WATER AVAILABILITY IN THE TWIN CITY METROPOLITAN AREA: THE WATER BALANCE

Working Paper No. 3

June, 1991

Sheryl Corrigan

METROPOLITAN COUNCIL
Mears Park Centre, 230 East Fifth Street, St. Paul, Minnesota 55101
Publication No. 590-91-008

METROPOLITAN COUNCIL MEMBERS

Mary Anderson, Chair

Liz Anderson, District 1
Dede Wolfson, District 2
James W. Senden, District 3
Carol Kummer, District 4
David F. Fisher, District 5
Donald B. Riley, District 6
Esther Newcome, District 7
Susan E. Anderson, District 8
Ken Kunzman, District 9
James J. Krautkremer, District 10
Dottie Rietow, District 11
Sondra R. Simonson, District 12
Dirk devries, District 13
Bonita D. Featherstone, District 14
Margaret Schreiner, District 15
E. Craig Morris, District 16

The Metropolitan Council coordinates the planning and development of the seven-county Metropolitan Area. The Council is authorized by state and federal laws to plan for highways and transit, sewers, parks and open space, airports, land use, air and water quality, health, housing, aging and arts.

CONTENTS

Appendix

Figures

Tables

ABOUT THIS REPORT

This report is Working Paper No. 3 in a series of eight. The reports are being prepared as background technical studies for the preparation of a long-term water supply plan for the Metropolitan Area. The long-term plan preparation was required by the 1989 legislature and must be presented to the legislature on February 1, 1992.

The other technical reports in the series are:

- No. 1 Alternative Sources of Water for the Twin Cities Metropolitan Area. Metropolitan Council Report No. 590-91-011.
- No. 2 Water Demand in the Twin Cities Metropolitan Area. Council Report No. 590-91-009.
- No. 3 Water Availability in the Twin Cities Metropolitan Area: The Water Balance. Council Report No. 590-91-008.
- No. 4 The Public Water Supply System: Inventory and the Possibility of Subregional Interconnection. Council Report No. 590-91-010.
- No. 5 Water Conservation in the Twin Cities Metropolitan Area. Council Report No. 590-91-020.
- No. 6 The Effects of Low Flow on Water Quality in the Metropolitan Area. Council Report No. 590-91-054.
- No. 7 The Economic Value of Water. Council Report No. 590-91-065.
- No. 8 The Institutional Framework for Water Supply Management. Council Report No. 590-91-064.

The report was prepared by Sheryl Corrigan of the Metropolitan Council Natural Resources and Parks Division. Questions on the content of the study can be directed to her at (612) 291-6572. Graphics were prepared by Judy Hartsoe and Craig Skone.

INTRODUCTION

The availability of water has been, and continues to be, a key factor in sustaining growth and a high quality of life in the Twin City Metropolitan Area (TCMA). The easy access to clean, cheap water is one reason the area has become one of the major industrial centers in the Midwest. In the past, water was viewed as a seemingly infinite resource; when a new source of water was needed for a particular use, a new intake was constructed or new well was dug, with little regard for how the system would respond to the new demand. Today, although vestiges of this viewpoint linger on, a more realistic view of water resources and water supply issues is emerging.

The drought of 1986-1989 made it apparent that the people living in the TCMA must shed their "endless supply" attitude. Recognizing this, the legislature mandated the development of a long-term water supply plan, which is intended to serve as a blueprint for regional water supply planning.

An integral part of water supply planning is a quantitative assessment of the resource. In this paper, the assessment is accomplished through the construction of overall, ground, and surface water average annual balances. The balances identify and quantify the sources and uses of water in the area, thereby giving a comprehensive view of water availability.

The purpose of this study is to determine water availability in the TCMA over the 1988-2010 interval. The study is split into two parts. The first section of the paper is dedicated to developing the overall water balance. From the information supplied through this endeavor, separate ground and surface water balances are then developed, which result in a determination of water availability for each system.

The second section of the study deals with the factors affecting water availability; namely, future demand and the distribution of this demand. The discussion in this section focuses on the ground water system, since the projected increases in demand occur primarily in communities that rely on ground water as their source of supply.

It should be noted that because either mean or median values were used to evaluate each component of the balances, the numbers do not show the variations that naturally occur from year to year. In addition, the averaging process increases the error associated with each term in the balance. Although a separate error analysis was not undertaken in this study, a conservative estimate of error for streamflow measurements would be 5 percent; for precipitation, 10 percent; for evapotranspiration; 15 percent, and for consumptive use, 5 percent (Winter, 1981). Because these errors are propagated in the balance calculation, using the numbers generated in this report for anything other than general characterizations is not recommended.

PURPOSE AND SCOPE

The TCMA relies on both surface and ground water to satisfy the demands of the industrial, residential, and agricultural communities in the area. While the area has never suffered a severe shortage of water, the recent drought raised important questions regarding the impact drought and development can have on the water resources within the region. The purpose behind the construction of the water balance was to identify and generally quantify the major sources and sinks of water in the TCMA so that an overall picture of water availability, and hence, water supply could be obtained.

In terms of water supply, the primary surface water sources for the TCMA are the Mississippi, St. Croix, and the Minnesota Rivers. Historically, the Mississippi has been the only source used for drinking water, while the other two are used for industrial purposes, power generation, and irrigation. Aside from the water withdrawn to satisfy these uses, surface water passes through the area largely unused. To determine whether the surface water system could be used more fully, i.e., how much additional surface water could be captured, an average annual surface water balance was constructed.

The ground water system, on the other hand, is used extensively throughout the TCMA as a source for drinking water, industrial, and irrigation purposes. A recent ground water modeling study done by the United States Geological Survey (USGS) suggested that in some areas, additional pumping focused on the three primary aquifers could result in significant reductions in hydraulic head, as well as reductions in the amount of ground water discharged to TCMA streams. To better understand how the ground water system is responding to the pressures of development--both existing and planned--an average annual ground water balance was constructed.

The results from each of the balances are used in the paper to formulate conclusions regarding the direction we should take in planning for future water supplies.

THE OVERALL WATER BALANCE EQUATION

If steady state, or equilibrium conditions are assumed to exist in the area, then, over the long-term, the same amount of water can be expected to flow into the system as will flow out, as expressed by the equation:

$$\text{INFLOW} = \text{OUTFLOW}$$

This equation represents a water balance in its simplest form. When the inflow/outflow balance is disrupted over the long-term, either by overuse or natural climatic changes, the system begins to move to a new state of equilibrium. Examples of the kinds of adjustments that can occur include a lowering of ground water levels, a decrease in stream discharge, and an increase in recharge to the regional aquifer system. The impact that these changes can have on water supply can be severe.

To gain a better idea of how much water typically enters the area on an annual basis, an average annual water balance was constructed. The balance describes the system as if it were in a steady-state, or equilibrium condition. This entailed defining the system and time period under consideration and all of the inputs and outputs affecting it.

STEADY-STATE BALANCE EQUATION

The water inputs to the study area can be represented by precipitation (P), and streamflow into the study area (I). Conversely, evapotranspiration (ET), streamflow out of the study area (O), and consumptive use (U) constitute the outputs. Ground water flow into and out of the study area is also considered an input and output, but under steady-state conditions they are assumed to be equal, which cancels them from the equation. The sign of each of the terms denotes whether it is being added to, or taken from the system. In equation form, this relationship is set equal to zero, because the inputs should equal the outputs.

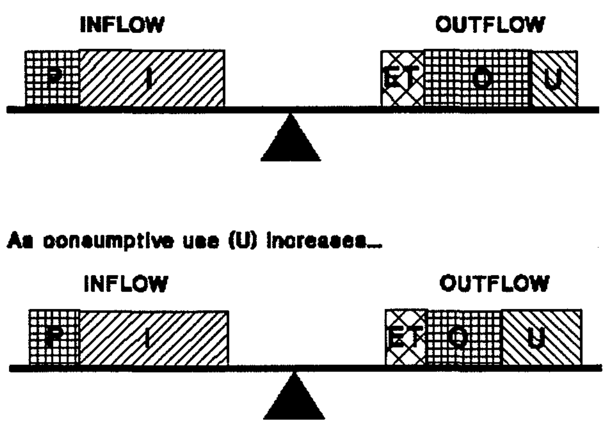
$$P + I - ET - O - U = 0$$

This equation represents the overall water balance, assuming steady-state conditions. This balance equation is valid only if surface and ground water storage within the study area remains constant, meaning the volume of water stored in lakes, depressions, and reservoirs, as well as within the aquifer system does not change over time. Of course, significant changes in storage during the summer months and short drought periods can lower surface and ground water levels considerably. However, to fulfill the steady state condition, it is assumed the system rebounds from these seasonal depletions during the fall and winter when most recharge occurs.

Under predevelopment conditions, the consumptive use term (U) in the equation would be zero, and the only outputs in the area would be evapotranspiration and streamflow. Under these conditions, the system equilibrium is inherently preserved. But because the TCMA is an urban area, natural conditions no longer exist. Therefore, the consumptive use element that accompanies development must be accounted for in the overall water balance equation.

Figure 1 is a diagram that shows the relationship between the inputs and outputs to the system. In both sections of the diagram, blocks representing precipitation and stream inflow are placed on the input side of the balance. On the output side, evapotranspiration and outflow blocks appear in both, along with a block representing consumptive uses. The sizes of the blocks indicate the relative volumes associated with each input and output.

Figure 1
WATER BALANCE



From the figure, the effects of a growing consumptive use term on the other outputs can be seen. Keeping inputs constant, either the evapotranspiration or the stream outflow term must be reduced to accommodate the increase in consumption. Since evapotranspiration is only dependent on climatic conditions, it is not affected by consumption. Therefore, to "balance" consumption, a reduction in stream outflow from the study area must occur.

In the following sections, each term of the balance is evaluated to determine the flows associated with the equilibrium condition.

Study Area

The study area encompasses most of the seven-county TCMA, as well as approximately 260 additional square miles in neighboring Wisconsin (Figure 2). The boundaries of the study area are formed by the river drainage area boundaries upstream of the U.S. Geological Survey (USGS) gaging stations at Anoka, Jordan, and St. Croix Falls. The upstream areas were subtracted from the drainage area of the Mississippi at Prescott to arrive at an approximate area that could be used to represent a TCMA "watershed". The additional miles can be attributed to the portion of the St. Croix River watershed that lies between the TCMA and the gaging station at St. Croix Falls.

Although the study area is not a true watershed, an average annual water balance can be calculated if the following assumptions about the study area are taken to be true: (1) the study area approximates a drainage basin; (2) the data used to calculate precipitation and evapotranspiration are representative of the study area,; and (3) evapotranspiration over the study area can be represented adequately by an unweighted, average value.

The period 1963-1989 was chosen as the study interval primarily because it included a relatively long period of near steady-state conditions (late 1970s).

Precipitation

To determine an average annual precipitation value for the TCMA, an effective uniform depth (EUD) over the study area was calculated (Fetter, 1988). Annual precipitation data for 19 United States Weather Bureau (USWB) stations in and around the TCMA (Figure 3) was collected for the study period (MDNR, 1990). For each station, monthly precipitation data for 1963-1989 was summed to arrive at 27 annual precipitation values for each station. The mean annual value for each station was then calculated, and used to generate a precipitation contour map (Figure 4).

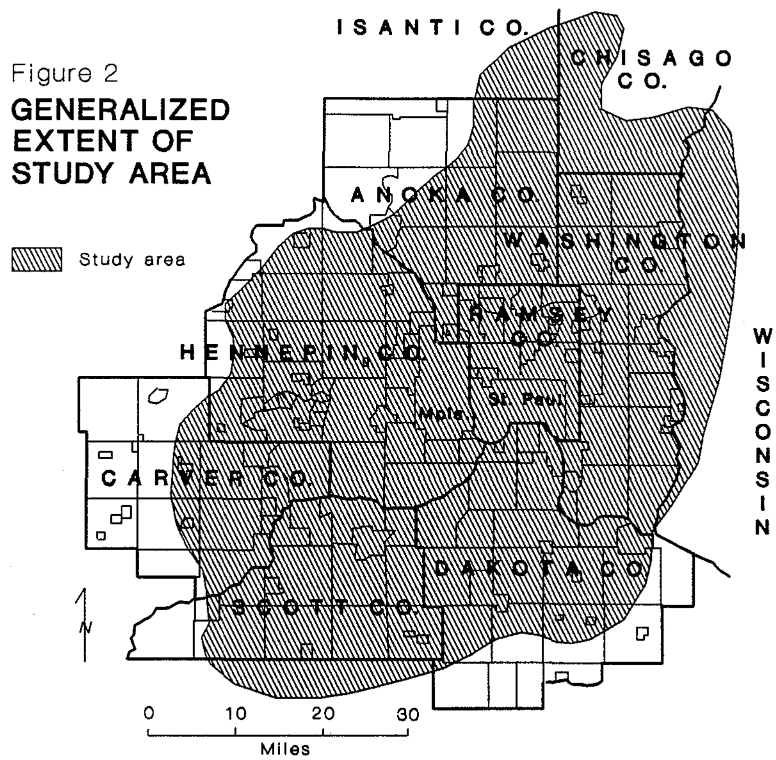


Figure 2
GENERALIZED EXTENT OF STUDY AREA

The mapping was done at the State Climatologist's Office (MDNR), and entailed running the data first through "MinnMap", a program developed by the Climatology Office to generate base maps, and then through "Surfer" (Golden Software, Inc.) which is the program used to draw the isohyets across the region. From this map, weighted precipitation averages were computed and summed, (Appendix A) resulting in a value of 29.57 inches (4,592 million gallons per day) for an effective uniform depth, or EUD. It should be noted that this figure is approximately four inches greater than the 1951-1980 precipitation normal for Minneapolis-St. Paul (MSP). The variation can probably be attributed to the fact that precipitation levels increase significantly with distance from the MSP weather station (Kuehnast et al, 1975), in addition to the 10 percent error associated with areal averaging (Winter, 1981).

Figure 3
TWIN CITIES METROPOLITAN AREA
LOCATIONS OF WEATHER STATIONS IN AND AROUND THE METROPOLITAN AREA

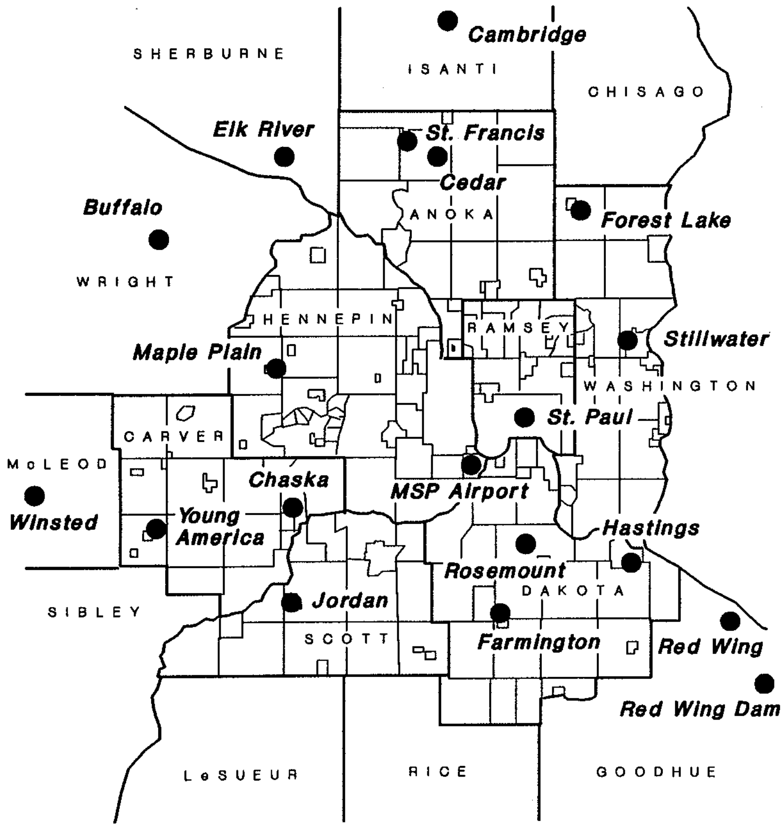
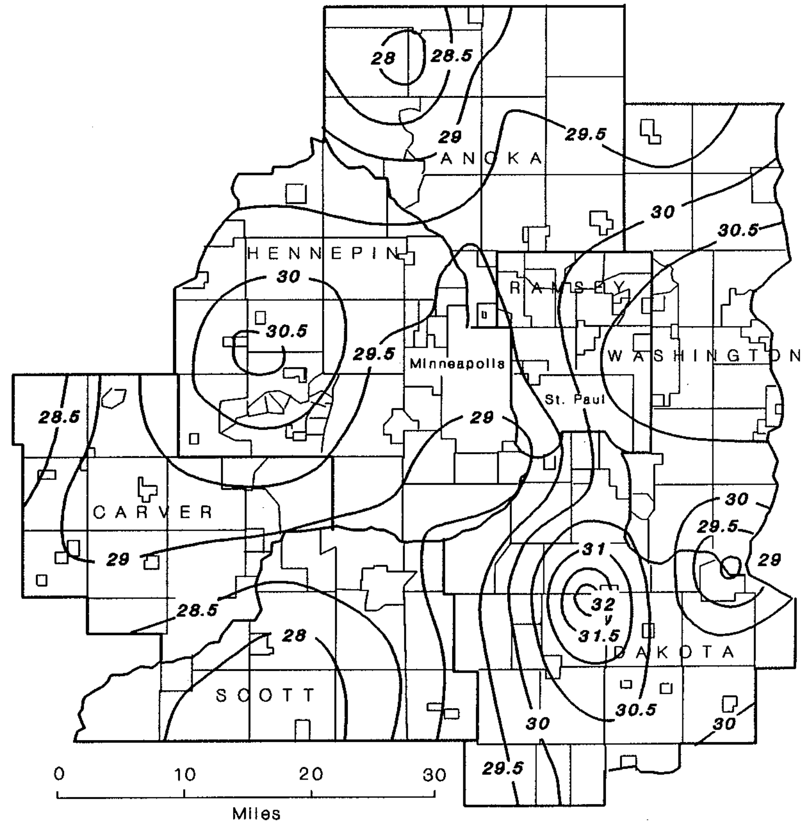


Figure 4
TWIN CITIES METROPOLITAN AREA
AVERAGE ANNUAL PRECIPITATION IN INCHES
BASED ON MONTHLY DATA, 1963-1989



Source: MDNR, State Climatologist's Office

Evapotranspiration

Unlike precipitation, direct measurement of evapotranspiration is a difficult task, and is seldom undertaken. In the TCMA, only one station, St. Paul, has recorded evapotranspiration data. Because actual measurements are so rare, several methods of calculating evapotranspiration indirectly have been developed. Perhaps the most widely used method is the Thornthwaite method (Thornthwaite, and Mather, 1957), which was the method of choice for this study.

To compute potential evapotranspiration using the Thornthwaite method, mean monthly temperature, mean monthly precipitation, latitude and the holding capacity of the soil must be known. The climatological data were provided by the State Climatologist's Office, while the soil information was obtained from county soil survey maps. Holding capacity estimates for various soil types were provided by Thornthwaite. Using this information, in addition to the conversion and computational tables developed by Thornthwaite, it was possible to make a determination of potential evapotranspiration at each site. It should be pointed out that the value arrived at through the Thornthwaite analysis is a theoretical value--it represents the amount of water that could be lost to evapotranspiration, not necessarily the actual loss. In humid regions such as the TCMA, however, potential and actual evapotranspirative losses are closely aligned (Baker, 1979).

Potential evapotranspiration for 11 of the 19 USWB stations was determined according to the Thornthwaite method (Appendix A). As in the precipitation calculations, these average values were used to generate a contour map; however, no spatial relationship between evapotranspiration and geographic location was evident from the map. Since evapotranspiration is dependent on the site-specific parameters discussed earlier, and since these parameters are highly variable across the study area, this result was not surprising. In lieu of a map, the mean annual evapotranspiration was characterized by the median of the mean values determined by the Thornthwaite calculations. This figure was found to be 23.36 inches (3,629 million gallons per day), which is again higher than is generally expected for the area. The higher value can probably be attributed to the error inherent in the measurements used in Thornthwaite analysis, as well as error associated with the analysis itself.

Streamflow

Four USGS gaging stations account for roughly 97 percent of the inflow to the TCMA (Norvitch, 1974): the Mississippi River at Anoka, the Minnesota River at Jordan, the St. Croix River at St. Croix Falls and the Crow River at Rockford. One gaging station, the Mississippi River at Prescott, accounts for approximately 99 percent of the outflow. Because the unaccounted portion of the inflows and outflow was so small, it was assumed that any error in the water balance caused by these flows would be well within the margin of uncertainty expected in this type of analysis.

Flow data records for the five gaging stations were collected for the study period (USGS, 1990). Table 1 shows the median of the annual mean normal flows for each station for the period 1963-1989. The Crow River is not depicted in the table, because its confluence with the Mississippi occurs above the Anoka gage.

Table 1
MEDIAN OF THE ANNUAL MEAN NORMAL FLOWS FOR SELECTED STATIONS, 1963-1989

USGS Gaging Stations	Flow (mgd)
Mississippi River at Anoka, MN	6,920
St. Croix River at St. Croix Falls, WI	3,300
Minnesota River at Jordan, MN	2,440
Mississippi River at Prescott, WI	13,300

For the purposes of this study, normal flows are defined as those that occur between the 25th and 74th percentile. High flows, or those associated with wet years, occur between the 75th and 99th percentile; low flow years occur between the 1st and 24th percentiles.

CONSUMPTIVE USE

Surface Water Consumptive Use

Surface water resources, e.g., the Mississippi, St. Croix, and Minnesota Rivers are used primarily as sources of drinking water in the TCMA, and as a cooling agent for power plants. These two uses account for over 90 percent of total surface water withdrawals, with the Mississippi being tapped for drinking water and cooling water, and the St. Croix and Minnesota being used only for cooling purposes. The current average withdrawal over the TCMA for these two uses alone totals more than 660 million gallons per day (mgd); however, only a small portion of this volume is actually consumed. To evaluate the use term in the water balance, this small volume must be determined.

Power plant consumption amounts to approximately 1 percent of the total withdrawal (Oberts, 1990), with the remaining 99 percent returned to the respective rivers as discharge. Municipal consumptive use of water is somewhat greater than that of power plants; it is usually estimated at 10 percent of withdrawals (Solley, et al., 1983). The 90 percent that is not consumed is returned to the surface water system as wastewater.

To arrive at a figure for annual consumptive use, records of reported surface water withdrawals from the three major rivers for 1984-1988 were used (MDNR, 1990). Although this data is not representative of the study period, it was assumed to be within the same order of magnitude of the actual consumptive use for 1963-1989, and it better reflects current actual use than historic data from the study period.

Table 2 lists withdrawals and consumption by use. Municipal consumptive use was assumed to be 10 percent of the total withdrawal for each year. Consumptive use by power plants was assumed to be 1 percent of the total annual withdrawal. The withdrawals associated with the other uses listed in Table 2 were all considered to be consumed, since there is very little or no return flow associated with them. Total consumption for each of the years was calculated, and the median of the annual values was determined. This was found to be approximately 43 mgd, or 3 percent of the total withdrawals.

Table 2
SURFACE WATER WITHDRAWALS AND CONSUMPTIVE USE, 1984-1988

SURFACE WATER USES	AVERAGE WITHDRAWALS* (mgd)	AVERAGE CONSUMPTION (mgd)
Municipal Water Works	111	11
Private Water Works	0	0
Power Generation	553	6
Commercial, Industrial and Institutional	<1	<1
Air Conditioning	0	0
Sewage Treatment	0	0
Water Level Maintenance	26	26
Irrigation	<1	<1
Miscellaneous	<1	0
TOTAL	690	43

* Represents withdrawals from major rivers only

Ground Water Consumptive Use

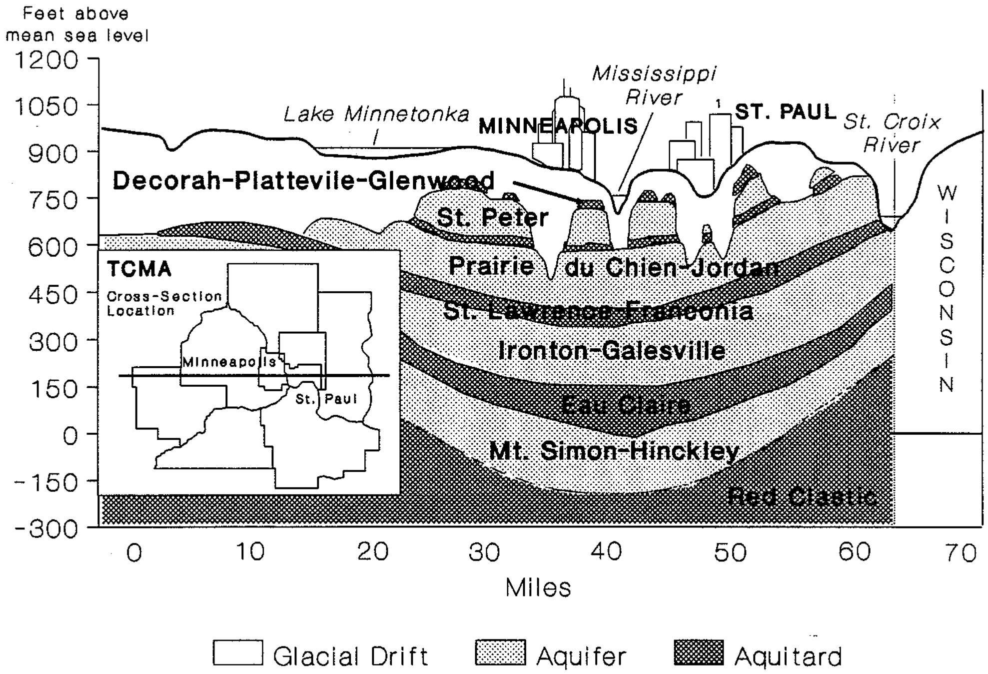
The TCMA depends heavily on ground water as a source for municipal water supply, and for industrial/commercial and agricultural needs. Five aquifers are available to provide for the needs of the area, but not all are suited for each use.

Each aquifer possesses unique physical and hydrologic properties that make them desirable or undesirable as sources of supply, depending on the ground water needs associated with a particular use. For example, private domestic wells are often completed in shallow, unconfined aquifers, because the low-capacity, low-yield wells most common to water table aquifers adequately fulfills the needs of one household. In contrast, the needs associated with municipal and industrial use demand high-capacity, high-yield wells to ensure an adequate supply. Typically, confined aquifers with high hydraulic conductivities and transmissivities provide the highest yield, thus making them the most likely choice for municipal and industrial/commercial supply.

Along with yield, accessibility is another major factor that governs the selection of an aquifer for a particular use. The drift aquifer is the closest to the surface, thereby making it the most accessible. Although the drift is mostly unconfined, it can produce locally high yields. In these areas, the drift aquifer is used extensively both for municipal and industrial/commercial supply. In areas where the drift is not suitable, deeper bedrock aquifers are the alternative. The Prairie du Chien-Jordan (PDCJ) aquifer is the first high-yielding bedrock aquifer from the surface, and as a result, supports the heaviest use in the TCMA. But when adverse physical or chemical conditions constrain the use of the PDCJ or the drift, other deeper aquifers must serve as alternative sources of supply. Figure 5 shows a cross-section of the aquifers and confining layers under the TCMA.

Figure 5

GENERALIZED TCMA GEOLOGIC CROSS-SECTION



Vertical exaggeration approximately 130x

In some parts of the TCMA, the Ironton-Galesville formation is a viable source of water; however, it is not widely used for municipal supply because of problems with low yields and poor water quality. The aquifer underlying the Ironton-Galesville is the Mount Simon-Hinckley (MTSH), which contains relatively pure, soft water. Because the MTSH recharges at a very slow rate, it is prone to over pumping and subsequent hydraulic head losses. Although some municipalities have developed wells in the MTSH, any new development in this aquifer could depress water levels significantly. For this reason, Minnesota Department of Natural Resources (MDNR) policy prohibits development in the MTSH unless all other reasonable alternatives are exhausted. Recent ground water flow modeling done by the USGS supports this position and is discussed later in this paper.

For all practical purposes, the drift, PDCJ, and in a marginal capacity, the MTSH aquifers support the major ground water uses across the TCMA.

To track the major users of ground water, the MDNR administers a permitting system that requires users who withdraw 10,000 or more gallons per day or 1 million gallons per year to obtain a permit. The permit contains information about the aquifer used, the permitted withdrawal, and an estimate of the actual amount withdrawn for every year it is valid. Thus, a reasonably good record of current ground water use is available. Unfortunately, reliable records do not exist for the study period as it was defined earlier. Reported ground water withdrawal data from 1984-1988 was used in lieu of 1963-1989 data in the balance equation, based on the assumption that the volume of ground water lost through consumption is small compared to the volumes of the other components of the balance. Thus, the error associated with using data from the 1984-1988 period was assumed to be small compared to the error inherent in the other component calculations. Table 3 lists annual ground water withdrawals and consumption for the 1984-88 period.

The median value for the five year period was used to represent withdrawals, which were found to be approximately 237 mgd. Of this 237 mgd, an estimated 41 mgd was consumed, based on consumptive use rates of 10 percent for municipal, commercial, and industrial withdrawals; 90 percent for irrigation; 3 percent for air-conditioning; and, 100 percent for water level maintenance (Solley et al, 1983). Neither the reported withdrawals nor the consumptive use reflects self-supplied domestic ground water use, or withdrawals from unpermitted wells. While there is no way currently to measure unpermitted withdrawals, it is possible to estimate domestic ground water use. Using population figures and per capita use, domestic self-supplied water used can be estimated to be 13 mgd across the TCMA. Combining this figure with the permitted ground water withdrawals and consumptive use yields approximately 250 mgd, and 55 mgd, respectively.

Table 3
GROUND WATER WITHDRAWALS, 1984-1988

GROUND WATER USES	AVERAGE WITHDRAWALS (mgd)	AVERAGE CONSUMPTION (mgd)
Municipal Water Works	138	13.8
Private Water Works	1.1	0.1
Commercial, Industrial and Institutional	48.2	4.8
Air Conditioning	20.8	0.6
Sewage Treatment	6.5	0.7
Water Level Maintenance	1.7	1.7
Irrigation	17	15.3
Miscellaneous	2	3.7
TOTAL	237	41

The portion of the ground water withdrawal that is not consumed is returned to the surface water system, and is accounted for in streamflow measurements.

OVERALL BALANCE EVALUATION

Given the values for precipitation, evapotranspiration, streamflow and consumptive use, it's possible to construct the overall water balance. Recall that the overall water balance equation is:

$$P + I - ET - O - U = 0$$

Substituting in the calculated values yields (in mgd):

$$4590 + 12660 - 3630 - 13300 - 100 = 220$$

Ideally, the terms on the left side of the equation should equal zero; however, in this equation, a residual of 220 mgd remains. Because of the propagation of error within the balance calculation, obtaining a zero residual is highly unlikely. Since the residual is small compared to the total outflow (<2%), it can be assumed that it is not significant.

The overall balance is useful in that it describes the flows needed to maintain a theoretical equilibrium. These can be compared to the current flows to determine how the system differs from steady-state conditions. To determine the current capacities of the surface and ground water system, a balance was developed for each.

GROUND WATER BALANCE

Ground Water Balance Equation

The ground water system underlying the TCMA can be thought of as a layer cake of aquifers and aquitards. Figure 5 shows the five principal aquifers, or water-bearing units, along with the aquitards, or confining layers. Although the system consists of discrete layers, it is treated holistically in the ground water balance because aggregated data was used.

Assuming that ground water inflow to and outflow from the study area is constant, the single input to the ground water system is recharge (R), while ground water withdrawal (W), and leakage to major rivers (L) represent the major outputs. In equation form, the ground water balance can be represented by:

$$\mathbf{R - W - L = \pm S}\ *$$

*Source: Guide Manual for Preparation of Water Balances, U.S. Army Corps of Engineers

The resultant, or (S) term in the equation represents the change in ground water storage associated with the level of withdrawal identified in the balance. A positive result indicates that storage is being replenished, while a negative result indicates that storage is being depleted.

Under normal climatic conditions, if the resultant change in storage is negative, more water is being pumped from the system than is being replaced. This means that to support the withdrawal, water from storage must be used, causing a lowering of ground water levels and/or reduced discharge to surface waters. Conversely, if the resultant is positive, more water is being added to the system than is being pumped out. This translates into an increase in aquifer water levels. To ensure that ground water remains a viable source for water supply, large negative changes in storage should be avoided. To determine what the change in storage is under varying climatic conditions, the ground water balance was evaluated.

Study Area

The same study area (Figure 2) was used, as the three main rivers represent major ground water divides. It should be noted, however, that the withdrawal data only covers the seven-county TCMA.

Recharge

Recharge to the ground water system occurs through two processes: percolation of surface runoff through the soil to the water table, and seepage from lake and stream beds or other aquifers. Either directly, as in the case of the former, or indirectly, in the case of the latter, these processes are dependent on the amount of runoff generated in the watershed. Therefore, to get an idea of the amount of recharge emanating within the study area, it is necessary to briefly understand the runoff process.

Runoff is the result of precipitation falling on saturated soil. When the holding capacity of the soil has been reached, precipitation flows horizontally along the surface and below it, eventually collecting in topographic lows. The amount of runoff generated is dependent on the duration and intensity of the precipitation event, and antecedent soil moisture. A short duration, high intensity event can result in saturation of the uppermost layer of soil, but may not last long enough to allow the precipitation to percolate through the soil. Large amounts of runoff can be the result, despite the fact that the soil is only "temporarily" saturated. This situation commonly occurs during times of drought when soils are extremely dry. Conversely, a long duration, low intensity event typically results in a more normal runoff regime, with deep percolation of precipitation.

Thus, runoff is a function of both precipitation and evapotranspiration, since evapotranspiration controls soil moisture levels. Translating this relationship into an equation yields:

$$\mathbf{P - ET = TR}$$

where P, ET, and TR represent precipitation, evapotranspiration and total runoff, respectively. Total runoff refers to the maximum amount of water that could become runoff. From the discussion above, some portion of the total runoff infiltrates the soil and recharges the underlying aquifers. Unfortunately, there is no way to directly measure the amount of recharge reaching the ground water system. Consequently, it is usually determined indirectly.

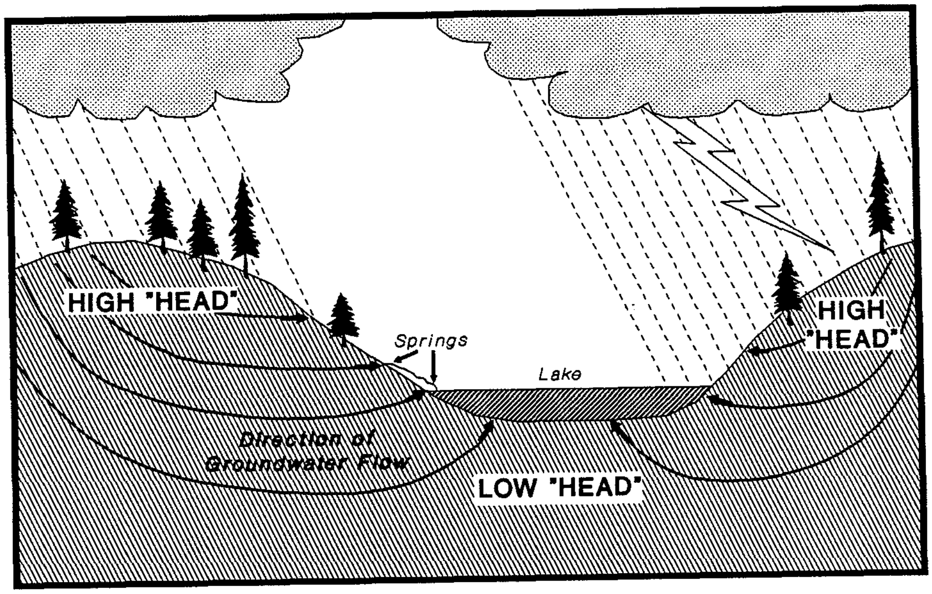
Over the long term, it can be assumed that ground water recharge is equal to ground water discharge. Discharge from the ground water system occurs when the land surface intersects the aquifer system. Examples of common discharge points are wetlands, rivers, springs, and some lakes. Discharge typically occurs in these areas because they are situated in topographic lows, which generally exhibit lower "heads", (piezometric head) or ground water pressures, than topographic highs.

Figure 6 shows a generalized relationship between discharge and topography for a local flow system. In the figure, ground water flow is driven by the difference between the head in the uplands and the lowlands. The flow direction is towards the areas with lower head; consequently, discharge is situated in the lowlands.

The discharge of ground water to rivers, wetlands and so on is critically important, in that it literally prevents them from disappearing during times of drought, or during winter when surface runoff does not occur. In streams, this ground water discharge is called baseflow. Although baseflow is not directly measured, a good approximation of it can be made during the winter months. From December through February, surface water runoff can be assumed to be minimal since most of the precipitation occurs as snow.

Figure 6

GENERALIZED RELATIONSHIP BETWEEN PIEZOMETRIC HEAD AND TOPOGRAPHY IN A LOCAL GROUND WATER FLOW SYSTEM



With the surface runoff component negligible, the flow sustained in the stream can only be due to the influx of ground water in its channel. Assuming that baseflow and ground water discharge are the same, it follows that determining the baseflow for the streams in the study area will result in a determination of recharge.

To calculate recharge over the TCMA, winter monthly flow data spanning the 1963-1989 period was used. For each station, a median of the monthly mean winter flows was calculated. The flow from stations that represent the inflow boundaries of the study area was subtracted from the flow at Prescott, which represents the outlet. The result was a determination of baseflow for the TCMA, and hence an estimation of recharge. Table 4 shows the flow values for each station and recharge calculation. Note that the table also contains values for wet and dry conditions, which were defined earlier in the paper.

The values for recharge for normal and wet conditions represent roughly 3.5 and 4 inches per year, respectively. The negative value for dry conditions indicates that recharge to the ground water system does not occur; that is, baseflow is provided by water removed from storage.

Table 4
MEDIAN OF THE MONTHLY MEAN WINTER FLOWS FOR NORMAL, WET, AND DRY CONDITIONS, 1963-1989

STATIONS	NORMAL	WET	DRY
Mississippi River at Anoka, MN	3,410	4,480	2,680
St. Croix River at St. Croix Falls, WI	1,530	2,020	1,250
Minnesota River at Jordan, MN	460	1,210	310
Mississippi River at Prescott, WI	5,920	8,320	4,200
RECHARGE	520	610	-40

Leakage

Ground water leakage to the surface water system is the last variable that must be accounted for in the balance. A recent USGS modeling study indicated that during the 1970-1979 period, leakage from the ground water system to the primary rivers in the TCMA totalled approximately 300 mgd (Schoenberg, 1990). It should be noted that this number represents annual leakage for the 10 year period; it does not represent summer or drought conditions when leakages may be higher due to lower head in the river system. The leakage value obtained for the 1970-1979 period was used as an estimate for average leakage in this study, based on the assumption that the error involved in using this number was small compared to the error inherent in the other component calculations.

Turning back to the original ground water balance equation:

$$\mathbf{R - W - L = \pm S}$$

it is now possible to solve for the change in storage. Recharge to the ground water system was found to be 520 mgd, while ground water withdrawals (from the overall water balance calculation) and estimated leakage total 250 and 300 mgd, respectively. Substituting these numbers gives (mgd):

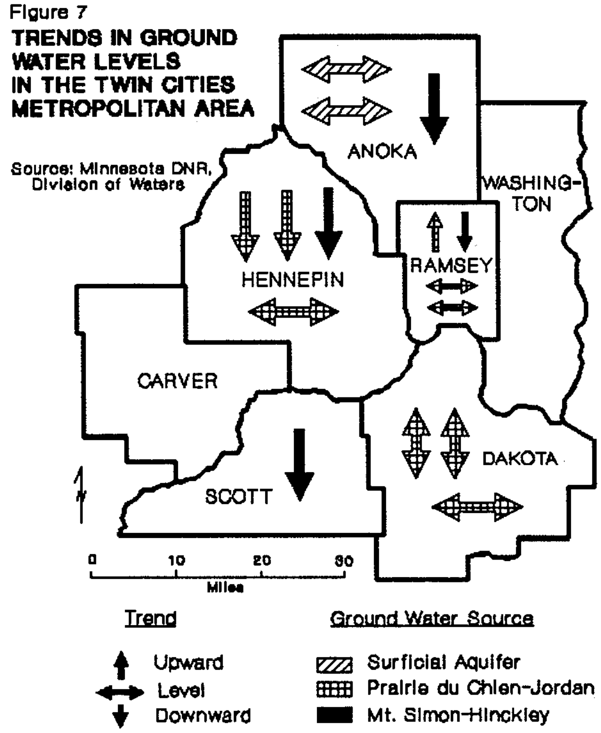
$$520 - 250 - 300 = -30$$

Thus, under normal conditions, approximately 30 mgd is taken from the ground water reservoir annually under the existing withdrawal regime. It is important to remember that the error in each of the balance terms is transferred to the residual. A realistic estimate of error for each term would be 5-15 percent, which suggests that the value obtained for storage in the balance calculation could be as low as -46 mgd or as high as -16 mgd.

The significant finding from the ground water balance calculation is the negative nature of the residual, which indicates that over the 1963-1989 period, ground water levels in the TCMA aquifers were decreasing. To get an idea of the magnitude of the decrease, the average lowering of the water table associated with a storage loss of 30 mgd was calculated. It was found to be close to an inch, assuming a storage coefficient of 0.3, suggesting that the expected annual drop in water levels under normal conditions is very small. Thus, over the 1963-1989 period, generally level or gentle downward trends in water levels should have occurred.

As a check, long-term hydrographs for observation wells within the TCMA were examined (MDNR, 1989). Figure 7 summarizes the water level trends for the aquifers in the area. From the figure, water levels for the PDCJ are increasing in Dakota and Ramsey county, while in Hennepin county they are dropping. The drift is mostly level throughout the area, while the MTSH is trending downward throughout the TCMA. Even though in some parts of the TCMA aquifer levels are rising, these increases are canceled by the reductions in others. If the system is looked at from an aggregated viewpoint, the overall trend seems to be for level or slightly decreasing water levels, which is supported by the findings of the water balance.

Figure 7
TRENDS IN GROUND WATER LEVELS IN THE TWIN CITIES METROPOLITAN AREA



Ground Water Contamination

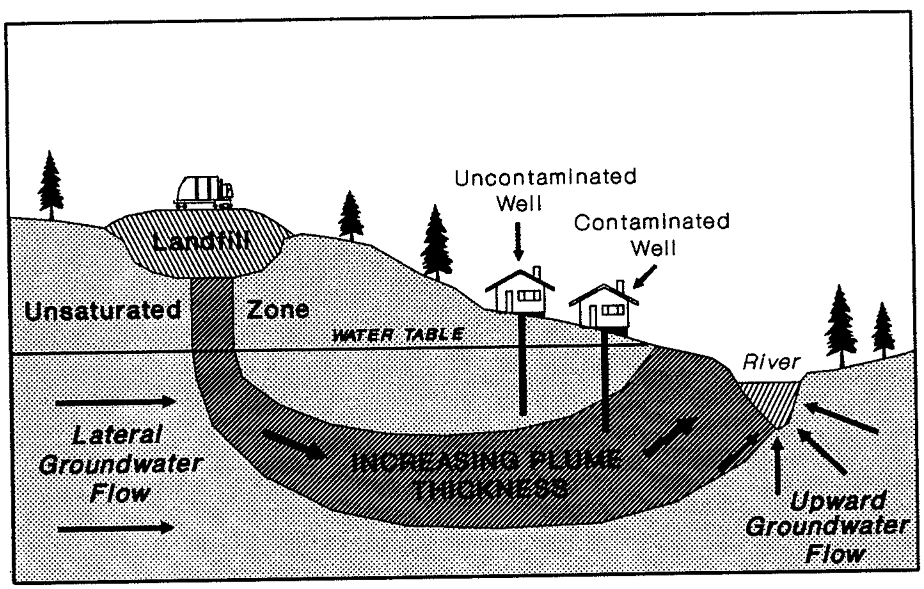
Large- and small-scale ground water contamination is a significant problem in the TCMA. With a total of 78 sites currently on the Superfund list (MPCA, 1990), the existing impact on ground water resources is substantial, and continues to grow. Because contamination effectively "removes" ground water from the potable water supply, it should be accounted for in the ground water balance as a negative component.

By far, the two most common known sources of large scale aquifer contamination by hazardous constituents are landfills and chemical spills. Of the 78 Superfund sites, 18 are due to "leaky" landfills or dumps, and 60 are due to chemical leaks, spills or improper chemical disposal.

Landfills, especially older ones, can contain toxic and hazardous wastes along with municipal refuse, demolition debris, garbage, etc. When precipitation infiltrates the buried waste, it can mix with liquids already present and leach harmful compounds from the solid waste. This leachate then can move into the water table and into underlying aquifers. The leachate forms a plume that spreads in the direction of ground water flow, becoming larger and less concentrated as it moves away from the source (Fetter, 1989). Figure 8 shows a cross-section of a typical plume generated from a landfill. The extent of the plume is constrained by the hydraulic characteristics of the aquifer and the associated confining layers. In this particular case, the plume is stopped by the river to the east, which provides a flow barrier.

The volume of leachate produced depends on the amount of water percolating through the buried waste. In humid climates, more leachate is produced because higher precipitation and soil moisture levels allow more of the precipitation infiltrating the cover soils to percolate into the solid waste below. Fortunately, some constituents of this leachate are naturally attenuated as they pass through the soil; however, significant amounts can reach the water table and underlying aquifers, adversely affecting water supply.

Figure 8
LANDFILL LEACHATE PLUME CROSS-SECTION



Ground water contamination due to organic and inorganic compounds is often the result of improper disposal of waste chemicals, chemical spills, and leaking underground storage tanks. Fifty-seven of the 78 sites in the TCMA can be attributed to at least one of these three modes of introduction. The plumes formed from spills and leaks can be quite complex, because of the different travel times of the various compounds and their chemical properties. The contamination front can spread for miles, making it possible for a single plume to affect a large area.

Two well known sites of regional ground water contamination in the TCMA are the Twin City Arsenal and Ammunitions Plant (TCAAP) located in Arden Hills and the Reilly Tar site in St. Louis Park. These are both good examples of contamination due to improper chemical disposal techniques. In the case of TCAAP, solvents were dumped at the site in areas that were later found to be hydrogeologically sensitive. Consequently, regional contamination of the surficial and PDCJ aquifers occurred, and several wells in the area were closed. At the Reilly Tar site, wastewater laden with creosote and other hazardous compounds was discharged directly into multi-aquifer wells, and also into a nearby wetland, where it infiltrated the ground water system. Contamination of the PDCJ aquifer due to the discharge resulted in the closure of municipal wells in St. Louis Park and Hopkins.

Ground water contamination on a smaller scale is often attributed to leaking underground storage tanks. The Minnesota Pollution Control Agency (MPCA) estimates that 1,400 of the 15,174 registered underground storage tanks located in the TCMA are leaking, causing localized contamination problems. However, in cases where tanks have been leaking for long periods of time, extensive plumes of contamination have resulted in regional contamination.

Using hydrologic information provided by the MPCA for 74 of the 78 Superfund sites (information for the other four was not available at the time this paper was being written), it was possible to make rough estimates regarding the extent of ground water contamination in the TCMA. It should be emphasized that the estimates listed here are very rough approximations. For the purposes of this study, only ground water associated with the Superfund sites was considered, since these sites were the most likely to contain large volumes of ground water polluted beyond maximum contaminant levels (MCLs)--the highest concentration of a solute permissible in a public drinking water supply.

Table 5 shows the estimated volumes of affected ground water associated with each aquifer. It should be noted that the calculation of these volumes entailed using estimated or assumed values when essential data was not provided. For example, if the vertical thickness of an aquifer was not given, it was assumed to be 100 feet; when a range of porosities was included, the average was used; and when a porosity measurement was not given, a value of 0.3 was assumed for the Prairie du Chien-Jordan, and 0.25 for the Platteville. More information regarding individual sites can be found in Appendix B.

Table 5
ESTIMATED VOLUMES OF CONTAMINATED GROUND WATER BY AQUIFER

AQUIFER	NUMBER OF IMPACTED SITES	IMPACTED VOLUME (billion gallons)
Surficial/Glacial Drift	46	47
Platteville	5	14
St. Peter	6	44
Prairie du Chien	14	100
Jordan	2	24
Ironton-Galesville	1	<1
Mount Simon-Hinckley	0	0
TOTAL	74	230

From the MPCA data and subsequent estimation, there may be about 230 billion gallons of contaminated ground water underlying the study area. Looking at this number in terms of mgd, it equals roughly three times the volume of ground water used in the area for one year. That is not to say that the entire volume of contaminated ground water within the region is accounted for; localized areas of contamination not on the Superfund list, less well-known areas of widespread, low-level degradation, and areas contaminated by nitrates are not included in this calculation. Taking this into consideration, the estimate presented above is probably quite low if all contaminated ground water was to be quantified.

Ground Water Balance Evaluation

To account for contamination in the ground water balance, the calculated volume was changed to a discharge rate so it could be compared to the other terms. Even under the worst drought scenario, it was assumed that the entire volume of contaminated ground water would not be used within a year; consequently, an alternative time interval was chosen. A ten year period was chosen as a reasonable pumping scenario, which gives a discharge rate of 64 mgd per year. To account for the volume of ground water "lost" to contamination, 60 mgd was subtracted from the amount of available ground water in the balance calculation. Of course, this volume is not lost in the sense that it can never be recovered; with remediation, such as air-stripping and carbon filtration, this water can be used. However, the treated water is typically discharged to a storm sewer or receiving water, and not used for potable purposes. If necessary, this water could be used as a source of supply, although it would be quite costly.

Wet and Dry Ground Water Balance Evaluation

The method used to construct the wet and dry ground water balance was largely the same as that used to evaluate the normal balance. Recall that earlier in this study, wet conditions were defined by flows from the 75th to 99th percentile. Similarly, dry conditions were characterized by flows within the 1st to 24th percentile. Table 6 summarizes the results of the normal, wet, and dry balance calculations.

Table 6

NORMAL, WET, AND DRY GROUND WATER BALANCES (MGD)

CONDITION	RECHARGE	WITHDRAW-AL	CONTAMIN-ATION	LEAKAGE	STORAGE
Normal	520	250	60	300	-90
Wet	610	210	60	300	40
Dry	-40	290	60	300	-690

Note that the withdrawals associated with wet and dry flows differ from normal withdrawals. The wet and dry figures represent the total withdrawals for 1986 and 1988--1986 being a wet year according to the definition above, and 1988 being a dry year. Also, the leakage term is the same for all climatic conditions in the table. Although leakages to the river system can be expected to change with varying climatic conditions, ground water flow modeling (Schoenberg, 1990) indicates a minimal change in flux between "dry" and "normal" conditions. A representative value for "wet" leakage was not determined from the modeling. Considering the flux change from dry to normal was small and information regarding "wet" leakage was unavailable, the "normal" value was used as an estimate for each condition.

Ground Water Availability

To ensure the long-term viability of the ground water system, a significant negative change in storage should be prevented. It was shown that under normal conditions, the resultant lowering of the water table was on the order of inches. This is clearly not the case under dry conditions, as the storage loss is an order of magnitude more. This necessarily translates into a much greater head loss throughout the area--on the order of feet instead of inches. This suggests that several consecutive drought years could have a serious impact on water levels, which is supported by observation well data from the 1986-1989 drought (MDNR, 1990). Water levels in the primary aquifers plummeted; though they are currently rising, many have not yet reached pre-drought levels.

In terms of water supply, the results of the balance suggest that impact of a long-term (5-10 years) drought on the ground water reservoir could be sizable, with the associated recovery period possibly spanning decades.

SURFACE WATER BALANCE

Surface Water Balance Equation

The surface water balance can be represented by the following equation:

$$I + LI - ET - U = O \, *$$

*(Source: Guide Manual for Preparation of Water Balances, U.S. Army Corps of Engineers)

where I, LI, ET, U, and O represent stream inflow from outside the study area, stream and ground water inflow from within the study area, evapotranspiration from the stream valley, consumptive use, and stream outflow from the study area, respectively.

Study Area

The study area consists of the Mississippi, St. Croix, and Minnesota River valleys.

Surface Water Balance Evaluation

From the overall balance calculation, stream inflow, consumptive use, and stream outflow are already known. This leaves evapotranspiration and local inflow as unknowns in the surface water balance equation. Evapotranspiration from the stream valleys can be estimated by taking the basin value and applying it to the surface area associated with the river valleys. This calculation yielded a value of approximately 20 mgd.

The local inflow term represents the ground water influx to the major rivers, as well as the flow attributable to the ungaged tributary streams and creeks within the TCMA. To determine the local inflow, the terms of the balance equation can be rearranged to solve for local inflow:

$$LI = O + ET + U - I$$

Substituting in the appropriate values yields (mgd):

$$660 = 13300 + 20 + 40 - 12700$$

Of the 660 mgd, at least 520 mgd can be considered ground water inflow (see previous calculation), while the remainder can be attributed to small stream inflows.

Wet and Dry Surface Water Balance Evaluation

The surface water balance for wet and dry conditions was constructed in the same fashion as the normal surface water balance. Wet and dry years were selected according to the criteria discussed earlier in the paper.

Although precipitation information was not used directly in the surface water balance calculation, it was used to check the reasonableness of the "wet" and "dry" evapotranspiration calculation. Precipitation records for 11 USWB stations were used to calculate mean annual precipitation for wet and dry conditions (MDNR, 1990). 18.6 inches, or 2,885 mgd, and 33.9, or 5,259 mgd, respectively, represent the mean annual amount of precipitation that typically falls during dry and wet years within the TCMA. 18.6 inches is 40% less than the normal value of 29.6 inches, while 33.9 inches represents an increase of 13%.

Evapotranspiration was determined according to the Thornthwaite method for the 11 USWB stations identified above. 16.7 inches (2,592 mgd), and 24.8 inches (3,849 mgd) represent dry and wet conditions, respectively. These figures represent a departure from the calculated normal value of approximately -6.5 inches (dry), and +1.2 inches (wet).

Stream inflow and outflows were determined using the same methodology as in the "normal" water balance. Table 7 summarizes the results of the normal, wet and dry surface water balance evaluation.

Table 7

NORMAL, WET, AND DRY SURFACE WATER BALANCES

CONDITION	INFLOW	LOCAL INFLOW	EVAPO-TRANSPIRATION	CONSUMP-TION	OUTFLOW
Normal	12,700	660	20	44	13,300
Wet	15,200	2,500	16	50	17,600
Dry	7,900	900	24	53	8,800

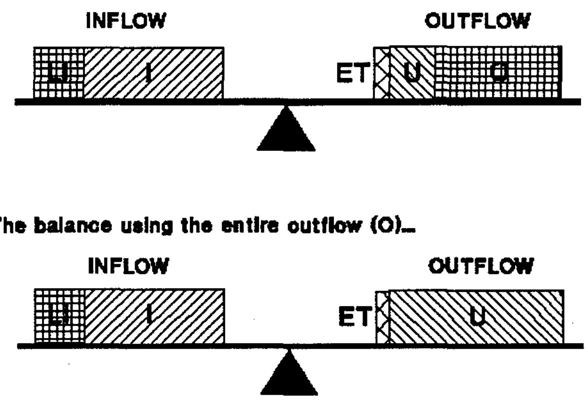
The local inflow term for the "normal" condition seems to be low when compared to the "dry" value. The most likely reason for the disparity is the propagation of error within the balance calculation. Using error estimations provided previously, the inflow value could contain an error of roughly 35 percent. This means that for the "normal" balance, the inflow could be between 430 and 900 mgd; similarly, the "dry" inflow could range from 575 to 1,200 mgd. Historical flow data for the study area (USGS, 1990) indicates that local inflows for drought periods such as the 1930s are typically on the low side of the range identified in the balance. "Normal" flows, such as those experienced during the early 1980s fall into the high end of the balance range. This suggests that the "dry" local inflow value calculated in the balance is probably higher than it should be, and that the "normal" value is probably lower than that of a typical year.

Another possible factor contributing to the higher local inflow value under the "dry" condition is that during drought the head in rivers is reduced, which can cause increased ground water leakage to streams. Whether or not this occurs is governed by the response of ground water levels. Typically, there is a lag time between the onset of drought impacts on the surface water system and on the ground water system. If ground water levels are relatively high, e.g. at the beginning of a dry period, higher leakages may occur.

Surface Water Availability

The amount of water leaving the study area can be thought of as the maximum amount of surface water available. From the surface water balance under normal conditions, this number is more than 13,000 mgd and is reflected in the outflow at Prescott. The balance shows that most of the water entering the TCMA passes through it. It could be used as a source of supply without affecting the surface water system. Figure 9 illustrates this concept.

Figure 9
WATER BALANCE



The increased use component causes the outflow to be reduced, but the balance is unaffected because the volume of output is the same.

While much of this outflow could theoretically be consumed, realistically, some constraints on the use of this water exist. Each of the major rivers has at least one wastewater treatment plant that relies on the river for effluent discharge purposes. Reducing flow in the channel through increased consumptive use could have a significant effect on the assimilation capacity of the rivers, particularly during low flow periods. This in turn could trigger in-stream water quality violations, which is an unacceptable outcome.

Another concern that should be explored is the increase in hydraulic gradient near ground water discharge points. Pumping could cause the head in the rivers to drop below natural levels. This would establish a steeper gradient, possibly resulting in increased ground water discharge to streams, and greater recharge. While this would probably not be a problem on the Mississippi due to the constant water levels of the pool elevations, the Minnesota and St. Croix River valleys could be affected.

Clearly, not all of the outflow can be used because of the concerns listed above, and because of downstream needs. A "critical outflow" must be established to serve as a lower limit. For wastewater assimilation and water quality standards development, the "7Q10"--the minimum seven day low flow with a recurrence interval of once every ten years--is the critical flow (USGS, 1990). The 7Q10 is the design flow for wasteload allocations. At flows less than the 7Q10, wastewater dischargers are not required by law to maintain water quality in the receiving stream. They must, however, continue to meet the stringent effluent limitations on their discharges.

To ensure that water quality standards are met in the TCMA and downstream, the 7Q10 at Prescott should not be breached. Looking at the surface water balance calculation, it looks as though this is a condition that can be easily met--outflow even under dry conditions is almost 9,000 mgd. However, this outflow represents a yearly average, and as such, does not give an indication of low flow conditions. A more useful comparison is that of the 7Q10 at Prescott and average summer flows, since the lowest stream flows typically occur during this time. By making this comparison, surface water availability for the worst case is determined. Table 8 summarizes surface water availability for wet and dry years using the 7Q10 as the critical flow and the median of the monthly mean summer flows as the outflow.

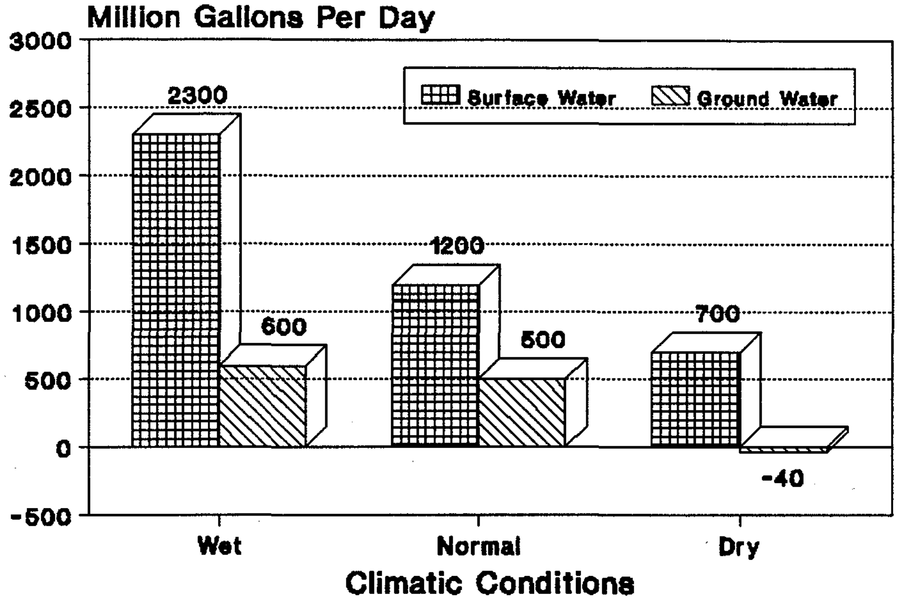
Table 8 shows that during the summer when demand for water peaks, the capacity of the surface water system to supply this demand is not significantly better than that of the ground water system. Furthermore, under peak-use and drought conditions, the ability of the surface water system to meet the existing demand is precarious. For example, during the summer of 1987, the flow in the Mississippi at St. Paul (986) fell far below the 7Q10. This could have caused major water supply problems if the TCMA had been totally dependent on surface water.

Table 8
SURFACE WATER AVAILABILITY DURING SUMMER LOW-FLOW

CONDITION	OUTFLOW	7Q10	AMOUNT AVAILABLE
Normal	3,300	2,061	1,240
Wet	4,400	2,061	2,340
Dry	2,800	2,061	740

Figure 10 compares surface water availability during the summer with ground water availability for normal, wet, and dry conditions. From the figure and the previous discussion, the capacity of the surface water system to support new uses is a function of the season. With the exception of summer low flow periods, the surface water system capacity far outweighs that of the ground water system. However, during the summer and particularly during drought situations, the surface water system can be stressed beyond its capacity to maintain the 7Q10 flow. These findings suggest that surface water may be the best choice for new water supplies, but that its use should be augmented by ground water during peak-use periods.

Figure 10
Surface And Ground Water Availability



Data from MDNR

FACTORS AFFECTING WATER AVAILABILITY

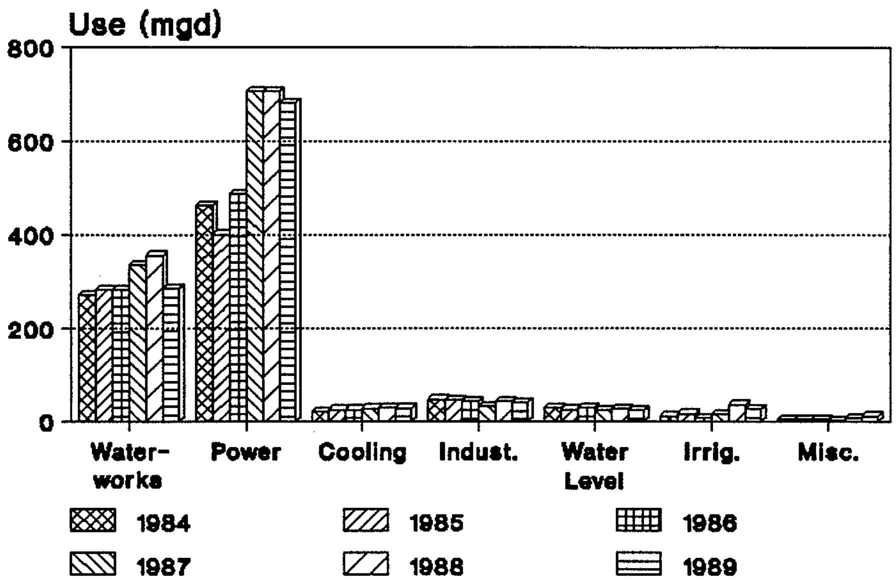
At this point, surface and ground water availability over the study area have been assessed for normal, wet, and dry conditions based on current consumptive use information. Although the results of the assessment indicate overall water availability, they do not accurately describe availability at a particular locality within the study area. Rather, the results represent the maximum capacity of each system to provide water for the entire TCMA. To adequately plan for future water supply needs in the TCMA, factors affecting this overall water availability must be explored in detail. Future water demand, and the distribution of this demand within the study area must be examined to ensure that future water supply needs can be met effectively.

Demand

Demand, or water use, has been looked at in terms of total use by source, for example, total ground water use and total surface water use. This approach was appropriate for the development of the water balances, but to get a clear picture of how water is being used in the TCMA and how these uses may affect availability, each use category must be examined. Figure 11 illustrates water use in the TCMA over the 1984-1989 period.

From the figure, municipal waterworks and power generation are by far the largest users of surface and ground water. Following these uses comes industrial/commercial and irrigation as the second and third largest users of water; both these uses are primarily supported by ground water. Residential use is supported by ground and surface water sources, however, the only cities that use surface water are Minneapolis and St. Paul, and the municipalities they supply. Other significant uses include air conditioning, and water level maintenance.

Figure 11
Water Use By Category, 1984-1989



Data from DNR

Because the TCMA is growing, demand for water is increasing--but not uniformly throughout the use categories. Some uses are being phased-out, thereby diminishing demand, while others are leveling out as shown in the figure. For example, the Ground Water Protection Act of 1989 prohibits the construction of any new once-through air conditioning systems, and mandates a phase-out of existing systems by 2010. From a water availability standpoint, the 23 mgd of ground water that had been devoted to this use may be available to fulfill other use requirements after 2010. Similarly, water level maintenance uses might be phased-out, possibly freeing an additional 4 mgd for future use, assuming that this water could be captured completely for other uses. Whether or not this occurs is a function of the position of the wells used for air-conditioning and water level maintenance, in relation to new wells and the river system.

Examples of uses that should remain constant within the TCMA include power generation and major crop irrigation, which together constitute a volume of approximately 44 mgd. This leaves residential and commercial/industrial uses as the only areas in which demand is likely to increase. To get an idea of the magnitude of the increases in these two areas, a statistical model was developed to forecast water demand. The model is described in detail in Working Paper No. 2, "Water Demand in the TCMA". Essentially, the model separates uses into residential and industrial/commercial sectors, and forecasts demand based on projections of population for indirect effect of the additional pumpage in the drift and PDCJ was the lowering of water levels in the MTSH. The lowest water levels occurred in Edina, and in northern Hennepin and southern Anoka counties (Schoenberg, 1990).

The second scenario projected a pumping rate of 510 mgd from the PDCJ and the drift, which represents an increase of 260 mgd from present levels. According to the model, the additional withdrawal further exacerbated the situation described in scenario one. Water levels in the PDCJ were projected to fall below natural discharge points at the cities mentioned in the first scenario, in addition to Eden Prairie, the Minneapolis Water Works in Fridley, Minneapolis, Energy Park in St. Paul, and in Roseville. Similarly, water levels in the MTSH dropped in the northern suburbs of Minneapolis, as well as St. Louis Park, Savage, and Edina due to greater pumpage from the aquifer (Schoenberg, 1990).

The third scenario projected a pumping rate of 370 mgd, but shifted the withdrawal from the drift to the MTSH. Thus, the pumpage was confined to the PDCJ and MTSH aquifers, as opposed to the PDCJ and the drift. The results indicated that water levels in the PDCJ could fall below discharge points in Burnsville, Bloomington, and the St. Paul Water Utility. MTSH water levels were lowest at Andover, Maple Grove, and Brooklyn Park, in addition to the cities mentioned in scenario two (Schoenberg, 1990).

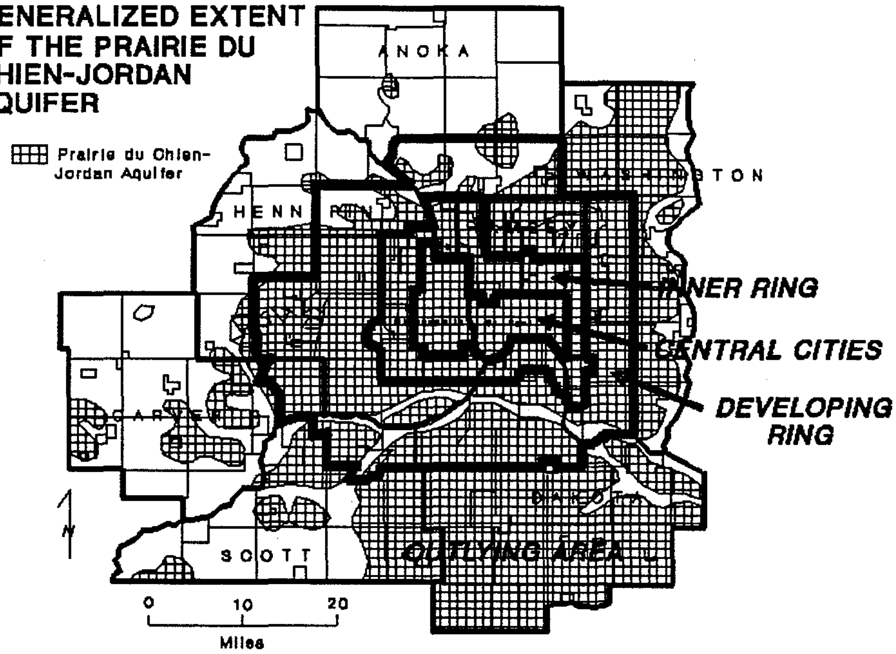
The fourth scenario projected pumpage of 670 mgd from the PDCJ and drift aquifers, representing an increase of 420 mgd from existing levels. This scenario approaches "maximum" capacity, since recharge to the system is roughly 500 mgd. Water levels in the PDCJ dropped by as much as 300 feet in the northern portions of Ramsey county as a result of the modeled increase in withdrawal. A similar decrease was predicted for the MTSH in the Brooklyn Park area (Schoenberg, 1990). Table 10 summarizes the results of the four modeling runs.

The ground water flow modeling results suggest that increased withdrawals from the three aquifers could seriously affect the ability of some areas to obtain sufficient water supplies. Even minimal increases in pumpage from the PDCJ and drift (Scenario #1) could result in significant lowering of water levels in the southern and northern portion of the developing ring, as well as for St. Paul. These problems are further aggravated in Scenario #2 by increasing the pumpage rate even further.

In Scenario #3, the shift in pumpage from the drift to the MTSH and the subsequent lowering of hydraulic head in the aquifer indicates that it is not capable of handling a large increase in pumpage. This could result in problems for the northern and western portions of the area where the PDCJ is not available, and the drift is the primary source of supply. If the drift became contaminated in these areas, the MTSH would probably not be a viable alternative due to increased pumping costs.

The final scenario indicates that at a pumping rate close to the maximum capacity of the system, large reductions in hydraulic head occur in the primary aquifers. The largest cone of depression occurs over the St. Paul Water Utility.

Figure 13
GENERALIZED EXTENT OF THE PRAIRIE DU CHIEN-JORDAN AQUIFER



While the PDCJ is available in the southern portion of the ring, the northwestern and southwestern portions lie on the outer edge of the aquifer. These areas are not likely to have access to the PDCJ, which implies that an alternative aquifer must be developed if ground water continues to be their source of supply. In the southern portion of the developing ring, the PDCJ is available. However, the increased pumpage needed to satisfy future demand for this area could trigger a lowering of ground water levels or other undesirable effects.

To determine how the PDCJ, MTSH, and the drift aquifer might respond to increased withdrawals from major pumping centers in the TCMA, the United States Geological Survey (USGS) in cooperation with the Metropolitan Council, developed a ground water flow model for the TCMA (Schoenberg, 1990). The model was used to predict static water levels in the PDCJ, drift, and MTSH aquifers under four different pumping scenarios.

The calibration of the model was carried out using hydraulic head data from 1970-1979, and a pumping rate for withdrawals of 200 mgd. In addition, the simulated locations for new pumpage were placed at the locations of the old pumpage.

The first scenario projected a total pumpage of 370 mgd, which represents an increase of approximately 120 mgd from present pumping levels. The model concentrated the additional pumpage in the drift and the PDCJ aquifers. Results from this exercise indicated that water levels in the PDCJ could fall below the point where the aquifer naturally discharges to the surface water system at Bloomington, Burnsville, and the St. Paul Water Utility at Vadnais Heights.

The model predicted a 12 percent drop in leakage to the Minnesota River from Burnsville to St. Paul, as well as a 30 percent decrease in leakage to the Mississippi from Anoka to Prescott. An residential use and number of employees for commercial/industrial use. A forecast of overall demand for residential and commercial/industrial sectors was made for 2000 and 2010, as well as separate forecasts for the 111 cities within the TCMA that have municipal water systems.

According to the model, by 2010 overall residential demand will increase by 17% from 1988 levels, which corresponds to an additional 40 mgd. To make up for this increased demand, the amount of available water must reduced by the same increment. Similarly, commercial use is projected to rise by 12%, corresponding to an additional 24 mgd. The amount of available water must be further reduced to balance this loss. Since most of the predicted growth will be in communities served by ground water, it is likely that the increases in demand will be focused on the ground water reservoir.

Table 9 shows how the projected residential and commercial/industrial demand increases for 2000 and 2010 would affect surface and ground water availability for normal, wet, and dry conditions if they were focused entirely on either system. The forecasts indicated that from 1988 to 1990, demand would increase by approximately 17 mgd. This volume was subtracted from the amount available in 1988 to show the "new" amount available for 1990. Similarly, from 1990 to 2000 demand was projected to increase by roughly 29 mgd, thereby reducing the amount available in 2000 by an additional 29 mgd. Finally, from 2000 to 2010, an increase of 18 mgd was projected, which reduced the amount available in 2010 by 18 mgd. Because there is no way of accurately predicting what portion of this additional demand will be focused on the surface or ground water system, it was assumed that the entire demand would be satisfied by either one or the other.

In doing this calculation, it was also assumed that the only significant increases in water demand would occur in the residential and commercial/industrial use sectors. The variation in demand for the other use categories was assumed to be insignificant when compared to the increases residential and commercial/industrial demand.

Table 9

PROJECTED WATER AVAILABILITY: GROUND AND SURFACE WATER SYSTEMS

SOURCE	CON-DITION	AMOUNT AVAILABLE 1988	AMOUNT AVAILABLE 1990	AMOUNT AVAILABLE 2000	AMOUNT AVAILABLE 2010
GW	Normal	520	503	474	456
GW	Wet	610	593	564	546
GW	Dry	-40	-57	-86	-104
SW	Normal *	1,240	1,223	1,194	1,176
SW	Wet *	2,340	2,322	2,293	2,275
SW	Dry *	740	723	694	676

* Indicates median of the monthly mean summer flows.

From the table it can be seen that while each system is capable of handling the increased demand, the ground water system would be significantly stressed during dry periods if the entire demand increase were focused on it.

Demand Distribution

The overall forecasts suggest that under normal conditions, the demand for water can be easily met. However, this overall forecast does not concentrate the demand where it actually occurs--rather, it spreads it over the entire TCMA. To help identify areas where future demand is likely to be the heaviest, individual city forecasts were used. From these forecasts, the northern portion of Dakota county, the northeastern portion of Hennepin county, and eastern Carver/western Hennepin county were identified as areas where major increases in water use were likely to occur.

Figure 12 shows the forecasted increases for each of the areas. The projected increases for Burnsville, Apple Valley, Eagan, and Rosemount account for roughly 46 percent of the total increase in water use from 1988-2010. This translates into an increase of about 19 mgd for just these four cities. The increases for Maple Grove, Brooklyn Park, Brooklyn Center and Plymouth in northeastern Hennepin county are not quite as dramatic, accounting for 30 percent of the total increase; while Minnetonka, Chanhassen, and Chaska account for 12 percent. The remaining 100 cities in the TCMA account for the remaining 12 percent of the forecasted increase in demand.

The increases noted above are significant, but they are made even more so by the fact that the three growth centers also occur in areas that rely solely on ground water as their source of supply. To accommodate the projected growth in the region, as many as 160 additional municipal wells may have to be developed, based on a rate of 1 new well for every 2,000 additional people served by the utility (Oberts et al., 1990). Figure 13 shows the "developing ring", which outlines the major growth areas, and the lateral extent of the region's most productive aquifer, the PDCJ.

Figure 12
FORECASTED INCREASES IN WATER USE

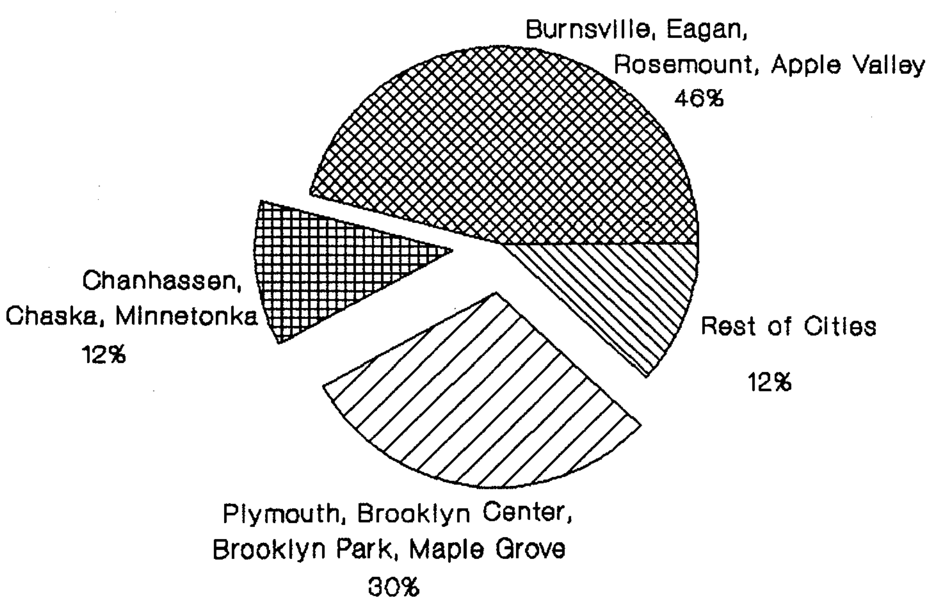


Table 10
FLOW MODEL INFORMATION

PUMPING SCENARIOS	MODELED INCREASE	AQUIFER PUMPED	AFFECTED AREAS
#1	120 mgd	Drift, PDCJ	Bloomington, Burnsville, St. Paul
#2	260 mgd	Drift, PDCJ	Same as Scenario #1, plus Minneapolis, Eden Prairie, Roseville
#3	120 mgd	PDCJ, MTSH	Same as Scenario #1, plus Andover, Maple Grove and Brooklyn Park.
#4	420 mgd	Drift, PDCJ	Same as Scenario #1, plus New Brighton, Blaine, Coon Rapids, Vadnais Heights.

The modeling results also suggest that well distribution is an important factor in obtaining ground water at the least possible cost. Increases in pumpage were placed in existing pumping centers to simulate wellfield conditions. The modeling shows that large cones of depression surrounding these areas can be expected to develop as a result of the increased withdrawals. This implies that instead of concentrating a number of wells in one area, an even distribution of wells should be developed. By doing this, the formation of the large cones could be circumvented, thus reducing pumping costs.

A final conclusion that can be drawn from the modeling runs is that if additional water supplies must be obtained from the MTSH aquifer instead of the drift, the MTSH could be seriously affected.

As a follow-up to the initial modeling done by the USGS, the Council is currently developing a flow model that will target the problem areas identified in the USGS effort. The first stage of the current modeling is focused on the drift aquifer in Maple Grove and Brooklyn Park; the objective is to determine whether the drift is capable of supplying the projected demand. This stage is nearing completion and the results will be published in the near future. The next stage will be to develop a similar model for western Hennepin and eastern Carver counties. Eventually, a working model for the entire aquifer system will be developed to help guide water supply development and management.

Clearly, both demand and the distribution of this demand are critical factors in determining water availability. It has been shown that although the projected demand for the next 20 year period is small compared to the 520 mgd currently available from the entire regional ground water system, the fact that the increased demand will probably be focused in areas where the ground water system is least capable of handling the demand magnifies the negative effects of this small withdrawal.

CONCLUSIONS

The water balance calculations indicate the TCMA has surplus of water available to meet future demand, but the use of this water is constrained by several factors. Although the surface water system on the whole can produce much more water than the ground water system, during critical summer low flow, it cannot be relied on to meet any increase in demand. This suggests that if surface water is looked at as a source of supply, a reservoir system such as in St. Paul, or a ground water backup would be necessary to ensure sufficient volumes during low-flow periods.

Another constraint on the use of surface water is the possibility of alterations in the hydraulic gradient as a result of pumpage from the rivers, which could cause increased ground water discharge to streams and induce increases in recharge. While this would probably not be a problem given the small increases in demand forecasted for 2010, it could become a concern as demand increases in the future.

The ground water balance showed that under normal conditions, water levels are dropping--albeit almost imperceptibly. While a loss in head on the order of inches over the aquifer system could probably be considered a tolerable loss, the question remains as to what constitutes an intolerable loss. These kind of limits need to be set so that potential ground water supply problems can be avoided.

The USGS modeling scenarios provide a snapshot of what the future may hold for the area regarding ground water impacts. The modeling results suggest that even a small increase in ground water withdrawals focused in existing pumping centers could reduce water levels in the major aquifers significantly. As more and more water is pumped from these areas, large cones of depression can be expected to develop. This translates into greater energy costs for pumping, in addition to possible reductions in stream flow in the TCMA.

One way to reduce the likelihood of these kinds of problems is to control the spacing of high capacity wells. With a more even distribution of wells, hydraulic head losses would not be concentrated in a small zone, thus reducing the impact on the resource. As an added benefit, the cost of pumping would also be reduced. Another possibility that merits exploration is the sharing of water across municipal boundaries. This concept is developed more fully in Working Paper #4.

Although the discussion provided here and throughout the paper points out several concerns regarding the use of surface and ground water, it is important to keep in mind that there is more than enough water available to meet forecasted demand. The issue that needs to be addressed is how this surplus will be managed so that: (1) existing and future withdrawals and uses can be maintained throughout the year; and (2) minimal impacts are imposed on the surface and ground water system to ensure long-term viability.

REFERENCES

An Analysis of Water Use in Minnesota. St. Paul: Minnesota Department of Natural Resources. 1987.

Baker, D.G., Nelson, W.W. and Kuehnast, E.L. "Climate of Minnesota Part XII--The Hydrologic Cycle and Soil Water." Minnesota Agricultural Experiment Station Technical Bulletin 322. Minneapolis: University of Minnesota. 1979.

Climatologic data obtained from the CLIMON database. St. Paul: Minnesota Department of Natural Resources. 1990.

County base maps generated from MINNMAP software, developed by the State Climatology Office. Minnesota Department of Natural Resources. 1990.

Delin, G.N. and Woodward, D.G. Hydrogeologic Setting and Potentiometric Surfaces of Regional Aquifers in the Hollandale Embayment, Southeastern Minnesota. U.S. Geological Survey Water-Supply Paper 2219. 1985.

Fetter, C.W. Applied Hydrogeology. 2nd ed. Columbus, Ohio: Merrill Publishing Co. 1988.

Golden Software, Inc. P.O. Box 281, Golden, Colorado 80402.

Handbook of Applied Hydrogeology. ed. V.T. Chow. McGraw-Hill, Inc. 1964. pp. 11-1, 14-49.

Hartsoe, J.A. Water Demand in the Twin Cities Metropolitan Area. St. Paul: Metropolitan Council. 1991.

Horn, M.A. Groundwater-Use Trends in the Twin Cities Metropolitan Area, 1880-1980. U.S. Geological Survey Water Resources Investigations Report 83-4033. 1983.

Kuehnast, E.L., Baker, D.G. and Enz, J.W. "Climate of Minnesota Part VIII--Precipitation Patterns in the Minneapolis-St. Paul Metropolitan Area and Surrounding Counties." Minnesota Agricultural Experiment Station Technical Bulletin 301. Minneapolis: University of Minnesota. 1975.

Liesch, B. A. and Associates. Ground Water Study: Final Report. Prepared for the Once-Through Usage of Water Steering Committee. 1990.

Metropolitan Area Short-term Water Supply Plan. St. Paul: Metropolitan Council. 1990.

Norvitch, R.F., Ross, T.G. and Brietkrietz, A. Water Resources Outlook for the Minneapolis-St. Paul Metropolitan Area. Prepared by the U.S. Geological Survey in cooperation with the Metropolitan Council. 1974.

Oberts, G.L. Alternative Sources of Water for the Twin City Metropolitan Area. St. Paul: Metropolitan Council. 1991.

Oberts, G.L., Hartsoe, J.A. and Corrigan, S.A. Water Supply Planning in the Land of 10,000 Lakes. Accepted for presentation at the Symposium of Water Supply and Water Use: 1991 and Beyond. San Diego. June 1991.

Schoenberg, M.E. Effects of Present and Projected Ground-Water Withdrawals on the Twin Cities Aquifer System, Minnesota. U.S. Geological Survey Water Resources Investigations Report 90-4001. 1990.

Schoenberg, M.E. "Factors Affecting Water-Supply Potential of the Twin Cities Metropolitan Area Aquifer System." Journal of the Minnesota Academy of Science. 55, No. 1. 1989. p. 8.

Schoenberg, M.E. Water Levels and Water-Level Changes in the Prairie du Chien-Jordan and Mount Simon-Hinckley Aquifers, Twin Cities Metropolitan Area, Minnesota, 1971-1980. U.S. Geological Survey Water-Resources Investigations Report 83-4237. 1984.

Solley, W.B., Chase, E.B. and Mann, W.B. Estimated Use of Water in the United States in 1980. U.S. Geological Survey Circular 1001. 1983.

Stoner, J.D. and Schoenberg, M.E. Preliminary Evaluation of Effects of Groundwater Withdrawals on Mississippi River Flow Near the Twin Cities Metropolitan Area, Minnesota. Minnesota Water Resources Research Center Special Report No. 18. Minneapolis: University of Minnesota. 1989. pp. 5-6.

Superfund Permanent List of Priorities as of December, 1989. St. Paul: Minnesota Pollution Control Agency. 1990.

Thornthwaite, C.W. and Mather, J.R. "Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance." Climatology. 10, No. 3. Centerton, N.J.: Drexel Institute of Technology. 1957.

Understanding Ground Water Level Trends: A Key to Managing Water Use. St. Paul: Minnesota Department of Natural Resources. 1989.

Guide Manual for Preparation of Water Balances. U.S. Army Corps of Engineers. Hydrologic Engineering Center. Davis, California. 1980.

U.S. Geological Survey. Hydrologic data obtained from the WATSTORE database. 1990.

Winter, T.C. "Uncertainties in Estimating the Water Balance of Lakes." Water Resources Bulletin, Vol. 17, No. 1. American Water Resources Association. February, 1981.

APPENDIX A

PRECIPITATION AND EVAPOTRANSPIRATION DATA

USWB Station	Co-Twp-Rng-Sec	Location	Normal	Dry	Wet	Normal	Dry	Wet
			P	P	P	E	E	E
1107	86-120-25-19	Buffalo	28.55	16.39	35.42	23.57	16.28	26.02
1227	30-036-23-32	Cambridge	29.02	20.73	33.26	22.10	18.21	23.35
1390	02-033-24-26	Cedar	29.47	14.12	33.88	23.27	10.80	23.49
1465	10-115-23-04	Chaska	28.99	23.95	33.87	23.83	21.96	25.71
2500	71-033-26-33	Elk River	29.07	*	*	*	*	*
2737	19-114-20-14	Farmington	30.03	21.04	36.43	22.57	16.71	25.28
2881	82-032-21-13	Forest Lake	29.22	16.08	33.84	23.36	12.47	23.39
3567	19-115-17-21	Hastings	28.62	*	*	*	*	*
4176	70-114-23-29	Jordan	27.49	19.64	32.58	23.85	19.26	25.00
5136	27-118-24-25	Maple Plain	30.82	*	*			
5435	27-028-23-30	Minneapolis	28.23	21.60	33.81	22.28	17.88	23.76
6817	25-113-14-29	Red Wing	31.74	*	*	*	*	*
6822	25-115-15-10	Red Wing Dam	29.02	*	*	*	*	*
7107	19-115-19-33	Rosemount	32.91	18.60	37.75	24.47	16.92	24.81
7308	02-033-24-19	St. Francis	27.42	*	*	*	*	*
7377	62-029-22-20	St. Paul	30.56	17.36	34.81	24.31	14.15	24.05
8037	82-030-20-34	Stillwater	31.57	16.78	35.48	24.38	13.66	25.79
9085	43-117-27-03	Winsted	27.39	*	*	*	*	*
9208	10-115-26-11	Young America	29.22	*	*	*	*	*

All data reported in inches.
Each number represents the mean value for the station over the 1963-1989 period

APPENDIX B

GROUND WATER CONTAMINATION DATA

SITE	SURF	PDCJ	STP	PLATT	JRDN	IG	POR	surfxpor	pdcjxpor	stpxpor	platxpor	jrdnxpor	igxpor
1	1.9e+06						0.27	5.1e+05	0.0	0.0	0.0	0.0	0.0
2	6.8e+06						0.30	2.0e+06	0.0	0.0	0.0	0.0	0.0
3	2.8e+08						0.30	8.4e+07	0.0	0.0	0.0	0.0	0.0
4							0.30	0.0	0.0	0.0	0.0	0.0	0.0
5							0.30	0.0	0.0	0.0	0.0	0.0	0.0
6		8.7e+08					0.30	0.0	2.6e+08	0.0	0.0	0.0	0.0
7							0.30	0.0	0.0	0.0	0.0	0.0	0.0
8		1.1e+10					0.30	0.0	3.3e+09	0.0	0.0	0.0	0.0
9	1.3e+08						0.30	3.9e+07	0.0	0.0	0.0	0.0	0.0
10	3.0e+08	3.0e+08					0.30	9.0e+07	9.0e+07	0.0	0.0	0.0	0.0
11							0.30	0.0	0.0	0.0	0.0	0.0	0.0
12							0.30	0.0	0.0	0.0	0.0	0.0	0.0
13		4.6e+08					0.30	0.0	1.4e+08	0.0	0.0	0.0	0.0
14	4.5e+07			6.9e+06			0.30	1.4e+07	0.0	0.0	2.1e+06	0.0	0.0
15	3.5e+08	3.5e+08			3.5e+08		0.30	1.0e+08	1.1e+08	0.0	0.0	1.1e+08	0.0
16	2.6e+07						0.35	9.1e+06	0.0	0.0	0.0	0.0	0.0
17	1.0e+05						0.30	3.0e+04	0.0	0.0	0.0	0.0	0.0
18	1.2e+06						0.27	3.2e+05	0.0	0.0	0.0	0.0	0.0
19	1.1e+08						0.37	4.1e+07	0.0	0.0	0.0	0.0	0.0
20	6.0e+05	6.0e+04					0.30	1.8e+05	1.8e+04	0.0	0.0	0.0	0.0
21	2.3e+07						0.30	6.9e+06	0.0	0.0	0.0	0.0	0.0
22		5.6e+08					0.30	0.0	1.7e+08	0.0	0.0	0.0	0.0
23	1.2e+06						0.30	3.6e+05	0.0	0.0	0.0	0.0	0.0
24	5.0e+08						0.30	1.5e+08	0.0	0.0	0.0	0.0	0.0
25							0.30	0.0	0.0	0.0	0.0	0.0	0.0
26	4.5e+06						0.30	1.4e+06	0.0	0.0	0.0	0.0	0.0
27							0.30	0.0	0.0	0.0	0.0	0.0	0.0
28							0.30	0.0	0.0	0.0	0.0	0.0	0.0
29	3.7e+07						0.30	1.1e+07	0.0	0.0	0.0	0.0	0.0
30	2.2e+08						0.30	6.6e+07	0.0	0.0	0.0	0.0	0.0
31							0.30	0.0	0.0	0.0	0.0	0.0	0.0
32	2.3e+08						0.30	6.9e+07	0.0	0.0	0.0	0.0	0.0
33	1.6e+08						0.30	4.8e+07	0.0	0.0	0.0	0.0	0.0
34	4.2e+06						0.30	1.3e+06	0.0	0.0	0.0	0.0	0.0
35							0.30	0.0	0.0	0.0	0.0	0.0	0.0
36	3.8e+08		3.3e+08	1.3e+08			0.30	1.1e+08	0.0	9.9e+07	3.3e+06	0.0	0.0
37	1.6e+07						0.30	4.8e+06	0.0	0.0	0.0	0.0	0.0
38	4.1e+09						0.30	1.2e+09	0.0	0.0	0.0	0.0	0.0
39	1.8e+08	1.5e+08					0.30	5.4e+07	4.5e+07	0.0	0.0	0.0	0.0
40	2.0e+08						0.30	6.0e+07	0.0	0.0	0.0	0.0	0.0
41	3.0e+05						0.25	7.5e+04	0.0	0.0	0.0	0.0	0.0
42							0.30	0.0	0.0	0.0	0.0	0.0	0.0
43	3.5e+06			2.1e+07			0.20	7.0e+05	0.0	0.0	5.3e+05	0.0	0.0
44	1.6e+09		1.8e+10	3.0e+09			0.30	4.8e+08	0.0	5.4e+09	9.0e+08	0.0	0.0
45							0.30	0.0	0.0	0.0	0.0	0.0	0.0
46							0.30	0.0	0.0	0.0	0.0	0.0	0.0
47	1.8e+07						0.30	5.4e+06	0.0	0.0	0.0	0.0	0.0
48	6.4e+08		1.0e+08	3.5e+09			0.30	1.9e+08	0.0	3.0e+07	1.1e+09	0.0	0.0
49	3.5e+07						0.30	1.1e+07	0.0	0.0	0.0	0.0	0.0
50							0.30	0.0	0.0	0.0	0.0	0.0	0.0
51	1.0e+09						0.30	3.0e+08	0.0	0.0	0.0	0.0	0.0
52	1.4e+09	1.2e+10	1.2e+09		1.0e+10	9.6e+07	0.32	4.5e+08	3.8e+09	3.8e+08	0.0	3.2e+09	3.1e+07
53							0.30	0.0	0.0	0.0	0.0	0.0	0.0
54		3.5e+08					0.30	0.0	1.1e+08	0.0	0.0	0.0	0.0

	SURF	PDCJ	STP	PLATT	JRDN	IG	POR	surfxpor	pdcjxpor	stpxpor	platxpor	jrdnxpor	igxpor
55							0.30	0.0	0.0	0.0	0.0	0.0	0.0
56	4.4e+06						0.30	1.3e+06	0.0	0.0	0.0	0.0	0.0
57	4.5e+06						0.30	1.4e+06	0.0	0.0	0.0	0.0	0.0
58	3.0e+07						0.25	7.5e+06	0.0	0.0	0.0	0.0	0.0
59			1.8e+07				0.15	0.0	0.0	2.7e+06	0.0	0.0	0.0
60							0.30	0.0	0.0	0.0	0.0	0.0	0.0
61	5.0e+07						0.25	1.3e+07	0.0	0.0	0.0	0.0	0.0
62	1.0e+06	3.0e+06					0.30	3.0e+05	9.0e+05	0.0	0.0	0.0	0.0
63	1.3e+07						0.20	2.6e+06	0.0	0.0	0.0	0.0	0.0
64							0.30	0.0	0.0	0.0	0.0	0.0	0.0
65	3.4e+09	1.1e+10					0.30	1.0e+09	3.3e+09	0.0	0.0	0.0	0.0
66	2.6e+08						0.37	9.6e+07	0.0	0.0	0.0	0.0	0.0
67							0.30	0.0	0.0	0.0	0.0	0.0	0.0
68	5.1e+09	6.9e+09					0.30	1.5e+09	2.1e+09	0.0	0.0	0.0	0.0
69							0.30	0.0	0.0	0.0	0.0	0.0	0.0
70	2.6e+08	1.6e+08	7.8e+07				0.30	7.8e+07	4.8e+07	2.3e+07	0.0	0.0	0.0
71	4.6e+07						0.25	1.1e+07	0.0	0.0	0.0	0.0	0.0
72	1.8e+07						0.30	5.4e+06	0.0	0.0	0.0	0.0	0.0
73									0.0	0.0	0.0	0.0	0.0
74									0.0	0.0	0.0	0.0	0.0
TOTALS, FT3	2.1e+10	4.4e+10	2.0e+10	6.7e+09	1.0e+10			6.4e+09	1.3e+10	5.9e+09	2.0e+09	3.3e+09	3.1e+07
TOTALS, MGAL								4.8e+04	1.0e+05	4.4e+04	1.5e+04	2.5e+04	2.3e+02
ESTIMATED TOTAL CONTAMINATED VOLUME (MGAL)								**2.3e+05**					

KEY

SITE = location of contamination, contact Sheryl Corrigan for specific site information.
SURF = all non-bedrock aquifers
PDCJ = Prairie du Chien - Jordan
STP = St. Peter
PLATT = Platteville
JRDN = Jordan
IG = Ironton - Galesville
POR = estimated porosity