

Water Use and Availability in Minnesota

Daniel T. O'Shea

*Minnesota Department of Natural Resources
Division of Ecological Services
St. Paul, Minnesota 55107 USA*

ABSTRACT: The results of the analysis represent a new view of water management data in which water availability and water use were combined in a watershed framework. The goal was to describe water availability and use in a way that can be used in planning for future water development, provide an assessment of relative effects resulting from water use and management, and to raise awareness in watersheds of high water use. Although water use increased 40% between 1985 and 1995 in Minnesota, the data have neither been formally compared to water availability nor summarized to allow assessment of effects to aquatic resources through the Instream Flow Incremental Methodology. The annual and monthly volumes of river water available, permitted, and used were summarized for each of the 81 watersheds in Minnesota from 1988 to 1995. The percent of the available water permitted or used was variable depending on the temporal and geographic scale analyzed. The annual percent of the available water permitted ranged from 2% to 7% for the state and from 1% to 28% for individual watersheds. When data were examined on a monthly time scale, the differences were even greater with the permitted percent ranging from 0% to 660%. Twenty-three watersheds had at least one month with greater than 50% of the available water permitted and one watershed had at least one month with greater than 50% of the available water reportedly used.

KEY WORDS: Annual probability hydrograph, inter-annual water use, monthly water use, percent of available water used, water management.

INTRODUCTION

Water withdrawals, whether from surface or ground water sources, affect the hydrology and, subsequently, the offstream and instream resources. Part of an effective and proactive water management program is to periodically and systematically assess the effects of management practices; in this case, the level of actual and permitted water use. Jermar (1987) described two general categories of information needed for water management: how much water there is and the data to protect instream resources and stream function. The first category involves identifying and monitoring of the water resource and its use, evaluating future water needs, and balancing the protection and use of resources. The second involves identifying flows for protecting or sustaining instream resources and stream function, identifying watersheds where

the available water resources and offstream use may be in conflict, and defining the balance between resource protection and use. An incremental assessment of effects related to water withdraws can be accomplished using the physical habitat simulation system (PHABSIM) within the Instream Flow Incremental Methodology and a time series analysis of streamflows and withdraws. However, the first step is to quantify water withdrawals in a manner that is temporally and spatially significant to the resource being analyzed. As such, information on water use by month and watershed can then be used to assess effects to stream function and aquatic habitat.

In Minnesota, total water withdrawal increased nearly 40% between 1985 and 1995 (Minnesota Department of Natural Resources

Division of Waters 1997). During 1995, surface water accounted for 83% of the total water withdrawals but a large percentage of this was for power generation (Minnesota Department of Natural Resources Division of Waters 1997). During a similar period (1980–1995), Solley et al. (1998) reported a decrease in total water withdrawals from the 1980 peak for the United States based on data compiled every 5 years. This national trend of decreased per capita use was not consistent for all types of water use. From 1980 to 1995, water withdrawals for public water supply and rural domestic and livestock use increased an average of 25%. Additionally, the decreased water use trend may not have been recorded in all states as suggested by the results of the Minnesota Department of Natural Resources Division of Waters (DOW) (1997). Despite the rapid increase in water use in Minnesota and an extensive permit-based water management system, water use and availability have not been formally summarized in a temporal or geomorphic scale that will aid riverine habitat impact assessment.

The general effects of removing water directly from a stream are obvious. Both the biological and physical components, such as stream competency, capacity, and channel geometry (Leopold and Maddock 1953; Leopold et al. 1964; Morisawa 1968), can be changed and their interaction altered by decreasing the discharge. The volume and quality of habitat for instream resources and water quality can be reduced directly by simply decreasing the wetted area and indirectly by changing the channel geometry and hydraulics (Aadland 1993; Bovee et al. 1998). The reduced flows not only alter aquatic communities (Welcomme 1995) but also the riparian communities (Fenner et al. 1984; Stromberg and Patten 1991) and the interaction and energy pathways between the two

(Welcomme 1979; Ward and Stanford 1995). Because of the complex interactions between ground and surface water, the effects of pumping ground water on a stream may not be as obvious but they are no less important. Depending on the susceptibility of streams to ground water withdrawal, ground water pumping may reduce streamflow directly by removing water from the stream or, indirectly, by taking water before it reaches the stream, or have no effect on streamflow (Bouwer and Maddock 1997).

Current water management in Minnesota typically does not review water use in the context of what is available. The state maintains a database on the volume of water permitted and used and typically summarizes the data annually by a political boundary (county). Describing water resources and water use in a scale that incorporates the variability in time and space would be more useful for assessing environmental effects. For example, annual summaries of water use do not account for the seasonality of water availability and use. Additionally, water withdrawal is distributed unevenly over geographic regions and does not correspond with the amount of water available (Shiklomanov 1997).

The results represent a new view of the data in which the two forms of information (water availability and water use) were combined in a watershed framework. The goal was to (1) describe water availability and use in a way that can be used in planning for future water development, (2) provide an assessment of relative impacts resulting from water use and management, and (3) raise awareness in watersheds of high water use. The specific objectives were to estimate the percent of available river water that was reportedly used, and permitted for use, each year and each month from 1988 to 1995 for each of the 81 watersheds in Minnesota.

METHODS

Information from the DOW Permits Data base, and streamflow data from the U.S. Geological Services (USGS) were used to summarize the volumes of water permitted, used, and available by watershed, annually and monthly. The results are presented statewide and for each of the 81 major watersheds in Minnesota (Figure 1), which corresponded to the

USGS hydrologic units for the years 1988 through 1995. The years 1988 through 1995 were used in the analysis because permit data were available on the computer for these years. The exception was that Watersheds 54, 57, and 59, along the Red River were included in the analysis of the entire Red River Watershed designated as Watershed 99.



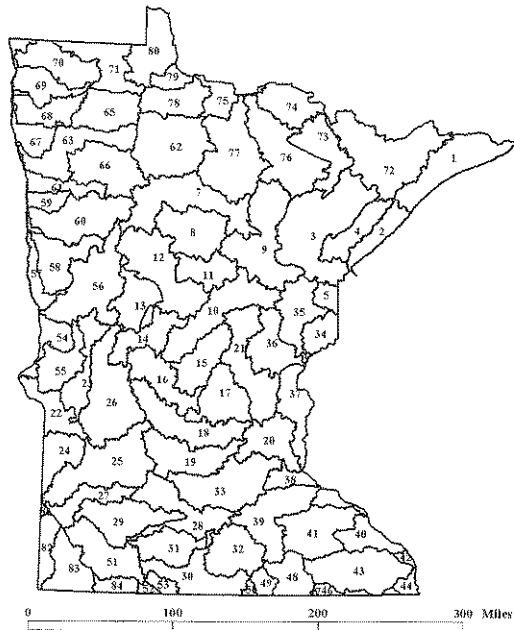


FIGURE 1. The location of individual watersheds in Minnesota with their identifying number.

The DOW permits data base provided a comprehensive accounting of reported water use and permitted use. The data base listed each permit and provided descriptive information including county and watershed of water withdrawal, volume of water permitted for use, volume of water used in each month, and how the water was used (Table 1). The permitted volume is an annual volume and the volume used is reported monthly. Reported water use was defined as the volume of water that each permit holder reports to the

DOW as being pumped or used. This volume probably represented a minimum volume used because it did not account for water that was used when no permit was required or water use that was not reported when it should have been reported.

Permits are required when pumping 10,000 gallons of water per day or more than 1,000,000 gallons per year. Permitted use was the annual volume of water that a permit holder may use or pump. However, to account for the effect of monthly water availability, the annual appropriations were separated into monthly allotments based on monthly reported use patterns. To define the monthly permitted volume, the total annual volume permitted was multiplied by the percent of the total reported water used in each month. Although the actual permit that a water user received did not partition the permitted volume into monthly allotments, it did provide a reasonable estimate for the monthly analysis.

The investigation was concerned only with water withdraws affecting riverine resources, as such; water permitted from Lake Superior was not included in the analysis. Additionally, permits for water level maintenance and power generation were not included in the final analysis. These two categories of water use are generally considered nonconsumptive, although they can affect the instream resources through other means. Young (1987) reported that power generation may return more than 97% of the water used and water level maintenance returns 100%.

The available water was defined as the volume of water that flows out of a watershed on the surface plus the volume of water reported-

TABLE 1

General use code category number and description used by the Minnesota Department of Natural Resources Division of Water (DOW) in the water permits data base and in this analysis, and the average annual number of permits, volume (million gallons) of water permitted and used.

Use Code	Description of Use	Permits	Volume Permitted	Volume Used
210	Waterworks	30	212,558	50,693
220	Power Generation	24	1,189,923	701,657
230	Air Conditioning	1	10	7
240	Industrial	99	115,776	60,052
250	Temporary	39	415	171
260	Water Level Maintenance	99	110,128	32,707
270	Special Categories	33	9,425	5,562
280	Noncrop Irrigation	162	4,169	1,037
290	Major Crop Irrigation	805	40,021	13,201



ly used over a given time period (annually or monthly). The amount of water available in each watershed was estimated using a combination of USGS records and DOW water use data. Gages were identified to represent the streamflow for the watershed and the monthly and annual volumes of water flowing past the gage were calculated by summarizing mean daily discharges. These flow volumes were adjusted for the size of the entire watershed (watershed of interest and all contributing watersheds) using the drainage area ratio method (Hirsch 1979). Because the drainage area ratio method was used to construct discharge records based on gage data that were located within the watershed of interest, or in close proximity to it, the geomorphology and hydrology of the basins were considered to be similar and discharge was probably proportional to drainage area (Morisawa 1962). The reported amount of water used for each period (month or year) was then added back into the adjusted gage volume to determine a total volume of water available for use.

For gages with incomplete records (not encompassing 1988 through 1995), the period of record was extended using one of three techniques: univariate autoregressive-integrated moving average (univariate ARIMA), maintenance of variance extension type 2 (MOVE2), or linear transfer function models (LTF) (Salas 1992; Hipel and McLeod 1994). The LTF models were used when a gage with a longer-term data record could be used to extend the record of the gage of interest. The MOVE2 technique, as described by Hirsch (1982) and Hirsch and Gilroy (1984), was used if a satisfactory LTF model could not be identified. The univariate ARIMA model was used only if a satisfactory gage with a longer-term record could not be identified. All development and diagnostic checking of time series models was completed with the Scientific Computing Associates Statistical System (1997) described by Pankratz (1991) and Liu and Hudak (1994).

The percent of the available water permitted and used was calculated annually and monthly. A monthly analysis was performed so that seasonal variation in reported water use and water availability could be assessed. Some USGS hydrologic units did not include all contributing waters upstream, such as Watershed 20 (Mississippi River Metro).

Watershed 20 included the area surrounding the cities of Minneapolis and St. Paul, including the Mississippi River, but not the upstream portions of the Mississippi River or contributing areas. The percent of available water permitted or used was estimated from volumes in all contributing watersheds and the specific watershed of interest.

There are many assumptions associated with these analyses. They were made out of necessity because the available data did not allow any further assessment. The net result of the assumptions was unknown; however, some assumptions affected the results by indicating a higher proportion of water use whereas other assumptions led to a lower proportion of water use.

The four assumptions that most likely led to an underestimation of the percent of available water used were that (1) impacts of water withdrawal were assessed at the outlet of the watershed, regardless of where the actual withdrawal occurred within the watershed; (2) unreported water use (illegal and legal) was zero; (3) examination of monthly permitted and reported water use provided an accurate representation of actual water use conditions in the watershed; and (4) the interaction between groundwater withdrawals and surface water availability was considered negligible and groundwater permits were not included in the analysis, although groundwater withdraws can reduce surface water discharge (Bouwer and Maddock 1997).

The two assumptions that probably led to an overestimation of the percent of available water used were that (1) all surface water permits were included in the analysis and considered equally consumptive, regardless of the type of use, whether water was withdrawn from a stream, lake, pit, or possibly a noncontributing area of a watershed; and (2) return flow from water used offstream was not considered because it was assumed that once water left the stream it was not available for immediate use by instream resources, essentially meaning that all uses were 100% consumptive.

These analyses represent a benchmark for future comparisons and provide basic information that can be used in water-use planning and for assessing the impacts to aquatic and riparian resources resulting from water management.

RESULTS

Statewide

The water conditions during the study years (1988 through 1995) represented a wide range of flow conditions experienced in Minnesota. For comparison, the mean annual flow for the Mississippi River at St. Paul (USGS gage 0533100) is plotted for the period of record of the gage with the years 1988 through 1995 emphasized (Figure 2). Of the 95 years represented in the figure, 1988 was the twelfth lowest and 1993 was the second highest. However, on average, the period from 1988 through 1995 was wetter than the average for the entire period of record as represented by the conditions at the Mississippi River gage. (The average for 1988 through 1995 was 15,749 ft³/s, and the average for the entire period of record was 11,569 ft³/s). Additionally, 5 of the years (1991–1995) were

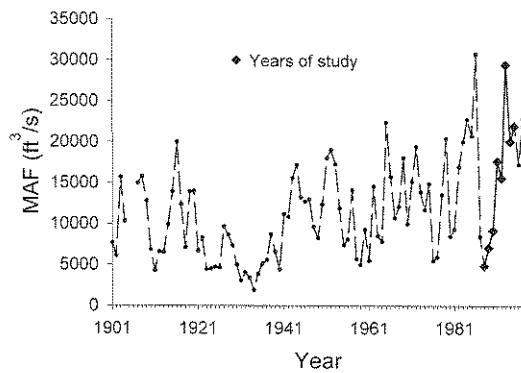


FIGURE 2. Annual hydrograph (mean annual flow; MAF) for the Mississippi River at St. Paul, Minnesota. Gage number 05331000.

in the top 25% of flows. The total volume of water flowing out of the state (available resources) ranged from a low of 5.4 trillion gallons in 1988 to a high of 15.5 trillion gallons in 1993 (Table 2). The amount of water flowing out of each of the basins was adjusted for the drainage area within Minnesota and included only watersheds in which water was permitted.

Permits for major crop irrigation (290) were the most numerous type of permit each year, accounting for over half of the permits (Table 1). Although permits for power generation (220) represented a small portion of the total number of permits, the volume of water permitted for use by power generation was far greater than any other use code accounting for 71% of

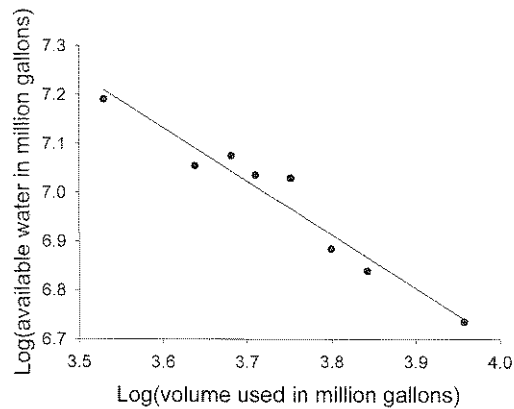


FIGURE 3. Relation between the volume reportedly used for major crop irrigation without wild rice production and the volume of the available water. The values were based on the total volume available and reportedly used in the state. The R^2 was 0.94 with a slope of -0.86 and S.E. of 0.03.

TABLE 2

The estimated available water in million of gallons (MG) flowing out of the state, total volume permitted (MG), and the total number of permits for each year from 1988 through 1995, and the percent of the available water permitted. The volume of water permitted for power generation and water level management was not included in the summary values under the column heading "limited."

Year	Available	Permitted	Permitted Limited	Permitted %	Permitted % limited	Number permits
1988	5,447,655	1,673,346	375,590	31	7	1,249
1989	6,911,006	1,711,295	412,452	25	6	1,327
1990	7,673,993	1,671,989	376,532	22	5	1,349
1991	10,706,541	1,678,593	380,034	16	4	1,381
1992	10,863,950	1,675,783	379,202	15	3	1,296
1993	15,529,780	1,675,963	380,167	11	2	1,302
1994	11,359,297	1,673,550	378,365	15	3	1,209
1995	11,902,419	1,698,898	376,663	14	3	1,223

TABLE 3

The estimated available water in million of gallons (MG) flowing out of the state, total volume used (MG), and the percent of the available water used. The volume of water used for power generation and water level management was not included in the summary values under the column heading, "limited."

Year	Available	Used	Used Limited	Used %	Used % limited
1988	5,447,655	863,171	178,250	16	3
1989	6,911,006	853,201	153,294	12	2
1990	7,673,993	837,104	110,923	11	1
1991	10,706,541	826,339	118,847	8	1
1992	10,863,950	842,527	128,795	8	1
1993	15,529,780	879,858	120,027	6	1
1994	11,359,297	918,734	119,196	8	1
1995	11,902,419	899,764	116,455	8	1

the total annual volume (Table 1). The volume of water permitted for use by major crop irrigation (290) accounted for 2% of the total volume (Table 1). The total annual volume of water permitted remained relatively constant between 1988 and 1995 (Table 2). Unlike the permitted volume, the volume of surface water reportedly used varied from a low of 826,339 million gallons (MG) in 1991 to a high of 918,734 MG in 1994 (Table 3). Water reportedly used for power generation (220) accounted for the majority of the water used during each year from 1988 to 1995. The volume of water used for crop irrigation (290) accounted for less than 2% of the volume. There was a significant negative correlation between the amount of water used for major crop irrigation, not including the volume used for wild rice production, and available water (Figure 3).

Annually, the percent of the total volume of available water permitted (including permits for power generation and water level maintenance) for use ranged from 11% to 31% (Table 2). The percent of the available water reportedly used was less and ranged from 6% to 16% (Table 3). When permits for power generation and water level maintenance were not included, the percent permitted ranged from 2% to 7% (Table 2) and the percent used ranged from 1% to 3% (Table 3).

Individual Watersheds

Annual. Annual water use was generally low, but varied depending on water year and watershed location. Of the 81 watersheds in Minnesota, permits for water use were recorded in 76 watersheds. Those with no permits included watersheds 47, 52, 71, 80,

and 81, primarily along the states' borders. During 1988, the annual percent of the available water permitted among the watersheds ranged from less than 1% to 28% (Figure 4A). During 1988, 10% or more of the available water was permitted in 11 watersheds and most were located in the Red River basin. Four watersheds, all in the Red River basin, had 20% of the available water permitted. In the high water year, 1995, the annual percent of available water permitted ranged from less than 1% to 8% (Figure 4B). The highest annual percent of available water reportedly used in 1988 was 9% and 5% in 1995 (Figure 5). Watersheds with the highest reported use were concentrated in the Red River basin and along the main-stem of the Mississippi River. The largest annual percent of available water permitted for individual watersheds between 1988 and 1995, on average, was 13 times larger (SD=22, N=67, Median=5) than the lowest annual percent. The largest annual percent of available water reportedly used, on average, was 121 times larger (SD=121, N=67, Median=13) than the lowest.

Monthly. Examination of the percent of available water permitted and used by month revealed that much more of the available water was permitted or used at certain times than was shown by the annual statistic. The monthly percent of the available water permitted ranged from 0% to 660% (Figure 6A). As expected, the percent of available water reportedly used was less and ranged from 0% to 100% (Figure 6B). For the months analyzed (7,104) and all watersheds combined, there were 79 months with at least 50% of the avail-

able water permitted and these occurred in 23 watersheds (Table 3). There were 15 months with at least 50% of the available water used and these occurred in seven watersheds (Table 3). For individual watersheds, the proportion of months between 1988 and 1995 with 50% or more of the available water per-

mitted ranged from 0 to 0.16 (Figure 7A) whereas the range for reported use was 0 to 0.05 (Figure 7B).

The watersheds with the largest number of months with high permitted and reported use were located in the Red River and Minnesota basins (Figure 7).

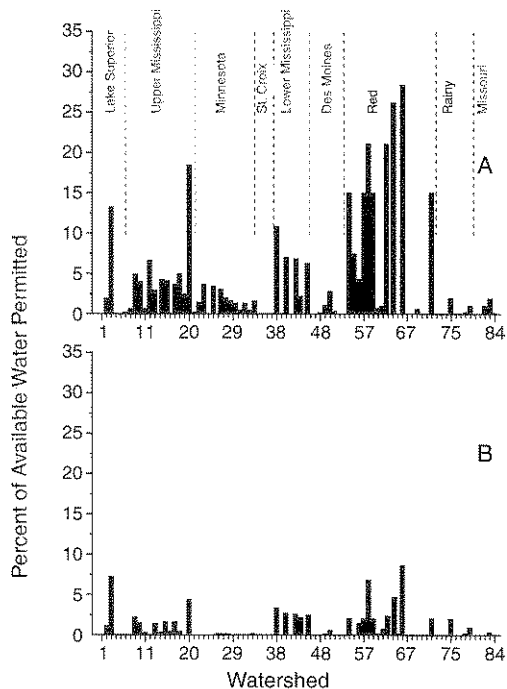


FIGURE 4. Annual percent of the available water that was permitted in each watershed during 1988 (A) and 1995 (B). The watersheds in each of the nine major basins in Minnesota are delineated by the dotted lines.

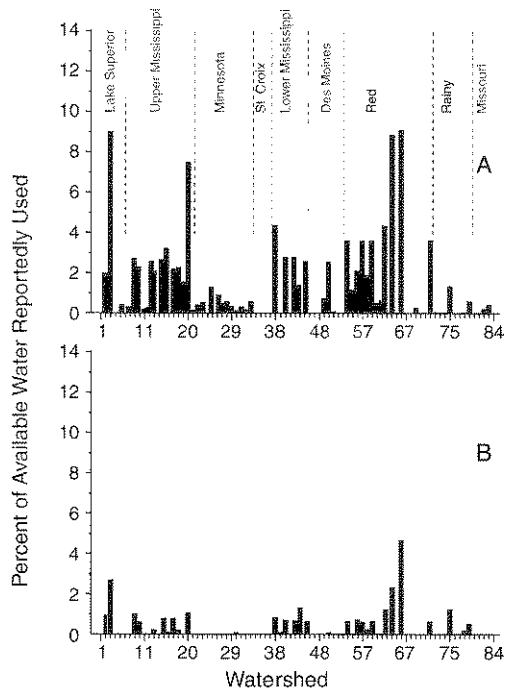


FIGURE 5. Annual percent of the available water that was used in each watershed during 1988 (A) and 1995 (B). The watersheds in each of the nine major basins in Minnesota are delineated by the dotted lines.

TABLE 4

Total number of months and percent of months for all watersheds in each category of percent of the available water permitted for use and reportedly used. The total number of months analyzed was 7,104.

Percent of available Water	Permitted		Used	
	Number of Months	Percent	Number of months	Percent
0 - 9.99	6,526	91.87	6,880	96.85
10 - 10.99	273	3.84	147	2.07
20 - 29.99	128	1.80	41	0.58
30 - 39.99	72	1.01	15	0.21
40 - 49.99	26	0.37	6	0.085
50 - 59.99	15	0.21	3	0.03
60 - 69.99	15	0.21	2	0.03
70 - 79.99	13	0.18	2	0.03
80 - 89.99	4	0.06	1	0.01
90 - 99.99	4	0.06	1	0.01
> 100.00	28	0.39	6	0.085
> 50.00	79	1.11	15	0.21

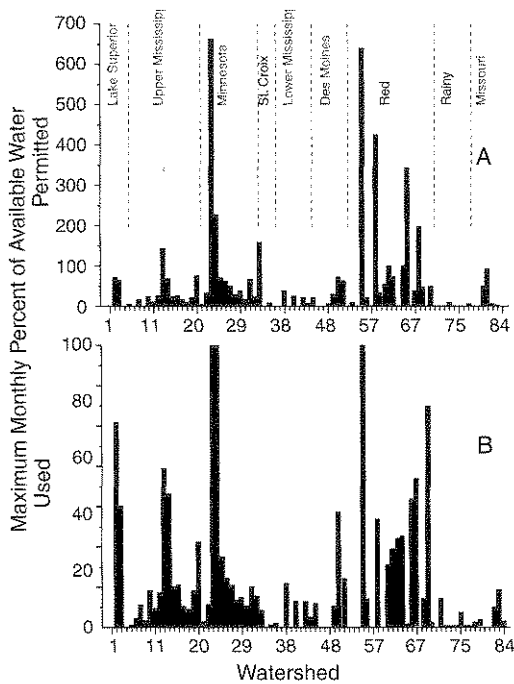


FIGURE 6. The maximum monthly percent of available water that was permitted (A) or used (B) in each watershed between 1988 and 1995.

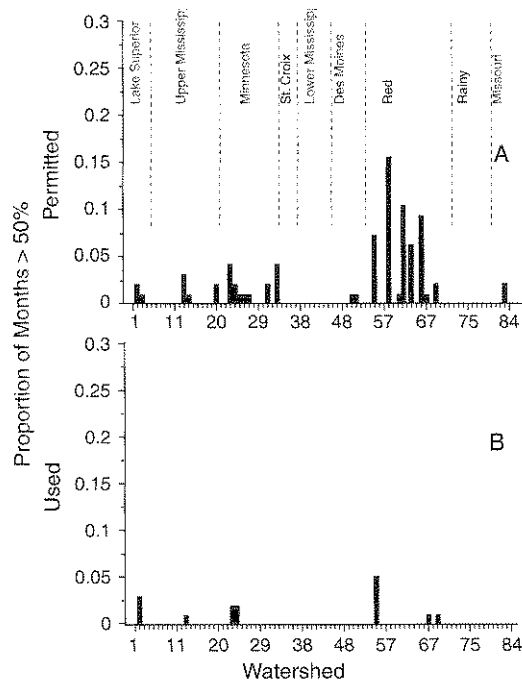


FIGURE 7. The proportion of months between 1988 and 1995 that had at least 50% of the available water permitted (A) or used (B) in each watershed.

TABLE 5

The number of months and percent in each year that had at least 50% of the available water permitted and reportedly used. There were 888 months during each year (12 months x 74 watersheds with a permit).

	Year							
	1988	1989	1990	1991	1992	1993	1994	1995
Permitted frequency	29	21	12	11	3	0	1	2
Percent	3.27	2.36	1.35	1.24	0.34	0.00	0.11	0.22
Used frequency	9	3	2	0	1	0	0	0
Percent	1.01	0.34	0.22	0.00	0.11	0.00	0.00	0.00

TABLE 6

The number of times each month that had at least 50% of the available water permitted and reportedly used for the years 1988 through 1995. There were 592 months analyzed for each month of the year (8 years x 74 watersheds).

	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Permitted Frequency	2	2	4	7	10	5	16	21	8	4	0	0
Percent	0.34	0.34	0.68	1.18	1.69	0.84	2.70	3.55	1.35	0.68	0.00	0.00
Used Frequency	2	2	0	0	0	0	4	4	1	1	0	1
Percent	0.34	0.34	0.00	0.00	0.00	0.00	0.68	0.68	0.17	0.17	0.00	0.17

High permitted and reported use months were recorded in nearly all the years between 1988 and 1995, but the majority occurred in 1988 and 1989 (Table 4). Also, there was high permitted and reported use in each month of the year except November (Table 5), but the

majority occurred during the summer. All of the occurrences—when there was at least 50% of the available water permitted during March, April, and May—took place in watersheds of the Red Lake River (Watersheds 62–66) when wild rice ponds were being filled.

DISCUSSION

The time scale (annual, monthly) in which water availability and use were examined affected the interpretation of the level of permitted and reported water use. Examining the data on an annual scale disguised the fact that there were large seasonal variations in the availability of water and in water use. The maximum monthly percent of the available water permitted ranged from 2 to 3,130 times larger than the annual percent for individual watersheds; the average was 101 times larger with a median of seven. The numbers representing the maximum monthly percent of the available water used were similar to the permitted ratio.

Watershed 58 (Buffalo River) is used as an example to detail the difference between annual and monthly percentages. The average annual percent of available water permitted was 13% whereas the maximum monthly percent was 422%. The disparity between the annual and monthly percent of available water permitted and used resulted from the variability in available water and the seasonal use of water for irrigation (Figure 8). Compounding the problem in watersheds with irrigation as a major component of water withdrawal (such as the Buffalo River Watershed) is that more water is used in dry periods (Figure 3). Normally the highest percent of available water used occurred during the summer; however, there were several notable exceptions. In the Clearwater River (66), Upper and Lower Red Lakes (62), and the Red Lake River (63) watersheds, the peak in water use and, consequently, the percent of available water used occurred during the spring and fall. The high use of water in the spring and fall resulted from wild rice production.

A high average annual percent of available water permitted or used alone could not be used to accurately predict the maximum monthly percent used. The maximum monthly value was influenced by many factors, such as the variability in streamflow, the total volume of water used, the timing of water use, and weather conditions. If only annual permit or use data were examined when developing water management plans the effect would be to clearly underestimate the effects related to water withdraws. To more accurately examine the effects, variation in water use and availability should be accounted for by analyzing monthly data.

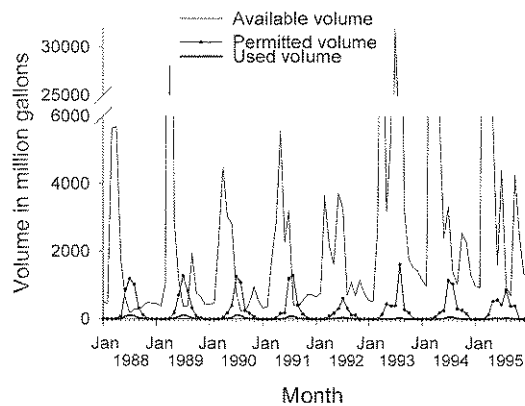


FIGURE 8. The monthly volume of water (million gallons; mg) available, permitted and used in Watershed 58 (Buffalo River).

The inter-annual variation in the number of months with high permitted and reported use was pronounced. As expected, the water conditions (wet or dry year) influence the percent of available water used. Greater than 63% of the high permitted use months and 80% of the high reported use months occurred during 1988 and 1989 (dry years, Figure 2). Additionally, the intra-annual variation was large. The month of August was three times as likely to have at least 50% of the available water permitted or used compared to the average of all months (Tables 5).

There can be significant implications in choosing one year to represent the use for a long period of time. If a wet year, such as 1993 in Minnesota, were chosen to represent the long-term conditions, the annual percent of the available water used could grossly underestimate the conditions in a dry year by an average of 121 times (largest annual percent of available water used divided by the lowest annual). By underestimating the percent of the available water used or permitted, the number and severity of water use conflicts may increase during dry periods. Conversely, if the percent of the available water used or permitted is overestimated, then permits may be rejected or altered when data do not support the decision. To best regulate water use and estimate water use effects, the years analyzed should be put into perspective based on a long-term data set of streamflows.

When considering the state as a whole, it appears that the permitted and reported use volumes were not excessive. In 91% of the months the permitted use was 10% or less,

whereas in 1% of the months 50% or more of the available water was permitted for use (Table 3). The overall frequency of months with at least 50% of the available water permitted was roughly 1 month every 8 years. Examining only the volume of water reportedly used, revealed that 96% of the months had less than 10% of the available water used, and in only 0.2% of the months, 50% or more of the water was used (Table 3).

Although the permitted and reported use levels were low compared to available water for the state in general, an analysis of the state as a whole would not have identified the watersheds of potential conflict. Twenty-three watersheds had months in which 50% of the available water was permitted for use. One watershed (Watershed 58, Buffalo River) averaged one month per year in which all of the available water was permitted. The high monthly reported use (>50% of available used) months occurred in seven watersheds.

Shiklomanov (1997) observed a similar pattern when reviewing water use globally. Of the world's water resources, 8.4% were withdrawn globally. However the global average masks the potential severity of the problem much like a statewide average. Within Europe, the southern and central regions use 24%–30% of the renewable water resource whereas the northern areas use only 1.5%–3%. In North America, the northern areas withdraw only 1% of the resource while in the continental United States the figure is 28% (Shiklomanov 1977). Shiklomanov (1997) forecasted this unevenness to remain at the same level or increase by the year 2025. Because of this unevenness in use and distribution and the expected increase in population, water-use projects to transfer water from areas of surplus to areas of deficit can be expected to increase (Shiklomanov 1997).

Managers of water should be concerned with the scale of the data being used to assess or develop water plans. Because water availability and use is not evenly distributed, a fine enough scale to capture the uneven distribution and to accurately account for the hydrologic connectedness between bodies of water should be used in plan development. By more accurately identifying the boundaries of high use areas, management efforts can be concentrated in these areas resulting in more efficient use and protection of resources.

Annual and monthly reported use values could provide us with valuable information

on how much water we need under various weather and economic conditions. The permitted volume was analyzed because this volume could potentially be used. The tendency may be to permit more water and expect individual permit holders to not use it all. In defense of this rationale, the entire permitted volume was seldom used, but the percent of the permitted volume that was reportedly used was variable over time, watershed, and use code.

The average over-all use codes and watersheds for the percent of the permitted water, reportedly used for each year from 1988 to 1995, ranged from 49% to 54%. The range was much larger among the individual use codes ranging from an average over all years of 24% for waterworks (annual range 21%–37%) to 64% for air conditioning (annual range 8% to >100%). For agricultural irrigation the average over all years studied for the percent of the permitted water reportedly used was 33 and ranged from 30 in 1993 to 41 in 1990. Among watersheds, the percent of the permitted volume reportedly used ranged from 1% to 90%.

Individual permit holders used anywhere from 0% to over 100% of the permitted volume. The average annual percent of permits using all or more than their permitted amount ranged from 13% in 1988 to 3% in 1993. The variability and unpredictability in the amount of the permitted volume being used points to the need to manage based on the permitted volume.

To monitor water use and anticipate water use conflicts, the cumulative volumes of water permitted and used should be documented and compared to water availability on a watershed scale. Use of an annual probability hydrograph provides a convenient means of monitoring and presenting the information, accounting for the seasonal variability in both water availability and use (Dunne and Leopold 1978). By comparing the monthly flow probability with monthly permitted use and reported use, one can identify watersheds and time periods where water use conflicts are most likely to occur. The annual probability hydrograph is provided for Watershed 66 (Clearwater River, Figure 9). The volumes of water permitted and reportedly used were converted to a mean monthly ft^3/s value. The graphs reveal the seasonal availability of water and the probability that the mean discharge will be less than the values indicated.

In the Clearwater River Watershed, the April monthly permitted discharge reaches its highest value; however, the highest chance of conflict occurs during March when the permitted discharge exceeds the 50% exceedence value (Figure 9). This occurs because typically there is less water available during March compared to April. Such data allow one to efficiently document the current level of water appropriations relative to water availability. Additional physical and biological data would allow estimation of the reliability of

cumulative permitted and reported use is a fundamental need. In particular, the data must be compiled by watershed and month so that future management can include assessment of impacts. If a more accurate watershed specific investigation is to be completed, then the assumptions of this more general study must be addressed. Particularly, the interaction between ground water withdraws and surface water availability must be quantified. For this study, it was assumed that the interaction between ground water withdraws and surface water availability was negligible. Bouwer and Maddock (1997) described how streams vary in their susceptibility to ground water pumping, but the data were not available for quantification for this investigation. Also, the return of water to a stream after use should be addressed. For this study, it was assumed that water use was 100% consumptive. However, the estimated percent of available water used or permitted was based on the volume used added to the available volume as determined from gaging data. If return flow is to be quantified then the quality of the returning water should also be accounted for.

Flows that protect habitat and higher flows that maintain a channel and the riparian zone (Hill et al. 1991) are required if a water management policy includes maintenance of instream resources. In Minnesota, these flows typically are available. However, maintaining instream resources requires long-term planning, including, protection standards that will work under unanticipated water use conditions, such as inter-state water diversions.

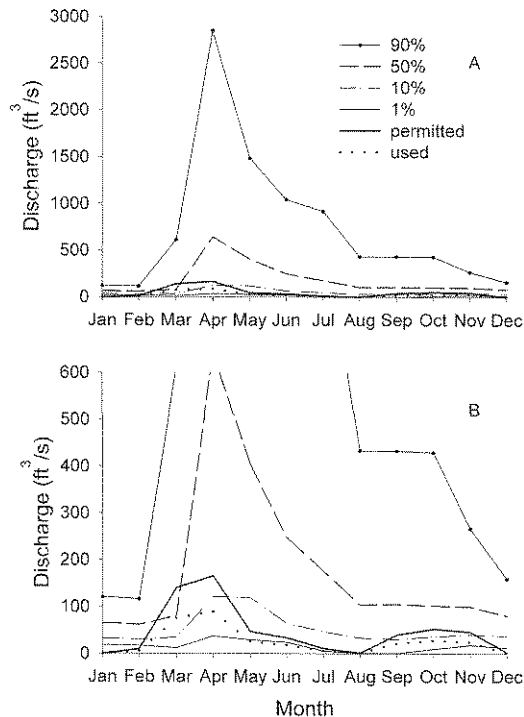


FIGURE 9. Annual probability hydrograph for Watershed 66 (Clearwater River). Percent values indicate the probability that discharge will be less than the values indicated on the ordinate. Graph B represents a close up of discharges less than the 50% probability.

flows to absorb additional withdrawals while minimizing impacts.

If the goal of sustainable water management is to maintain stream resources and allow some development of water resources, then information on water availability and

Acknowledgments

Funding for this project was approved by the Minnesota Legislature (ML 1997, Chapter 216, Section 15, Subd. 4 (d)) as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Environmental and Natural Resources Trust Fund. The Minnesota Department of Natural Resources Division of Waters provided assistance with and access to the Permits Data base. Individuals in the Minnesota Department of Natural Resources Ecological Services Stream Habitat Program provided valuable insight, assistance, and ideas.

REFERENCES

- Aadland, L. P. 1993. Stream habitat types: Their fish assemblages and relationship to flow. *North American Journal of Fisheries Management* 13:790-806.
- Bouwer, H., and T. Maddock, III. 1997. Making sense of the interactions between groundwater and streamflow: Lessons for water masters and adjudicators. *Rivers* 6:19-31.



- Bovee, K. D., B. L. Lamb, J. M. Bartholow, C. B. Stalnaker, and others. 1998. Stream habitat analysis using the Instream Flow Incremental Methodology. Fort Collins, CO: U.S. Geological Survey, Biological Resources Division Information and Technology Report (USGS/BRD-1998-0004). 131 pp.
- Dunne, T., and L. B. Leopold. 1978. *Water in Environmental Planning*. New York: W. H. Freeman and Company.
- Fenner, P., W. W. Brady, and D. R. Patton. 1984. Observations on seeds and seedlings of Fremont cottonwood. *Desert Plants* 6:55-58.
- Hipel, K. W., and A. I. McLeod. 1994. *Developments in Water Science: Time Series Modelling of Water Resources and Environmental Systems*. New York: Elsevier Science Publishers.
- Hirsch, R. M. 1979. An evaluation of some record reconstruction techniques. *Water Resources Research* 15:1781-1790.
- Hirsch, R. M. 1982. A comparison of four streamflow record extension techniques. *Water Resources Research* 18:1081-1088.
- Hirsch, R. M., and E. J. Gilroy. 1984. Methods of fitting a straight line to data: Examples in water resources. *Water Resources Research* 20:705-711.
- Hill, M. T., W. S. Platts, and R. L. Beschta. 1991. Ecological and geomorphological concepts for instream and out-of-channel flow requirements. *Rivers* 2:198-210.
- Jermar, M. K. 1987. *Developments in Water Science: Water Resources and Water Management*. New York: Elsevier Science Publishers.
- Leopold, L. B., and T. Maddock, Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geological Survey Professional Paper 252. Washington D.C. 57 pp.
- Leopold, L. B., W. H. Wolman, and J. P. Miller. 1964. *Fluvial Processes in Geomorphology*. San Francisco: W. H. Freeman and Company.
- Liu, L.-M., and G. B. Hudak. 1994. *Forecasting and Time Series Analysis Using the SCA Statistical System*. Oak Brook, IL: Scientific Computing Associates Corp.
- Minnesota Department of Natural Resources Division of Waters. 1997. 1995 and 1996 Water Year Data Summary. St. Paul.
- Morisawa, M. E. 1962. Quantitative geomorphology of some watersheds in the Appalachian Plateau. *Geological Society of America Bulletin* 73:1025-1046.
- Morisawa, M. 1968. *Streams: Their Dynamics and Morphology*. New York: McGraw-Hill.
- Pankratz, A. 1991. *Forecasting with Dynamic Regression Models*. New York: John Wiley and Sons Inc.
- Salas, J. D. 1992. Analysis and Modeling of Hydrologic Time Series. Pages 19.1-19.72 in D. R. Maidment, editor. *Handbook of Hydrology*. New York: McGraw-Hill.
- Scientific Computing Associates Statistical System. 1997. The PC SCA Statistical System release 5.2 Enterprise. Oak Brook, IL.
- Shiklomanov, I. A. 1997. Comprehensive assessment of the freshwater resources of the world: Assessment of water resources and water availability in the world. World Meteorological Organization. Final Report (Contract No. E/CN.17/1997/9) to the U.N. Commission for Sustainable Development.
- Solley, W. B., R. R. Pierce, and H. A. Perlman. 1998. Estimated use of water in the United States in 1995. U. S. Geological Survey Circular 1200. Denver, CO. 71 pp.
- Stromberg, J. C., and D. T. Patten. 1991. Flood flows and dynamics of Sonoran riparian forests. *Rivers* 2:221-235.
- Ward, J. V., and J. A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers: Research and Management* 11:105-119.
- Welcomme, R. L. 1979. *Fisheries Ecology of Floodplain Rivers*. London: Longman Group Limited.
- Welcomme, R. L. 1995. Relationships between fisheries and the integrity of river systems. *Regulated Rivers: Research and Management* 11:121-136.
- Young, P. G. 1987. Report to the Legislative Commission on Minnesota Resources: An analysis of water use in Minnesota. St. Paul: Minnesota Department of Natural Resources Division of Waters.