1260	9	1390	9	1690	12	2450	16	2750	19	2790	17	3620	23
1979	3010	46	3230	46	3870	51	4020	49	4060	43	4130	39	4280	38	4360	35	5460	41
1980	2810	41	3260	47	3720	49	3820	46	4140	45	4810	49	5000	46	5300	47	5830	43
1981	1450	16	1800	19	2010	18	2140	18	2280	18	2580	20	2790	20	2950	20	3490	21
1982	2810	42	3080	43	3510	46	3750	44	4440	48	4600	48	4690	44	5060	43	6400	48
1983	2990	45	3060	41	3390	42	3450	38	3570	37	4470	44	5440	50	6480	53	8660	57
1984	4360	58	4860	58	5140	58	5440	58	5880	58	6070	58	6970	57	7480	57	7510	51
1985	2880	44	2970	40	3110	38	3180	35	3510	36	3930	37	4810	45	6900	54	8130	55
1986	5740	61	6310	61	6430	61	6620	60	6860	61	7210	61	7760	61	7940	59	10500	60
1987	4790	59	5230	59	6190	60	6690	61	6830	60	7000	60	7410	60	7990	60	11000	61
1988	1980	30	2290	30	2590	30	2810	28	2960	28	3070	25	3290	27	3570	27	3710	24
1989	842	5	855	4	885	4	993	5	1060	5	1240	7	1770	9	2050	11	2620	13
1990	1380	14	1560	13	1730	16	1850	16	2080	16	2500	17	2550	16	2780	16	3300	19
1991	1700	23	1970	22	2530	28	2630	26	2860	26	2910	24	2930	22	3110	23	3730	25
1992	3770	54	3950	54	4130	52	4640	53	5060	53	5720	55	6470	56	6950	55	7690	52
1993	2440	34	2890	38	3140	40	3520	39	3710	39	3770	35	3810	33	4010	33	4270	31

Table 5b.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River at St. Paul, Minnesota

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1895	1060	7	1220	8	1250	7	1270	7	1300	7	1440	6	1660	7	2010	10	2750	11
1897	2280	42	2520	46	3150	54	3200	50	3230	47	3360	44	3800	46	3930	42	4370	37
1901	2200	38	2200	32	2200	29	2200	27	2200	21	2250	19	2670	23	3100	27	5640	57
1902	2950	61	2950	55	2950	50	2950	45	2950	40	2950	35	2970	32	3220	32	4060	31
1903	2000	31	2070	28	2190	28	2240	28	2270	24	2530	24	2780	27	3960	43	4410	38
1904	2730	52	2730	49	2730	44	2730	39	2760	35	3140	38	3610	43	3860	40	10500	83
1905	2500	49	2510	44	2510	36	2510	33	2510	32	2790	33	3150	35	4340	54	7080	70
1907	8050	94	8050	94	8050	92	8050	91	8080	91	8290	91	8580	88	9150	85	12200	88
1908	3500	67	3500	65	3500	61	3500	59	3500	55	3590	53	3820	47	4330	53	6200	63
1909	3500	68	3500	66	3500	62	3500	60	3500	56	3510	47	3930	54	4460	55	5860	59
1910	4650	84	4650	80	4650	75	4650	74	4650	70	4870	69	5360	71	6180	72	6910	66
1911	1960	29	1960	25	1960	20	1960	19	1960	16	2010	16	2090	15	2280	14	2880	16
1912	2700	51	2700	48	2700	43	2700	38	2700	34	2750	32	2880	31	3100	28	4160	32
1913	2350	43	2350	36	2350	31	2350	30	2380	29	2580	28	2780	28	3000	26	3500	25
1914	3280	65	3300	62	3300	57	3300	52	3330	48	3500	46	3570	42	4010	44	5000	49
1915	3860	72	3860	70	3860	67	3860	64	4000	65	4120	63	4530	62	5240	67	7130	71
1916	5900	88	5900	87	5900	86	5900	85	5910	84	6080	81	6530	81	7550	81	9060	79
1917	3800	71	3850	69	4190	70	4340	70	4490	69	4580	68	4760	67	5160	65	7020	68
1918	2400	46	2430	40	2540	38	2790	41	3100	44	3280	43	3370	39	3740	37	4740	46
1919	2920	60	3020	58	3120	52	3160	48	3340	49	3910	59	4610	64	5520	69	5320	53
1920	2900	57	2970	56	3210	55	3390	55	3460	51	3530	49	3670	44	4130	47	5000	50

Table 5b.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River at St. Paul, Minnesota--Continued

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1921	2900	58	3050	59	3210	56	3400	56	3500	57	3560	52	3880	50	4540	58	5570	56
1922	2450	47	2520	45	2620	40	2670	37	2810	36	2880	34	3020	34	3130	29	3650	29
1923	2050	32	2070	29	2160	27	2290	29	2420	30	2570	26	2670	24	2860	23	3310	21
1924	1850	25	1930	24	1980	21	2020	21	2110	20	2220	18	2310	18	2420	16	2830	15
1925	1130	9	1310	10	1410	10	1530	10	1620	10	1650	9	1800	8	2170	12	3500	26
1926	1450	17	1480	11	1500	11	1570	11	1670	12	1730	10	1840	9	2080	11	2770	12
1927	1820	24	1970	26	2010	24	2150	26	2370	28	2570	27	2670	25	2910	24	4590	41
1928	2140	36	2190	31	2350	32	2510	34	2580	33	2630	30	2840	29	3480	34	4330	36
1929	2820	55	2920	54	3320	58	3400	57	3470	52	3550	51	3900	51	4250	52	6410	64
1930	1600	20	1620	16	1670	14	1750	14	1810	14	1840	13	1940	12	2650	18	3490	24
1931	1760	23	1840	21	1910	19	1960	20	2060	18	2170	17	2260	17	2380	15	2790	13
1932	1090	8	1120	7	1290	8	1440	9	1570	9	1740	11	1860	10	1960	7	2280	9
1933	1240	11	1280	9	1350	9	1370	8	1420	8	1520	7	1620	6	1700	6	1680	5
1934	1020	4	1070	6	1130	6	1180	5	1250	5	1420	5	1500	5	1580	5	1590	4
1935	632	1	705	1	741	1	807	1	857	1	927	1	1050	1	1140	1	1250	1
1936	1280	12	1480	12	1560	12	1580	12	1630	11	1810	12	1940	13	1990	8	2130	7
1937	668	2	720	2	787	2	847	2	1100	2	1220	2	1250	2	1270	2	1290	2
1938	1360	14	1670	19	1760	18	1840	17	1860	15	1910	15	1930	11	2000	9	2260	8
1939	2370	44	2650	47	2940	48	3440	58	3590	58	3800	57	3770	45	3900	41	4690	43
1940	1020	5	1060	4	1080	4	1120	4	1180	4	1280	4	1380	4	1540	4	1970	6
1941	1330	13	1500	15	1740	17	1840	18	2030	17	2300	20	2400	19	2810	21	3190	19
1942	2900	59	3210	61	3890	68	4110	66	4420	66	4940	70	5060	70	5380	68	7360	73
1943	4440	82	4640	79	4730	77	5140	81	5330	79	5540	76	5560	72	5990	70	7630	74

Table 5b.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River at St. Paul, Minnesota--Continued

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1944	4730	85	4810	84	5190	83	5380	83	5770	83	6290	83	6540	82	6540	75	7050	69
1945	4220	78	4500	77	4750	78	4800	76	5150	77	5610	78	5900	77	6370	74	6950	67
1946	3110	62	3440	64	3590	65	3710	63	3930	62	4170	64	4410	59	4700	62	6030	60
1947	4110	75	4220	74	4380	73	4560	72	4990	74	5750	79	6150	78	6770	79	8500	78
1948	3230	63	3340	63	3550	64	3660	61	3730	60	3970	61	4220	57	4470	56	4710	44
1949	2220	39	2440	41	2620	41	2880	43	3190	45	3230	40	3410	40	3520	35	3640	28
1950	2810	54	3080	60	3370	59	3680	62	3860	61	3920	60	4020	55	4200	49	4560	40
1951	1930	28	1990	27	2550	39	3200	49	3980	64	4340	65	4540	63	4620	60	5110	51
1952	6620	90	7090	90	7150	90	7250	90	7550	89	8000	89	8630	89	9840	90	11400	87
1953	2800	53	2900	53	3370	60	4290	67	4450	68	4540	66	4730	65	4880	64	5270	52
1954	4420	81	4790	83	5550	84	5750	84	6020	85	6250	82	6400	79	6640	77	7220	72
1955	3280	64	3620	67	3790	66	3900	65	3950	63	4080	62	4360	58	4590	59	5480	55
1956	2120	34	2260	33	2640	42	2950	44	2970	41	3020	37	3210	36	3340	33	3730	30
1957	2110	33	2350	37	2370	33	2390	31	2470	31	2610	29	2840	30	3130	30	3430	22
1958	4020	73	4100	72	4150	69	4310	69	4670	71	5090	72	5830	75	6340	73	7910	75
1959	1420	15	1660	18	1700	15	1730	13	1750	13	1860	14	2030	14	2260	13	2670	10
1960	1970	30	2150	30	2320	30	2430	32	2870	38	3370	45	3920	52	4010	45	4270	33
1961	1870	26	1890	23	2020	25	2090	24	2210	22	2340	21	2540	20	2730	20	3240	20
1962	1540	19	1650	17	1720	16	1820	15	2240	23	2530	25	2650	22	2850	22	2920	18
1963	2260	40	2360	38	2870	47	3370	54	3480	53	3540	50	3830	48	4210	51	5400	54
1964	2370	45	2470	43	2810	45	2870	42	2900	39	3000	36	3010	33	3220	31	3630	27
1965	2170	37	2320	35	2440	34	2590	35	2990	42	3760	55	3830	49	3850	39	4640	42

Table 5b.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River at St. Paul, Minnesota--Continued

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1966	4070	74	4590	78	5930	87	6270	87	6330	87	8110	90	10300	94	11800	94	12400	90
1967	2280	41	2850	52	3530	63	4300	68	4910	72	4940	71	5020	69	5230	66	5810	58
1968	1220	10	1480	13	1990	22	2150	25	2350	26	2460	23	2560	21	2660	19	2800	14
1969	4600	83	4780	82	4870	80	5000	79	5680	82	7280	86	7680	84	8550	84	12700	92
1970	2650	50	2810	51	2870	46	3040	46	3370	50	3900	58	4420	60	4530	57	4730	45
1971	1690	22	1880	22	2030	26	2040	22	2110	19	2370	22	3230	37	4200	50	6790	65
1972	2880	56	2980	57	3150	53	3230	51	3620	59	3800	56	4940	68	7610	82	11000	85
1973	5680	87	5940	88	6620	88	6890	88	7440	88	7930	88	8020	87	9490	87	10500	84
1974	3780	70	3970	71	4280	72	4700	75	5650	81	6590	85	6530	80	7300	80	10200	82
1975	1450	16	2380	39	2470	35	2760	40	3030	43	3520	48	4450	61	4680	61	4810	47
1976	3760	69	4170	73	4950	81	5300	82	5420	80	5510	75	5820	74	5990	71	6060	61
1977	723	3	953	3	993	3	1040	3	1140	3	1220	3	1330	3	1400	3	1440	3
1978	1480	18	1500	14	1600	13	1820	16	2280	25	3250	41	4060	56	4090	46	4990	48
1979	3430	66	3660	68	4230	71	4390	71	4430	67	4560	67	4730	66	4820	63	6120	62
1980	5040	86	5650	86	5890	85	5980	86	6170	86	6360	84	6990	83	8140	83	9400	80
1981	1920	27	2310	34	2530	37	2640	36	2820	37	3150	39	3420	41	3790	38	4420	39
1982	4370	80	4830	85	5020	82	5090	80	5180	78	5430	74	5790	73	6570	76	8040	76
1983	4120	76	4250	75	4500	74	4610	73	4930	73	6010	80	7760	85	9460	86	12600	91
1984	6120	89	6580	89	6840	89	6980	89	7570	90	7840	87	8900	90	9530	88	9440	81
1985	4220	77	4370	76	4660	76	4810	77	5100	75	5550	77	7830	86	9840	89	11300	86
1986	7140	93	7840	93	8270	94	8310	93	8630	93	9320	93	10000	91	10600	91	15300	93
1987	6840	91	7190	91	8170	93	8640	94	8720	94	9360	94	10300	92	11500	93	17600	94
1988	2480	48	2800	50	3090	51	3310	53	3490	54	3660	54	3930	53	4170	48	4310	35

Table 5b.--Lowest mean discharge, in cubic feet per second, and ranking for the indicated number of consecutive days in year ending March 31, Mississippi River at St. Paul, Minnesota--Continued

Year	1 day	Rank	3 days	Rank	7 days	Rank	14 days	Rank	30 days	Rank	60 days	Rank	90 days	Rank	120 days	Rank	183 days	Rank
1989	1060	6	1070	5	1100	5	1190	6	1290	6	1560	8	2160	16	2430	17	2900	17
1990	1640	21	1820	20	2000	23	2090	23	2370	27	2680	31	2720	26	2960	25	3480	23
1991	2130	35	2450	42	2950	49	3140	47	3190	46	3280	42	3330	38	3570	36	4300	34
1992	6940	92	7200	92	7870	91	8110	92	8270	92	9130	92	10300	93	11200	92	12300	89
1993	4350	79	4660	81	4810	79	4950	78	5140	76	5350	73	5900	76	6770	78	8430	77

References

Gunard, K.T., Hess, J.H., Zirbel, J.L., and Cornelius, C.E., 1990, Water resources data-Minnesota water year 1988--Volume 2. Upper Mississippi and Missouri River Basins: U.S. Geological Survey Water-Data Report MN-88-2, 331 p.

Hutchinson, N. E., compiler, 1975, WATSTORE - National water data storage and retrieval system of the U.S. Geological Survey - Users guide: U.S. Geological Survey Open-File Report 75-426 (revised), 791p.

Sturrock, A.M., Winter, T.C., and Rosenberry, D.O., 1992, Energy budget evaporation from Williams Lake, a closed lake in North Central Minnesota: Water Resources Research 28, 1605-17.

U.S. Army Corps of Engineers, 1990, Mississippi River headwaters lakes in Minnesota--low flow review: U.S. Army Corps of Engineers, St. Paul District, 62 p.

_____1993, Riverine emergency management model-users manual and program documentation, version 2.0: U.S. Army Corps of Engineers, St. Paul District, 25 p.

U.S. Geological Survey, 1977, Water resources data for Minnesota, water year 1976: U.S. Geological Survey, 896 p.

_____1981, Water resources data-Minnesota water year 1980—volume 2. Upper Mississippi and Missouri River Basins: U.S. Geological Survey Water-Data Report MN-80-2, 435 p.

Appendix A

Procedures used for Estimating Ungaged Discharges

Subreach 1

Leech Lake River.--Streamflow at the mouth of Leech Lake River (fig. 1) was estimated on the basis of records of pool elevations for Mud Lake Reservoir located near the mouth of Leech Lake River. Discharge was calculated by applying pool elevations to a weir-flow equation (Mark Rodney, U.S. Army Corps of Engineers, oral commun., 1994).

Ball Club River, White Oak Lake Outlet, Vermillion River, and Leighton Brook.--No discharge measurements were made in these streams during 1988. Discharge for these streams was estimated on the basis of the gain in flow of Leech Lake River between Federal Dam and Mud Lake Dam (157 square mile (mi^2) drainage area). The average daily gain in flow during July 1988 (20.0 ft^3/s) was equivalent to 0.13 ft^3/mi^2. The computed ft^3/mi^2 rate compares favorably with a ft^3/mi^2 rate of 0.13 computed from the July 6, 1988 discharge measured in Willow River near Hill City, Minnesota, a nearby stream that has a drainage area of 160 mi^2. The combined drainage area of Ball Club River, White Oak Lake Outlet, Vermillion River, and Leighton Brook (608 mi^2) was multiplied by 0.13 ft^3/mi^2 to obtain an estimate of their combined discharge (79.0 ft^3/s).

Minnesota Power Clay Boswell Plant.--The power plant withdrew an average of 17.2 ft^3/s during July 1988 (U.S. Army Corps of Engineers, 1990).

Blandin Paper and Wood Products Plants.--The combined net withdrawal of these two plants was 19.2 ft^3/s during July 1988 (U.S. Army Corps of Engineers, 1990)

Subreach 2

Grand Rapids, Minnesota municipal wastewater.--The average discharge (17.8 ft^3/s) reported for the Grand Rapids wastewater treatment facility during the latter half of July 1988 (U.S. Army Corps of Engineers, 1990) was used for all of July 1988.

Prairie River.--Discharge at the mouth of Prairie River was estimated on the basis of three discharge measurements of the Prairie River near Taconite, Minnesota made on June 1, July 1, and July 28, 1988. The daily ft^3/mi^2 rates for Prairie River near Taconite, Minnesota (331 mi^2 drainage area) were multiplied by the drainage area at the mouth of Prairie River (491 mi^2) to obtain daily discharges for Prairie River at the mouth.

Split Hand Creek.--Discharge at the mouth of Split Hand Creek was estimated by multiplying the drainage area at the mouth (52.6 mi^2) by the daily ft^3/mi^2 rate for the Swan River near Warba, Minnesota. The mean discharge for the month of July (3.8 ft^3/s) obtained using this method compares favorably with a flow estimate of 5 ft^3/s made by a USGS hydrographer during July 1988 (William A. Gothard, U.S. Geological Survey, oral commun., 1994).

Swan River.--Discharge at the mouth of Swan River was estimated on the basis of two discharge measurements made at Swan River near Warba, Minnesota on July 1, and July 26, 1988. The daily ft^3/mi^2 rates for Swan River near Warba, Minnesota (238 mi^2 drainage area) were multiplied by the drainage area for Swan River at the mouth (317 mi^2) to obtain daily discharges for Swan River at the mouth.

Pokegama Creek.--Discharge at the mouth of Pokegama Creek was estimated by multiplying the drainage area at the mouth (21.8 mi^2) by the daily ft^3/mi^2 rate for Swan River near Warba, Minnesota.

Unnamed tributaries.--Discharge for unnamed tributaries in the Mississippi River subreach extending from Grand Rapids to near Libby, Minnesota were estimated by multiplying the ft^3/mi^2 rate for Swan River near Warba, Minnesota by the drainage areas of the ungaged tributaries (63.3 mi^2 total). Tributaries in this subreach that had drainage areas of less than 2.0 mi^2 were assumed to have zero flow during July 1988.

Subreach 3

Willow River (includes White Elk Creek).--Discharge at the mouth of Willow River was estimated on the basis of two discharge measurements made at Willow River near Palisade, Minnesota on July 1, and July 27, 1988. The daily ft^3/mi^2 rates for Willow River near Palisade, Minnesota (525 mi^2 drainage area) were multiplied by the drainage area of Willow River at the mouth (552 mi^2) to obtain daily discharges for Willow River at the mouth.

Rice River.--Discharge at the mouth of Rice River was estimated on the basis of one discharge measurement made at Rice River at Hassman, Minnesota on July 1, 1988. The measurement and corresponding ft^3/mi^2 rate for Rice River was plotted on graphs with measurements and ft^3/mi^2 rates for Ripple, Prairie, and Little Pine Rivers. A flow recession curve was drawn through the Rice River measurement, based on the shape of the recession curves for Ripple, Swan, Prairie, and Little Pine Rivers. Daily discharges were obtained from the curve.

Sisabagamah Creek.--Discharge at the mouth of Sisabagamah Creek was estimated by multiplying the drainage area at the mouth (48.4 mi^2) by the ft^3/mi^2 rate for Ripple River at Aitkin, Minnesota.

Ripple River.--Discharge at the mouth of Ripple River was estimated on the basis of two discharge measurements made on June 2, and July 6, 1988 at Ripple River at Aitkin, Minnesota.

Unnamed tributaries.--Discharge for unnamed tributaries in the Mississippi River subreach extending from near Libby to Aitkin was estimated by averaging the daily ft^3/mi^2 rates for Rice River at Hassman, Minnesota and Ripple River at Aitkin, Minnesota and multiplying the results by the combined drainage areas (15.4 mi^2) of the unnamed tributaries. Tributaries in this subreach that had drainage areas of less than 2.0 mi^2 were assumed to have zero flow during July 1988.

Subreach 4

Aitkin, Minnesota municipal wastewater discharge.--The daily discharge (0.5 ft^3/s) reported for the latter part of July 1988 (U.S. Army Corps of Engineers, 1990) was used for all of July.

Little Willow River.--Discharge at the mouth of Little Willow River was estimated by multiplying the drainage area (85.3 mi^2) of Little Willow River at the mouth by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Cedar Creek.--Discharge at the mouth of Cedar Creek was estimated by multiplying the drainage area (41.0 mi^2) of Cedar Creek at the mouth by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Dean Brook.--Discharge at the mouth of Dean Brook was estimated by multiplying the drainage area (28.8 mi^2) of Dean Brook at its mouth by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Little Pine River.--Little Pine River is a tributary to Pine River, which is a tributary to the Mississippi River. Discharge at the mouth of Little Pine River was estimated on the basis of two discharge measurements made at Little Pine River near Cross Lake, Minnesota on June 2, and July 6, 1988. The daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota (132 mi^2 drainage area) were multiplied by the drainage area of Little Pine River at the mouth (142 mi^2) to obtain daily discharges for Little Pine River at the mouth.

Pine River.--Discharge at the mouth Pine River was estimated by adding daily discharge values computed by the U.S. Army Corps of Engineers for the Pine River at Cross Lake Dam to estimates of flow to Pine River from Little Pine River, Pelican Brook, and the watershed of Pine River between Cross Lake Dam and the mouth of Pine River. Estimates of flow contributions of Little Pine River (205 mi^2 drainage area), Pelican Brook (51.9 mi^2 drainage area), and Pine River watershed (41.3 mi^2 drainage area) were computed by multiplying their drainage areas by the daily ft^3/mi^2 rates for the Little Pine River near Cross Lake, Minnesota.

Mission Creek.--Discharge at the mouth of Mission Creek was estimated by multiplying the drainage area at the mouth (17.8 mi^2) by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Rabbit River.--Discharge at the mouth of Rabbit River (outlet of Rabbit Lake) was estimated by multiplying the drainage area at the mouth (42.6 mi^2) by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Sand Creek.--Discharge at the mouth of Sand Creek was estimated by multiplying the drainage area at the mouth (35.0 mi^2) by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Whiteley Creek.-- Discharge at the mouth of Whitely Creek was estimated by multiplying the drainage area at the mouth (10.0 mi^2) by the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota.

Unnamed tributaries.--Discharge for unnamed tributaries in the Mississippi River subreach extending from Aitkin, Minnesota to Brainerd, Minnesota was estimated by multiplying the daily ft^3/mi^2 rates for Little Pine River near Cross Lake, Minnesota by the drainage areas of the ungaged tributaries (42.1 mi^2 total). Tributaries in this subreach that had drainage areas of less than 8.8 mi^2 were assumed to have no flow during July 1988, based on two observations of no flow in Rabbit River near Crosby, Minnesota (8.8 mi^2 drainage area) on June 2, and July 6, 1988.

Subreach 5

Brainerd, Minnesota municipal wastewater and industrial discharges.--The net daily discharge (3.5 ft^3/s) resulting from municipal and industrial withdrawals, consumption, and discharge reported for the latter part of July 1988 (U.S. Army Corps of Engineers, 1990) was used for all of July 1988.

Buffalo Creek.--Buffalo Creek was assumed to have no flow on the basis of its drainage area (12 mi^2) and evaporation from extensive ponds and marshes along the channel of Buffalo Creek.

Unnamed tributaries.--Unnamed tributaries within the Mississippi River subreach extending from Brainerd to near Ft. Ripley that had drainage areas of less than 8.8 mi^2 were assumed to have no flow during July 1988, based on two observations of no flow in Rabbit River near Crosby, Minnesota (8.8 mi^2 drainage area) on June 2, and July 6, 1988. One unnamed tributary (9.3 mi^2 drainage area) was assumed to have no flow during July 1988, based on its drainage area and evaporation from Tamarack Lake and marshes at its source.

Subreach 6

Nokasippi River.--Discharge at the mouth of Nokasippi River was estimated on the basis of one discharge measurement made on the Nokasippi River below Ft. Ripley on June 24, 1988. The measurement and corresponding ft^3/mi^2 rate were plotted on graphs with measurements and ft^3/mi^2 rates for Prairie, Swan, Ripple, and Little Pine Rivers. A flow recession curve was drawn through the Nokasippi River measurement, based on the shape of the flow recession curves for Prairie, Swan, Ripple, and Little Pine Rivers. Daily discharges were obtained from the curve. Daily ft^3/mi^2 rates for Nokasippi River below Ft. Ripley, Minnesota (192 mi^2 drainage area) were multiplied by the drainage area at the mouth of the Nokasippi River (222 mi^2) to obtain daily discharges at the mouth of the Nokasippi River.

Fletcher Creek.--Discharge for Fletcher Creek (19.2 mi^2 drainage area) was assumed to be zero during July 1988. The assumption of zero flow was based on an observation of zero flow in Fletcher Creek on September 28, 1976, a previous drought that was less severe than the drought of 1988 (based on discharge records for Sauk River near St. Cloud, Minnesota and Elk River near Big Lake, Minnesota).

Little Elk River.--Discharge at the mouth of Little Elk River (152 mi^2 drainage area) was assumed to be zero during July 1988. The assumption of zero flow was based on an observation of zero flow in Little Elk River near Little Falls, Minnesota on September 28, 1976, a previous drought that was less severe than the drought of 1988 (based on discharge records for Sauk River near St. Cloud, Minnesota and Elk River near Big Lake, Minnesota).

Pike Creek.--Discharge at the mouth of Pike Creek (39.0 mi^2 drainage area) was assumed to be zero during July 1988. The assumption of zero flow was based on an observation of zero flow in an adjacent basin, Little Elk River near Little Falls, Minnesota on September 28, 1976, a previous drought that was less severe than the drought of 1988 (based on discharge records for Sauk River near St. Cloud and Elk River near Big Lake). The assumption of zero flow also was based on an observation of zero flow on July 12, 1988 in Spunk Creek near Royalton, Minnesota (83.6 mi^2 drainage area), a nearby basin.

Little Falls, Minnesota municipal wastewater and industrial discharges.--The net daily discharge (0.6 ft^3/s) resulting from municipal and industrial withdrawals, consumption, and discharge reported for the latter part of July 1988 (U.S. Army Corps of Engineers, 1990) was used for all of July 1988.

Swan River (tributary to Mississippi River near Little Falls, Minnesota).--Discharge at the mouth of Swan River (164 mi^2 drainage area) was estimated using comparisons with flows in Nokasippi River, a nearby basin that has a similar drainage area. No discharge measurements were made in Swan River during 1988, but a discharge measurement was made on September 30, 1976 during a previous drought. During the 1976 drought, the ft^3/mi^2 rate in Swan River was about 50 percent of the ft^3/mi^2 rate for Nokasippi River, based on a discharge measurement made in the Nokasippi River on September 3, 1976. Discharge in Swan River during July 1988 was estimated by multiplying the daily ft^3/mi^2 rates for Nokasippi River during July by 0.5.The resulting daily ft^3/mi^2 values were then multiplied by the drainage area of Swan River at the mouth to obtain daily discharges for Swan River at the mouth.

Hay Creek.--The discharge at the mouth of Hay Creek (14.8 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow in Spunk Creek near Royalton, Minnesota on July 12, 1988, a nearby basin that has a larger drainage area (83.6 mi^2).

Little Two River.--Discharge at the mouth of Little Two River (23.0 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow on July 12, 1988 in Spunk Creek near Royalton, Minnesota, a nearby stream that has a larger drainage area.

Two River.--Discharge at the mouth of Two River (158 mi^2 drainage area) was assumed to be zero during July 1988 based on a measurement of 0.27 ft^3/s in Two River near Bowlus, Minnesota on September 30, 1976, a previous drought that was less severe than the drought of 1988 (based on discharge records for Sauk River near St. Cloud and Elk River near Big Lake, Minnesota).

Hazel Creek.--Discharge at the mouth of Hazel Creek (3.1 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow in Spunk Creek near Royalton, Minnesota on July 12, 1988, an adjacent basin that has a larger drainage area (83.6 mi^2).

Spunk Creek.--Discharge at the mouth of Spunk Creek (83.6 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow in Spunk Creek near Royalton, Minnesota on July 12, 1988.

Platte River.--No discharge measurements were made at the mouth of Platte River during 1988, but several discharge measurements were made in Platte River and its tributaries upstream of the mouth. A discharge of 0.06 ft^3/s was measured in Platte River near Harding, Minnesota (101 mi^2 drainage area) on June 23, 1988. A discharge of 0.07 ft^3/s was measured in Big Mink Creek near Pierz, Minnesota (18.6 mi^2 drainage area) on June 23, 1988. Little Mink Creek near Pierz, Minnesota (18.8 mi^2 drainage area) was observed to have zero flow on June 23, 1988. A discharge of 3.72 ft^3/s was measured in Skunk River near Pierz, Minnesota on June 23, 1988. Water in these streams flows into Rice Lake, a 1.1 mi^2 reservoir located 16.4 river miles upstream from the mouth of Platte River. Evaporation from the surface of Rice Lake was estimated from evaporation rates for July 1988 determined at Williams Lake near Akeley, Minnesota (4.4 $ft^3/s/mi^2$) and at Becker, Minnesota (6.0 $ft^3/s/mi^2$). Comparison of the measured inflows to Rice Lake (3.85 ft^3/s) with the estimated evaporation from its surface (4.8-6.6 ft^3/s) suggested that evaporation losses exceeded inflow and that there was no flow out of Rice Lake during July 1988. The estimated evaporative loss during July 1988 is similar in magnitude to a calculated loss of 4.75 ft^3/s that was determined from measurements of Rice Lake inflows (8.02 ft^3/s) and outflow (3.27 ft^3/s) made on September 28-29, 1976. Discharge at the mouth of Platte River was assumed to be zero based on data from September 1976 and June 1988.

Stoney Creek.--Discharge at the mouth of Stoney Creek (17.2 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow in Spunk Creek near Royalton, Minnesota on July 12, 1988, an adjacent basin that has a larger drainage area (83.6 mi^2).

Little Rock Creek.--Discharge at the mouth of Little Rock Creek was estimated on the basis of one discharge measurement made in Little Rock Creek at Rice, Minnesota and estimated evaporation from Little Rock Lake. The discharge in Little Rock Creek at Rice, Minnesota (73.4 mi^2 drainage area) was 12.9 ft^3/s on May 4, 1988. Little Rock Creek flows into Little Rock Lake about two miles downstream of Rice, Minnesota. Based on flow recessions observed in tributaries to the Upper Mississippi River during 1988, it was assumed that the flow of 12.9 ft^3/s measured in Little Rock Creek at Rice, Minnesota during May 1988 would have decreased substantially by July 1988. Discharge in a nearby stream, Watab River near Sartell, Minnesota (90.1 mi^2 drainage area), for example, declined from 17.0 ft^3/s on May 4, 1988 to 0.19 ft^3/s on July 12, 1988. Evaporation from Little Rock Lake and Little Rock Creek flowage, which extends to the Mississippi River, was estimated to be 13.7 ft^3/s. The discharge at the mouth of Little Rock Creek was assumed to be zero based on the estimated flow into Little Rock Lake and the estimated evaporative loss from Little Rock Creek.

Champion International Paper Mill at Sartell, Minnesota.--The daily consumptive use of 0.9 ft^3/s reported for the latter part of July 1988 (U.S. Army Corps of Engineers, 1990) was used for all of July.

Watab River.--Discharge at the mouth of Watab River was estimated based on two discharge measurements made on May 4, and July 12, 1988 in Watab River near Sartell, Minnesota. Based on the measured discharge of 0.19 ft^3/s for Watab River near Sartell, Minnesota on July 12, 1988, the flow contribution of Watab River to the Mississippi River during July 1988 was determined to be insignificant and was assumed to be zero for the purposes of this study.

Sauk River.--Discharge at the mouth of Sauk River was estimated on the basis of three discharge measurements made on May 4, June 30, and July 12, 1988 in Sauk River near St. Cloud, Minnesota. The measurements were plotted and a flow-recession curve was drawn through the plotted points. Daily discharges obtained from the curve were used for estimates of discharge at the mouth of the Sauk River.

St. Cloud, Minnesota municipal withdrawals and wastewater discharge.--The net daily consumption (3.1 ft^3/s) reported for the latter part of July 1988 (U.S. Army Corps of Engineers, 1990) was used for all of July.

Johnson Creek.--Discharge at the mouth of Johnson Creek (46.7 mi^2 drainage area) was estimated on the basis of one discharge measurement made in Johnson Creek near St. Augusta, Minnesota on July 6, 1988. The measurement was plotted along with measurements for Plum Creek, an adjacent basin. A flow recession curve was drawn through the Johnson Creek measurement based on the shape of the flow recession curve for Plum Creek. Daily discharges were obtained from the Johnson Creek flow-recession curve.

Plum Creek.--Discharge at the mouth of Plum Creek (23.3 mi^2 drainage area) was estimated on the basis of two discharge measurements made on May 6, and July 5, 1988 in Plum Creek near Clearwater, Minnesota. The measurements were plotted and a smooth flow recession curve was drawn through the plotted points. Daily discharges were obtained from the curve.

Clearwater River.--Discharge at the mouth of Clearwater River (175 mi^2 drainage area) was estimated on the basis of two discharge measurements made on May 5, and July 5, 1988 in the Clearwater River above Clearwater, Minnesota. The measurements were plotted and a smooth flow recession curve was drawn through the plotted points. Daily discharges were obtained from the curve.

Fish Creek.--Discharge at the mouth of Fish Creek (10.0 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow on July 5, 1988 in Silver Creek near Hasty, Minnesota, an adjacent basin that has a larger drainage area.

Silver Creek.--Discharge at the mouth of Silver Creek (31.0 mi^2 drainage area) was assumed to be zero during July 1988 based on an observation of zero flow on July 5, 1988 in Silver Creek near Hasty, Minnesota (30.9 mi^2 drainage area).

Northern States Power industrial withdrawals.--The consumptive use (48 ft^3/s) reported for the Sherco and Monticello plants (U.S. Army Corps of Engineers, 1990) was used for all of July 1988.

Elk River.--Discharge at the mouth of Elk River was estimated on the basis of two discharge measurements made on June 30, and July 12, 1988 by the USGS and two discharge measurements made by the MDNR (Dana Dostert, Minnesota Department of Natural Resources, written communication, 1994) on June 18, and July 8, 1988 in Elk River near Big Lake, Minnesota. The discharge measurements were plotted with corresponding daily discharges for an adjacent basin, the Rum River near St. Francis, Minnesota, a continuous-record gaging station operated by the USGS. A line of best fit was drawn through the plotted points and an equation was developed from the line in order to relate discharge in Elk River to discharge in Rum River. Daily discharges for Elk River during July 1988 were obtained by applying the July 1988 daily discharges for Rum River to the equation. The daily discharge values obtained in this manner were then adjusted for evaporation in Orono Lake (0.5 mi^2 surface area) located near the Elk River mouth. The calculated evaporation rate for Orono Lake was 3.0 ft^3/s, based on the evaporation rate determined at Becker, Minnesota.

Elk River, Minnesota municipal wastewater discharge.--The average discharge was 0.7 ft^3/s during July 1988 (U.S. Army Corps of Engineers, 1990).

Crow River.--Discharge at the mouth of Crow River was estimated on the basis of daily discharge records for the USGS gaging station, Crow River at Rockford, Minnesota. Daily ft^3/mi^2 rates were computed for the Crow River at Rockford, Minnesota (2,660 mi^2 drainage area). The daily ft^3/mi^2 values were multiplied by the drainage area of Crow River at the mouth (2,750mi^2) to obtain daily discharges for Crow River at the mouth.

Rum River.--Discharge at the mouth of Rum River was estimated on the basis of daily discharge records for the USGS gaging station, Rum River near St. Francis, Minnesota. Daily ft^3/mi^2 rates were computed for Rum River near St. Francis, Minnesota (1,360 mi^2 drainage area). The daily ft^3/mi^2 rates were multiplied by the drainage area of the Rum River at the mouth (1,580 mi^2) to obtain daily discharges for Rum River at the mouth.

Metropolitan Waste Control Commission wastewater discharge, Anoka, Minnesota.--The average discharge was 3.5 ft^3/s during July 1988 (U.S. Army Corps of Engineers, 1990).

Elm Creek.--Discharge at the mouth of Elm Creek was estimated on the basis of daily discharge records for the USGS gaging station, Elm Creek near Champlin, Minnesota. Daily ft^3/mi^2 rates were computed for Elm Creek near Champlin (84.9 mi^2 drainage area). The daily ft^3/mi^2 rates were multiplied by the drainage area of Elm Creek at the mouth (103 mi^2) to obtain daily discharges for Elm Creek at the mouth. The values obtained by this procedure were then adjusted for evaporation from Hayden Lake and a mill pond in Champlin, Minnesota, which are located downstream of the gaging station. After comparing estimated evaporation (1.2 ft^3/s) with the daily discharge estimated for Elm Creek at the mouth, only five days during July 1988 had discharges exceeding the estimated evaporation rate. Flow at Elm Creek mouth, therefore, was considered negligible and zero flow was assumed during July for the purpose of this study.

Coon Creek.--Discharge at the mouth of Coon Creek was estimated on the basis of one discharge measurement made on June 28, 1988 in Coon Creek at Coon Rapids, Minnesota, discharge measurements made during a previous low-flow period during 1980, and daily discharge records for the Rum River near St. Francis, Minnesota, a USGS gaging station in an adjacent basin. The discharge measurements were plotted with corresponding daily discharges from Rum River near St. Francis, Minnesota. A line of best fit was drawn through the plotted points and an equation was developed from the line in order to relate discharge in Coon Creek to discharge in Rum River. Daily discharges for Coon Creek were obtained by applying July 1988 daily discharges from Rum River to the equation.

Appendix B

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988

Date	Leech Lake River	Ungaged tributaries[1]	Clay Boswell Power Plant withdrawal	Blandin Paper and Blandin Wood Products withdrawals	Grand Rapids municipal wastewater	Prairie River
June 28	--	--	--	--	--	25
29	--	--	--	--	--	24
30	--	--	--	--	--	23
July 1	127	79	17	19	18	22
2	127	79	17	19	18	22
3	127	79	17	19	18	21
4	127	79	17	19	18	21
5	127	79	17	19	18	19
6	127	79	17	19	18	19
7	127	79	17	19	18	19
8	127	79	17	19	18	18
9	127	79	17	19	18	18
10	127	79	17	19	18	18
11	127	79	17	19	18	18
12	127	79	17	19	18	18
13	127	79	17	19	18	16
14	127	79	17	19	18	16
15	127	79	17	19	18	16
16	127	79	17	19	18	16
17	127	79	17	19	18	16
18	127	79	17	19	18	15
19	127	79	17	19	18	15
20	127	79	17	19	18	15
21	127	79	17	19	18	15
22	127	79	17	19	18	15
23	127	79	17	19	18	14
24	127	79	17	19	18	14
25	127	79	17	19	18	14
26	127	79	17	19	18	13
27	127	79	17	19	18	13
28	127	79	17	19	18	13
29	127	79	17	19	18	13
30	127	79	17	19	18	13
31	127	79	17	19	18	13

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988--Continued

Date	Split Hand Creek	Swan River	Pokegama Creek	Sandy River	Unnamed tributaries in subreach 2	Willow River
June 28	--	--	--	--	--	--
June 29	5.6	33	--	--	--	--
June 30	5.3	32	--	--	--	70
July 1	5.3	32	2.2	24	6.4	67
2	5.1	31	2.1	23	6.1	64
3	5.1	31	2.1	23	6.1	61
4	4.9	29	2.0	23	5.8	59
5	4.9	29	2.0	23	5.8	57
6	4.7	28	1.9	23	5.6	55
7	4.7	28	1.9	23	5.6	53
8	4.5	27	1.8	23	5.3	50
9	4.5	27	1.8	23	5.3	48
10	4.2	25	1.8	23	5.0	46
11	4.2	25	1.8	23	5.0	44
12	4.0	24	1.7	23	4.8	42
13	4.0	24	1.7	23	4.8	40
14	4.0	24	1.7	23	4.8	39
15	3.8	23	1.6	23	4.5	38
16	3.8	23	1.6	23	4.5	37
17	3.6	21	1.5	23	4.2	36
18	3.6	21	1.5	23	4.2	35
19	3.6	21	1.5	23	4.2	34
20	3.3	20	1.4	23	4.0	32
21	3.3	20	1.4	23	4.0	30
22	3.3	20	1.4	23	4.0	29
23	3.3	20	1.4	23	4.0	29
24	3.1	18	1.3	23	3.7	28
25	3.1	18	1.3	23	3.7	27
26	3.1	18	1.3	23	3.7	26
27	2.9	17	1.2	23	3.4	25
28	2.9	17	1.2	23	3.4	25
29	2.9	17	1.2	23	3.4	24
30	2.7	16	1.1	23	3.2	23
31	2.7	16	1.1	23	3.2	23

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988--Continued

Date	Rice River	Sisabagamah Creek	Ripple River	Unnamed tributaries in subreach 3	Aitkin municipal waste-water	Little Willow River
June 28	--	--	--	--	--	--
June 29	--	--	--	--	--	--
June 30	--	--	--	--	--	--
July 1	14	1.4	3.6	0.58	0.50	2.5
2	14	1.3	3.5	.58	.50	2.4
3	13	1.3	3.4	.54	.50	2.3
4	13	1.3	3.3	.54	.50	2.3
5	13	1.2	3.2	.53	.50	2.2
6	12	1.2	3.1	.50	.50	2.1
7	12	1.2	3.0	.49	.50	2.1
8	12	1.2	3.0	.49	.50	2.1
9	11	1.1	2.9	.46	.50	2.0
10	11	1.1	2.8	.46	.50	1.9
11	11	1.1	2.8	.46	.50	1.9
12	10	1.0	2.7	.42	.50	1.9
13	10	1.0	2.6	.42	.50	1.8
14	9.9	1.0	2.6	.42	.50	1.8
15	9.8	.96	2.5	.41	.50	1.7
16	9.5	.96	2.5	.40	.50	1.7
17	9.2	.92	2.4	.39	.50	1.7
18	9.0	.92	2.4	.38	.50	1.6
19	8.8	.92	2.4	.37	.50	1.6
20	8.6	.88	2.3	.36	.50	1.6
21	8.4	.88	2.3	.36	.50	1.6
22	8.2	.84	2.2	.35	.50	1.5
23	8.0	.84	2.2	.34	.50	1.5
24	7.8	.84	2.2	.34	.50	1.5
25	7.7	.81	2.1	.33	.50	1.4
26	7.6	.81	2.1	.33	.50	1.4
27	7.5	.77	2.0	.32	.50	1.4
28	7.4	.77	2.0	.31	.50	1.4
29	7.1	.77	2.0	.31	.50	1.4
30	7.0	.77	2.0	.30	.50	1.3
31	6.9	.73	1.9	.29	.50	1.3

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988--Continued

Date	Cedar Creek	Dean Brook	Pine River	Mission Creek	Rabbit River	Sand Creek
June 28	--	--	--	--	--	--
June 29	--	--	--	--	--	--
June 30	--	--	--	--	--	--
July 1	1.2	0.83	37	0.51	1.2	1.0
2	1.1	.81	37	.50	1.2	.98
3	1.1	.79	36	.49	1.2	.95
4	1.1	.76	36	.47	1.1	.93
5	1.1	.74	36	.46	1.1	.90
6	1.0	.72	36	.44	1.1	.88
7	1.0	.72	36	.44	1.1	.88
8	.99	.70	36	.43	1.0	.85
9	.96	.68	36	.41	1.0	.82
10	.93	.65	35	.40	.97	.80
11	.90	.63	35	.39	.94	.77
12	.90	.63	35	.39	.94	.77
13	.87	.61	35	.38	.90	.74
14	.87	.61	35	.38	.90	.74
15	.84	.59	35	.36	.87	.72
16	.80	.57	35	.35	.84	.69
17	.80	.57	35	.35	.84	.69
18	.78	.55	34	.34	.81	.66
19	.78	.55	34	.34	.81	.66
20	.74	.52	34	.32	.77	.64
21	.74	.52	34	.32	.77	.64
22	.71	.50	34	.31	.74	.61
23	.71	.50	34	.31	.74	.61
24	.71	.50	34	.31	.74	.61
25	.68	.48	34	.30	.71	.58
26	.68	.48	34	.30	.71	.58
27	.65	.46	34	.28	.68	.56
28	.65	.46	34	.28	.68	.56
29	.65	.46	34	.28	.68	.56
30	.62	.44	34	.27	.65	.53
31	.62	.44	34	.27	.65	.53

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988--Contineud

Date	Whiteley Creek	Unnamed tributaries in subreach 4	Brainerd municipal wastewater	Crow Wing River	Nokasippi River	Little Falls municipal wastewater	Swan River (Mississippi River tributary near Little Falls)
June 28	--	--	--	--	--	--	--
June 29	--	--	--	--	--	--	--
June 30	--	--	--	--	--	--	--
July 1	0.19	0.82	3.5	268	17	0.60	6.0
2	.19	.80	3.5	248	17	.60	6.0
3	.18	.78	3.5	242	16	.60	5.6
4	.18	.76	3.5	248	16	.60	5.6
5	.17	.73	3.5	248	16	.60	5.6
6	.17	.71	3.5	293	16	.60	5.6
7	.17	.71	3.5	238	15	.60	5.1
8	.16	.69	3.5	129	15	.60	5.1
9	.16	.67	3.5	79	15	.60	5.1
10	.15	.65	3.5	70	15	.60	5.1
11	.15	.63	3.5	79	13	.60	4.7
12	.15	.63	3.5	94	13	.60	4.7
13	.14	.60	3.5	483	13	.60	4.7
14	.14	.60	3.5	387	12	.60	4.3
15	.14	.58	3.5	273	12	.60	4.3
16	.13	.56	3.5	248	12	.60	4.3
17	.13	.56	3.5	248	12	.60	4.3
18	.13	.54	3.5	207	12	.60	4.2
19	.13	.54	3.5	162	12	.60	4.1
20	.12	.52	3.5	129	11	.60	4.0
21	.12	.52	3.5	94	11	.60	3.9
22	.12	.50	3.5	94	11	.60	3.8
23	.12	.50	3.5	95	11	.60	3.8
24	.12	.50	3.5	249	11	.60	3.7
25	.11	.47	3.5	253	10	.60	3.7
26	.11	.47	3.5	249	10	.60	3.6
27	.11	.45	3.5	235	10	.60	3.5
28	.11	.45	3.5	113	9.8	.60	3.5
29	.11	.45	3.5	94	9.7	.60	3.4
30	.10	.43	3.5	94	9.5	.60	3.3
31	.10	.43	3.5	454	9.3	.60	3.3

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988--Continued

Date	Champion International withdrawal	Sauk River	St. Cloud municipal withdrawals	Johnson Creek	Plum Creek	Clearwater River	Northern States Power withdrawals
June 28	--	--	--	--	--	--	--
June 29	--	--	--	--	--	--	--
June 30	--	--	--	--	--	--	--
July 1	0.90	6.2	3.1	0.69	0.65	0.51	48
2	.90	5.9	3.1	.68	.65	.49	48
3	.90	5.7	3.1	.68	.64	.47	48
4	.90	5.4	3.1	.67	.64	.45	48
5	.90	5.3	3.1	.66	.63	.42	48
6	.90	5.0	3.1	.65	.63	.41	48
7	.90	4.8	3.1	.65	.62	.39	48
8	.90	4.7	3.1	.65	.62	.38	48
9	.90	4.5	3.1	.65	.62	.37	48
10	.90	4.4	3.1	.64	.61	.35	48
11	.90	4.2	3.1	.64	.61	.34	48
12	.90	4.1	3.1	.64	.60	.33	48
13	.90	4.0	3.1	.64	.60	.32	48
14	.90	3.9	3.1	.63	.60	.31	48
15	.90	3.7	3.1	.63	.60	.29	48
16	.90	3.6	3.1	.62	.59	.28	48
17	.90	3.5	3.1	.62	.59	.27	48
18	.90	3.4	3.1	.62	.58	.26	48
19	.90	3.3	3.1	.61	.58	.26	48
20	.90	3.2	3.1	.61	.58	.25	48
21	.90	3.1	3.1	.60	.57	.24	48
22	.90	3.0	3.1	.60	.57	.23	48
23	.90	2.9	3.1	.60	.56	.23	48
24	.90	2.8	3.1	.60	.56	.22	48
25	.90	2.7	3.1	.60	.56	.21	48
26	.90	2.7	3.1	.59	.56	.21	48
27	.90	2.6	3.1	.59	.56	.20	48
28	.90	2.5	3.1	.58	.56	.20	48
29	.90	2.4	3.1	.58	.56	.18	48
30	.90	2.4	3.1	.58	.55	.19	48
31	.90	2.4	3.1	.58	.55	.18	48

Table 6.--Tributary discharges, municipal discharges, and industrial withdrawals, in cubic feet per second, Upper Mississippi River, June and July 1988--Continued

Date	Elk River	Elk River municipal wastewater	Crow River	Rum River	Anoka municipal wastewater	Coon Creek
June 28	--	--	--	--	--	--
June 29	--	--	--	--	--	--
June 30	--	--	--	--	--	--
July 1	16	0.70	52	92	3.5	8.6
2	15	.70	50	88	3.5	8.4
3	15	.70	48	87	3.5	8.3
4	14	.70	47	85	3.5	8.1
5	14	.70	43	81	3.5	7.9
6	13	.70	40	78	3.5	7.7
7	12	.70	36	76	3.5	7.5
8	12	.70	35	74	3.5	7.5
9	13	.70	35	77	3.5	7.6
10	14	.70	33	82	3.5	8.0
11	15	.70	31	86	3.5	8.2
12	16	.70	31	92	3.5	8.6
13	18	.70	38	102	3.5	9.2
14	20	.70	37	112	3.5	9.7
15	19	.70	38	107	3.5	9.5
16	20	.70	34	108	3.5	9.5
17	18	.70	32	100	3.5	9.1
18	17	.70	31	96	3.5	8.8
19	17	.70	32	99	3.5	9.0
20	21	.70	41	113	3.5	9.8
21	22	.70	44	117	3.5	10
22	20	.70	40	108	3.5	9.5
23	18	.70	39	102	3.5	9.2
24	17	.70	33	99	3.5	9.0
25	16	.70	36	92	3.5	8.6
26	14	.70	35	81	3.5	7.9
27	12	.70	31	74	3.5	7.5
28	12	.70	28	73	3.5	7.4
29	11	.70	26	70	3.5	7.2
30	11	.70	24	70	3.5	7.2
31	16	.70	22	93	3.5	8.6

[1] Combined discharge of Ball Club River, White Oak Lake Outlet, Vermillion River, and Leighton Brook.