THE EFFECTS OF LOW FLOW ON WATER QUALITY IN THE METROPOLITAN AREA

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by Jim Larsen

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ABOUT THIS REPORT

This report is Working Paper No. 6 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. 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.

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THE EFFECTS OF LOW FLOW ON WATER QUALITY IN THE METROPOLITAN AREA

INTRODUCTION

Assessing the quality of water involves looking at a combination of its physical, chemical, and biological characteristics. All water in nature contains substances derived from the natural environment, or environments as they have been altered by humans. By measuring the concentrations of these substances, waters can be characterized according to their source and beneficial uses.

Water quality is a key factor in determining the adequacy of any water supply to satisfy the requirements of its intended uses. Water has a natural, but limited, self-cleansing ability to assimilate pollutant loadings. Aquatic bacteria utilize dissolved oxygen in water to stabilize organic pollutants. Pollutant sources are monitored in an effort to establish the maximum loadings their receiving waters can safely assimilate without environmental damage. Deterioration resulting from pollution can significantly alter the potential uses of water.

The U. S. Environmental Protection Agency (EPA) and Minnesota Pollution Control Agency (MPCA) have established water quality standards for designated water use classifications that have been applied to all waters within the state. These water quality standards are applied to dischargers of pollutants through the issuance of National Pollutant Discharge Elimination System (NPDES) permits. The permits establish allowable levels for the discharge of pollutants from point sources to a river or other receiving water. The permitted maximum pollutant levels are established to prevent the receiving water from exceeding applicable water quality standards and criteria, or compromise its availability for other established beneficial uses.

The greatest single factor controlling the overall waste-assimilative capacity of a surface water is the amount of dilution that it provides for pollutants. The waste-assimilative capacity increases as the amount of dilution water increases. Stream flows fluctuate seasonally in response to changing meteorological conditions. Stream flow rates are typically highest during late spring to early summer and taper off to a yearly low flow level in late winter. However, most violations of instream water quality standards occur during summer periods of concurrent low seasonal streamflow, high water temperatures, and highest demand for water withdrawal for municipal and agricultural uses. As a result, the required levels of treatment for point source dischargers of pollutants are established by modelling of a stream's natural processes at a statistically determined, summer season minimum flow. This ensures maintenance of instream water quality standards during all but the lowest weekly flow that will recur an average of only once every ten years. This flow is termed the 7Q10 flow.

The 1976-77 drought affected a larger part of the United States more severely than any other previous droughts in the 20th century. Locally, independent flow regulation of instream dams on the Mississippi River resulted in a record instantaneous low flow in the Mississippi River at Anoka of 529 cubic feet per second (cfs) in late August of 1976. During the equally severe winter of 1976-77, extreme low flows and increased ice coverage that prevented natural reaeration resulted in observed dissolved oxygen (DO) concentrations of zero in the Mississippi River within the Twin City Metropolitan Area (TCMA).

It is difficult for most people to think about drought planning when it is raining, and 1982 through 1986 was the wettest five-year period on record in the TCMA. Subsequent to this historic period of water over-abundance, precipitation levels diminished during the fall of 1986 within the TCMA and the Mississippi River Headwaters region to between 50 and 75 percent of average expected accumulations. This latest drought period, lasting from 1986 through 1989, caused Mississippi River flows as measured in St. Paul to drop below the established 7Q10 flow of 1708 cfs for 48 consecutive days during June through August of 1988. As a result of incorporation of both the diminished flow rates during this most recent extreme low flow period and the extremely high flow rates experienced during 1982 through 1986, future waste-assimilative capacity determinations for the Mississippi River will utilize a current recalculated summer season 7Q10 flow of 1910 cfs.

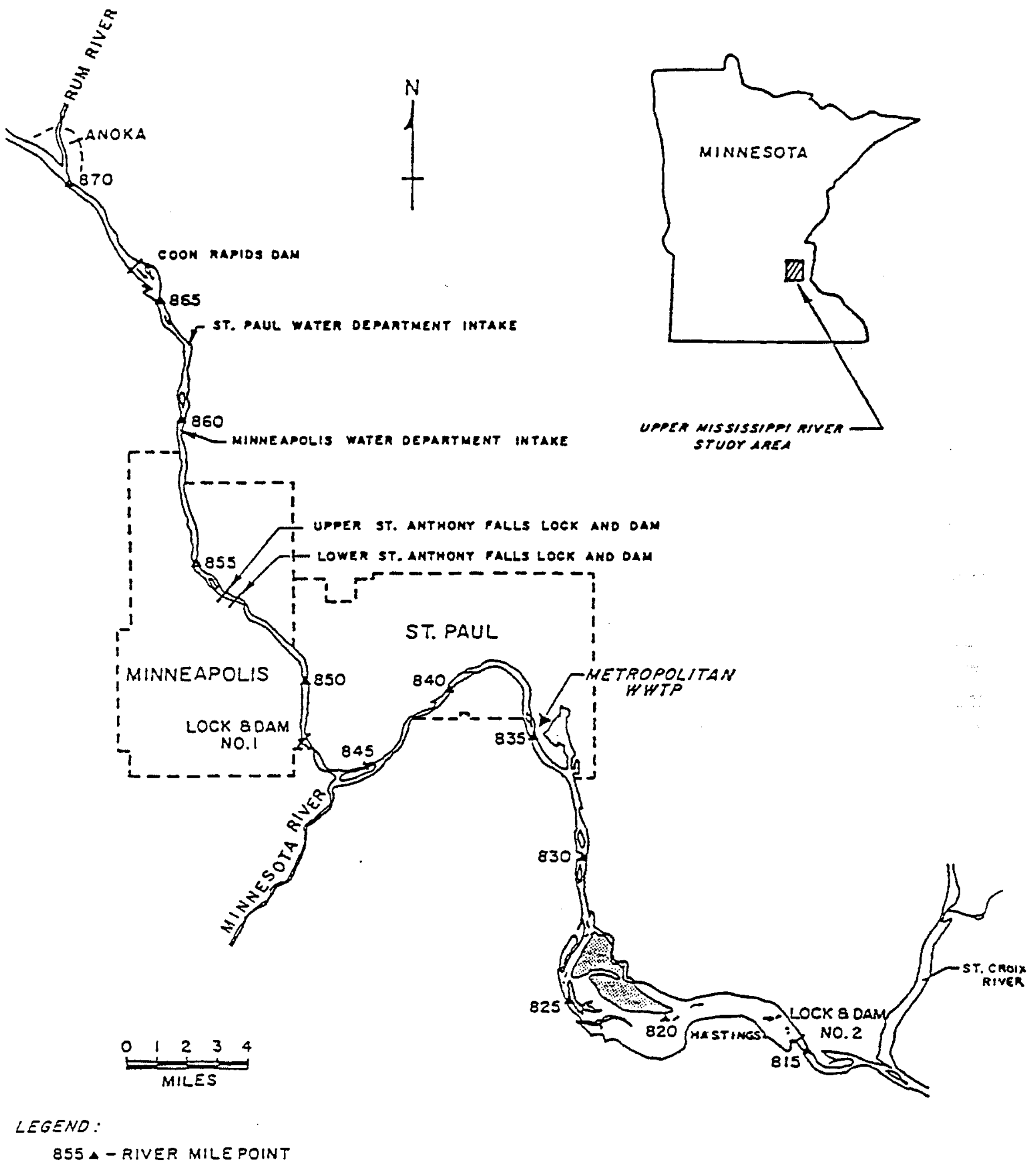
The newly established 7Q10 of 1910 cfs will allow additional pollutant assimilation capacity over the previous 7Q10 of 1708 cfs. Promotion of future consumptive uses of TCMA streamflows that will result in the reduction of 7Q10 flows is a short-sighted measure that will require increasingly more advanced degrees of wastewater treatment to handle current facility loads, irrespective of the additional loads continued growth in the area will create. Incremental increases in required levels of wastewater treatment to meet increasingly more stringent effluent limitations are possible only through the investment of incrementally larger sums of money to construct, operate, and maintain those facilities.

TCMA Stream Basins

Over 1.5 million square miles of the vast center of the United States and Canada is drained by the Mississippi River to the Gulf of Mexico near New Orleans, Louisiana. The confluence of the Mississippi and Ohio Rivers, designated as river mile (RM) 0, is used as a break point between upper and lower reaches of the Mississippi River. Points along the river, up to its origin in Minnesota's Lake Itasca, are defined by their distance above that confluence. A series of 29 locks and dams have been built above St. Louis, Missouri to enable the Upper Mississippi River to be used as an inland waterway. As indicated on Figure 1, there are five dams within the TCMA that form a series of controlled backwater pools, with constant water surface elevations. The only free flowing river reach within the TCMA has a slope of 2.0 feet per mile and extends from below Coon Rapids Dam near RM 867 to approximately RM 861. Within the 0.4 miles from the Upper to the Lower Dams at St. Anthony Falls, the river descends approximately 75 feet. The Mississippi River descends a total of 143 feet in the 52 mile stretch from the Coon Rapids Dam to the Hastings Pool behind Lock and Dam No. 2 (Corps, 1990).

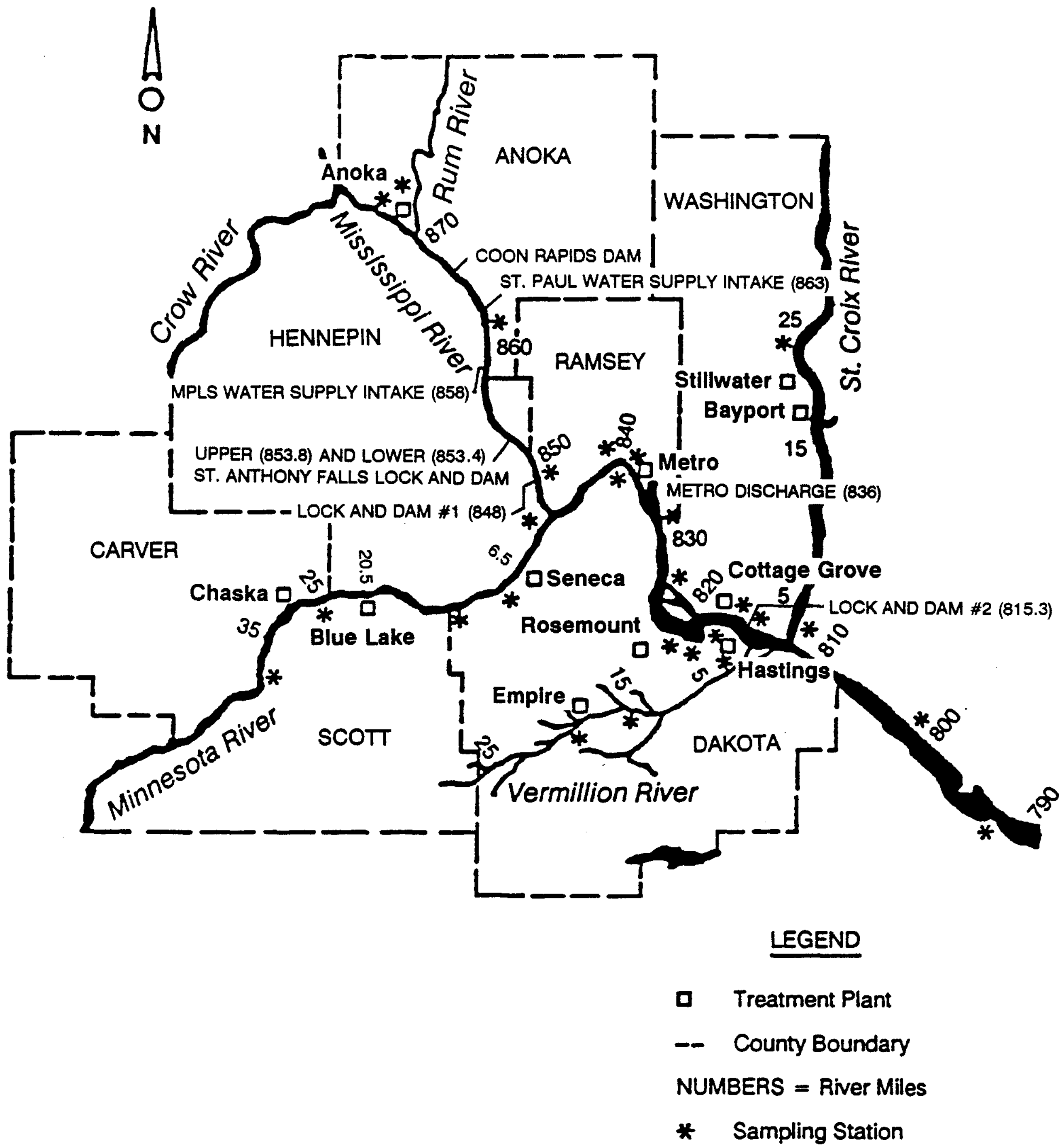
Within the seven county TCMA as shown in Figure 2, five major tributary streams contribute flow to the Mississippi River and therefore affect its quality: the Crow, Rum, Minnesota, Vermillion, and St. Croix Rivers. Each of these rivers is a recipient of treated municipal wastewater prior to its discharge into the Mississippi River.

Figure 1
MAP OF UPPER MISSISSIPPI RIVER STUDY AREA



Source: Hydroscience, 1979

Figure 2
TWIN CITIES METROPOLITAN AREA WATER QUALITY MONITORING NETWORK



In general, the valleys of the Mississippi, Minnesota, and St. Croix Rivers act as principal regional drains for the bedrock aquifers as well as the surficial glacial drift deposits. They form important hydraulic boundaries to all local aquifers. The valleys of the Rum, Crow, and Vermillion lie in drift deposits and generally have not cut down to bedrock. Sufficient long-term lowering of the head in wells near TCMA rivers due to future increases in ground water withdrawals could have the effect of reducing inflow to the rivers or even leakage of surface water into the aquifers. That inflow is currently depended upon for navigation, wastewater assimilation, public water supplies, power production, and many other uses, especially during periods of extreme low flow (Schoenberg, 1990).

Water Quality Rules And Regulations

Clean Water Act

The Federal Clean Water Act (Act) of 1972 and its amendments have established national water quality goals. The ultimate objective of the Act, as established by the United States Congress, is to "restore and maintain the chemical, physical and biological integrity of the nation's waters." The national goal of the act is to eliminate the discharge of pollutants into navigable waters; and wherever attainable, the water quality is to be sufficient to support fish, shellfish, wildlife, and recreational activities both in and on the waters. The EPA has the responsibility of establishing national criteria for significant pollutants. The goals of the act are implemented nationally and locally by the establishment of water quality standards and criteria.

The MPCA has been delegated certain program functions by EPA under the appropriate provisions of the act, including the NPDES program. MPCA has adopted national standards and criteria, and established some more stringent state-specific standards and criteria for pollutants that are of specific importance to Minnesota's waterways. These water quality standards are applied through the NPDES program by requiring each discharger to a river or other receiving water to hold a permit specifying the method of treatment, allowable maximum effluent characteristic limitations, monitoring and reporting requirements, and other related information. Federal law and the MPCA require all point source dischargers of sewage in the state of Minnesota to remove pollutants to minimum secondary wastewater treatment levels, as indicated in Table 1. More stringent levels of treatment can be required by MPCA if warranted by special conditions in the receiving water or by the special character of the wastewater discharge. Maximum allowable permit effluent pollutant levels are established in each case to prevent the receiving water from exceeding applicable water quality standards or criteria, and to allow the water body to meet its specific water quality goals (Oberts, 1987).

Pollution Sources

Water containing one or more diverse types of impurities may be said to be polluted. Pollution is the term typically assigned to an effluent or discharge considered potentially harmful to human health or capable of seriously interfering with the use of its receiving water or its immediate environment. Point sources of pollution are characterized by end-of-pipe discharges of domestic sewage or industrial waste byproducts. These types of pollution require NPDES permits to discharge to a receiving water (EPA, 1977).

Table 1

WASTEWATER TREATMENT PLANT SECONDARY EFFLUENT LIMITS[4]

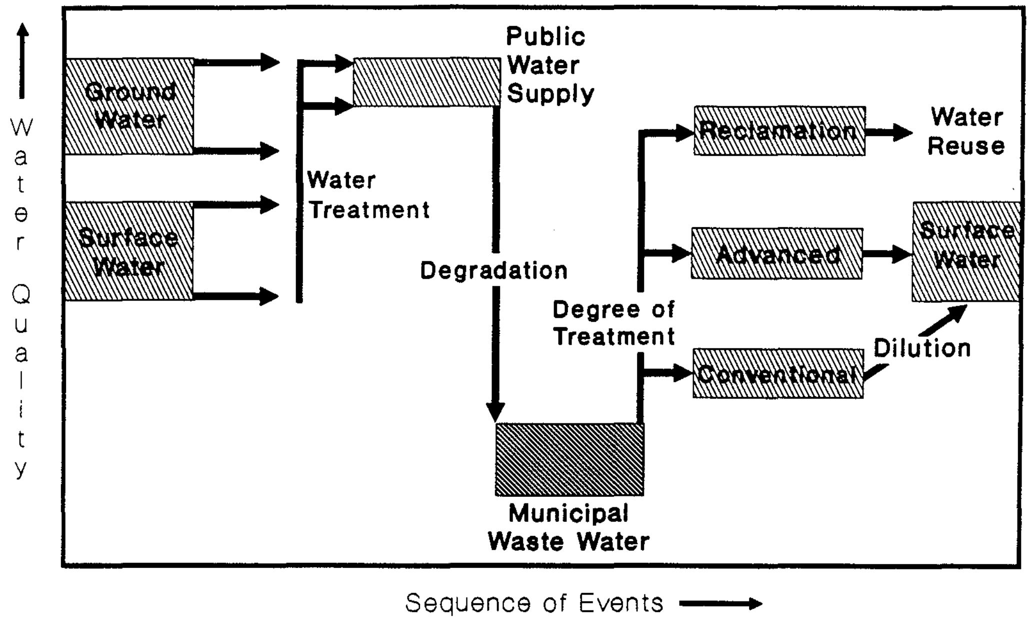
Substance or Characteristic	Limiting Concentration or Range[1]
5-Day carbonaceous biochemical oxygen demand[1]	25 milligrams per liter
Fecal coliform group organisms[3]	200 organisms per 100 milliliters
Total suspended solids[1]	30 milligrams per liter
Oil	Essentially free of visible oil
Phosphorus[2]	1 milligram per liter
pH range	6.0 - 9.0
Toxic or corrosive pollutants	See footnote[5]

1. The arithmetic mean for concentrations of five-day carbonaceous biochemical oxygen demand and total suspended solids shall not exceed the stated values in any calendar month. In any calendar week, the arithmetic mean for concentrations of five-day carbonaceous biochemical oxygen demand shall not exceed 40 milligrams per liter and total suspended solids shall not exceed 45 milligrams per liter.
2. Where the discharge of effluent is directly to or affects a lake or reservoir, phosphorus removal to one milligram per liter shall be required. In addition, removal of nutrients from all wastes shall be provided to the fullest practicable extent wherever sources of nutrients are considered to be actually or potentially detrimental to preservation or enhancement of the designated water uses. Dischargers required to control nutrients by this subpart are subject to the variance provisions of part 7050.0190.
3. Disinfection of wastewater effluents to reduce the levels of fecal coliform organisms to the stated value is required from March 1 through October 31 (Class 2 waters) and May 1 through October 31 (Class 7 waters) except that where the effluent is discharged 25 miles or less upstream of a water intake supplying a potable water system, the reduction to the stated value is required year around. The stated value is not to be exceeded in any calendar month as determined by the geometric mean of all the samples collected in a given calendar month. The application of the fecal coliform group organism standards shall be limited to sewage or other effluents containing admixtures of sewage and shall not apply to industrial wastes except where the presence of sewage, fecal coliform organisms, or viable pathogenic organisms in such wastes is known or reasonably certain. Analysis of samples for fecal coliform group organisms by either the multiple tube fermentation or the membrane filter techniques is acceptable.
4. With exception for some trickling filter and stabilization pond facilities.
5. Concentrations of toxic or corrosive pollutants shall not cause acute toxicity to humans or other animals or plant life or directly damage real property or exceed the final acute value unless the effluent satisfies the whole effluent toxicity test below. If a whole effluent toxicity test performed on the effluent results in less than 50 percent mortality of the test organisms, the effluent will not be considered acutely toxic unless the commissioner finds that the test species do not represent sensitive organisms in the affected surface water body or the whole effluent test was performed on a sample not representative of the effluent quality. The final acute value and whole effluent toxicity test are defined in part 7050.0218, subpart 3, items O and FF, respectively.

Source: State, 1991

Figure 3

WATER QUALITY CHANGES RESULTING FROM MUNICIPAL USE



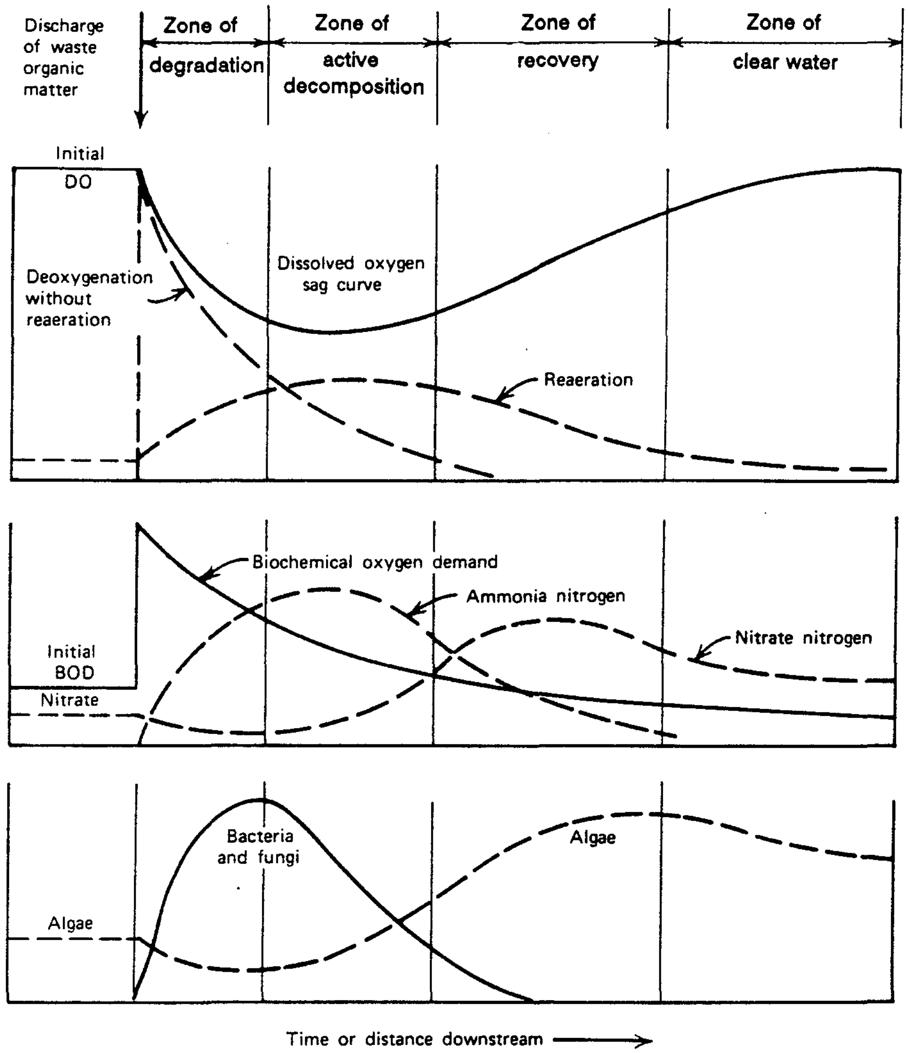
Source: Hammer, 1975

The best understood problem caused by most types of stream pollution is oxygen deficiency within streams. The cause of the oxygen deficiency is the presence of an excessive amount of degradable organic matter in the pollution. The best way to prevent this deficiency is to oxidize most or all of the organic matter prior to discharging the wastewater into streams, through a variety of methods of wastewater treatment. Figure 3 provides a graphical presentation of general water quality changes that result from municipal uses of water, and the degrees of treatment necessary for reuse of that water.

Figure 4 identifies many changes in water quality criteria that occur in a stream in response to receiving discharge from a point source of organic pollutants.

An alternative to establishing progressively more restrictive effluent permit limitations for a discharger that is utilizing a river's full assimilative capacity is a measurable and permanent reduction in pollutant loadings from upstream sources. Nonpoint source pollution, often a major component of in-stream pollutant loads, is a result of poor land and water resource management practices that allow runoff and erosion of fields, ditches, and stream banks. Nutrients, sediment, bacteria, toxic chemicals, and other pollutants can be transported from both rural and urban areas into surface and ground water.

Figure 4
GENERALIZED EFFECTS OF ORGANIC POLLUTION ON A STREAM



Source: Hammer, 1975

Major sources of nonpoint pollution include the misuse of pesticides and fertilizers; erosion from cropland and rural construction sites; urban runoff from city streets, yards, and urban construction sites; leachate from septic systems; runoff from forestry and mining activities; highway de-icing chemicals; dredging and drainage activities; and the impacts from the loss of wetlands (WSWCD, 1991).

The MPCA and EPA entered into an agreement during 1990 that established a goal of reducing nonpoint source pollution in the Lower Minnesota River by 40% from levels measured and presented in the Metropolitan Waste Control Commission's (MWCC) 1980 Minnesota River Low Flow Survey. The Metropolitan Council (Council), MPCA, and all watershed organizations in the Minnesota River Basin are working cooperatively on determining methods to achieve this goal, to be accomplished by July 1, 1996. The new NPDES permit limits requiring increased levels of treatment for the MWCC's two largest wastewater treatment plants (WWTPs) on the Minnesota River, the Blue Lake and Seneca plants that are currently being upgraded, assume the 40% reduction in nonpoint pollution to the River will be achieved.

Water Quality Standards

The MPCA has authority to establish water quality standards for all designated water use classifications, set effluent limitations, and enforce compliance of these limitations for all waters within the state. Each body of water has been evaluated and classified as to its current and best potential use. Water use classes and subclasses are defined in Minnesota Rules 7050.0200 and 7050.0220. All streams in the state have been assigned one or more of the seven use classifications as outlined in Minnesota Rules 7050.0400 through 7050.0470. Table 2 provides a listing of the classes.

Table 2
WATER USE CLASSIFICATION

Class	Designated Uses
1	Domestic consumption; food processing
2	Fisheries and recreation; protection of aquatic life
3	Industrial consumption or cooling water
4	Agriculture and wildlife; stock watering; irrigation
5	Aesthetic enjoyment and navigation
6	Other beneficial uses
7	Limited resource value waters; intermittent flow

Table 3

WATER QUALITY STANDARDS FOR METROPOLITAN AREA WATERS: MINNESOTA RULES, 1991, CHAPTER 7050

TCMA Water and Classification	Dissolved Oxygen (mg/l)	Ammonia as N (µg/l) un-ionized	Fecal Coliform (organisms/ 100 ml)	Chlorine Residual (µg/l)	Temperature	Turbidity (NTU)
Class 2Bd • Mississippi River (to USAF Lock and Dam) • St. Croix River Class 2B • Mississippi River* • Minnesota River* • Vermillion River • Rum River • Crow River • All other waters not specifically designated elsewhere.	5.0 daily minimum	40	200 geometric mean not to exceed 2000 in 10% of samples March 1 to Oct. 31	6	5°F above natural in streams 3°F above natural in lakes 86°F max.	25
Class 2C • Minnesota River (River Mile 22 to Mouth) • Mississippi River: a) Metro Plant to River Mile 830 Class 2B • b) River Mile 830 to Lock and Dam 2 (River Mile 815)	5.0 minimum daily average ----------------------- 5.0 minimum daily average April 1 to Nov. 30 4.0 minimum at all other times	40	200 geometric mean not to exceed 2000 in 10% of samples March 1 to Oct. 31	6	5°F above natural in streams 3°F above natural in lakes 90°F max. ------------------- 5°F above natural in streams 3°F above natural in lakes 86°F max.	25

TCMA Water and Classification	Dissolved Oxygen (mg/l)	Ammonia as N (μg/l) un-ionized	Fecal Coliform (organisms/ 100 ml)	Chlorine Residual (μg/l)	Temperature	Turbidity (NTU)
Class 1B, 2A • Trout Waters	7.0 daily minimum	16	200 geometric mean not to exceed 400 in 10% of samples March 1 to Oct.31	6	No material increase	5
Class 7 • Unnamed ditch and swamp, Hampton • Unnamed ditch, Bongard's • Unnamed ditch, Freeway Landfill • County Ditch No. 4, Norwood • Unnamed stream, Savage	1.0 minimum daily average, and measurable at all times	variable	1000 geometric mean, not to exceed 2000 in more than 10% of samples May 1 - Oct. 31			

*All segments except as noted.

Most of these seven use classes are further broken down into subclasses that further define their quality. Each use has a specific set of water quality standards that must be maintained in order for the stream to support that particular use. Table 3 lists selected water quality standards for TCMA waters. Use classifications of waters can be defined as any administrative classification done with the avowed intention that all waters assigned to a given class shall be maintained in, or returned to, a condition suitable for the same beneficial use or uses through the enforcement of appropriate water quality standards (EPA, 2/73). If a stream or stream segment has more than one use classification, all of the water quality standards for each of the classes apply, with the most restrictive numerical standards applying toward overlapping parameters, in an effort to protect all of the designated uses.

State law dictates that the water quality standards must be reviewed (and revised if necessary) every three years. The 1981 revisions to state water quality rules included a new water quality standard of 40 micrograms per liter (μg/l) for un-ionized ammonia that replaced the former standard of 1.0 milligram per liter (mg/l) for total ammonia nitrogen. The 1984 revisions included a change that redefined effluent limitations from units of 5-day biochemical oxygen demand (BOD_5) to 5-day carbonaceous biochemical oxygen demand ($CBOD_5$). The 1987 revisions were quite extensive. A site-specific dissolved oxygen (DO) standard for the Lower Minnesota River was adopted, and a state-wide repeal of site-specific effluent standards that affected the Vermillion River was put into place to provide uniformity in effluent rules. An expanded policy regarding nondegradation of state waters was also adopted, as well as an initial policy regarding nonpoint sources of pollution resulting from agricultural and urban runoff. The 1990 review resulted in the addition of water quality criteria for toxic pollutants, and the creation of a subclass of 2B waters (2Bd) that are now protected as a source of drinking water (State, 1991).

Water quality criteria may be designed for total protection of valuable fish populations, allowing virtually no impairment or risk of impairment of their growth, or they can be designed for various lower levels of protection that would merely limit possible impairment of their production. Average natural DO levels are often below saturation levels in streams, and therefore create natural levels of impaired growth and production rates of fish and phytoplankton, independent of human activities. When establishing water quality criteria for the protection of a stream, the potential cost to industry and municipalities of providing additional degrees of wastewater treatment must be taken into consideration. State statutes require MPCA to give "due consideration" to economic factors when establishing effluent discharge limitations for wastewater treatment facilities (MPCA, 1981).

Prior to instituting more stringent effluent limitations for a facility, an economic analysis of the proposed modification must first indicate the impacts upon the regional economy. All methods of incrementally raising DO concentrations or lowering nutrient concentrations of pollutants to receiving waters should be carefully weighed when establishing specific minimum acceptable DO levels for a stream. A broad zone of transition exists - from DO saturation down to levels that are known to result in impaired productivity and growth of fish populations (EPA, February 1973).

Waste Load Allocation

A waste load allocation (WLA) study is an analysis of a river to determine its capacity to assimilate organic pollution. It is based in general on the Streeter-Phelps theory that DO levels in rivers are controlled by two main mechanisms - biochemical oxidation of organic matter, and atmospheric reaeration of water in the river. The cumulative effect of discharge of pollution from one or more sources into a river can exceed the river's assimilative capacity, resulting in degradation of water quality and probable environmental damage. When routine water quality monitoring of point source discharges and river flow indicates degradation is occurring in a river, MPCA conducts a WLA study to determine the maximum pollutant loading that the river can safely assimilate. The MPCA then assigns effluent limitations to point source dischargers so that their current and projected loadings, when combined with the river's background loadings, will not exceed the total assimilative capacity of the river.

A WLA study can often recommend more stringent NPDES permit effluent characteristic concentrations and mass limitations for a WWTP. The TCMA is a developing area that is nearing its river-assimilative-capacity on some receiving streams. Additional contributions of pollutants from new sources, and flow or strength increases from existing sources to WWTPs, result in periodic plant upgrades to provide increased levels of treatment to maintain or improve a level of instream water quality. Increased levels of treatment tend to be progressively more complicated and costly to construct, operate and maintain.

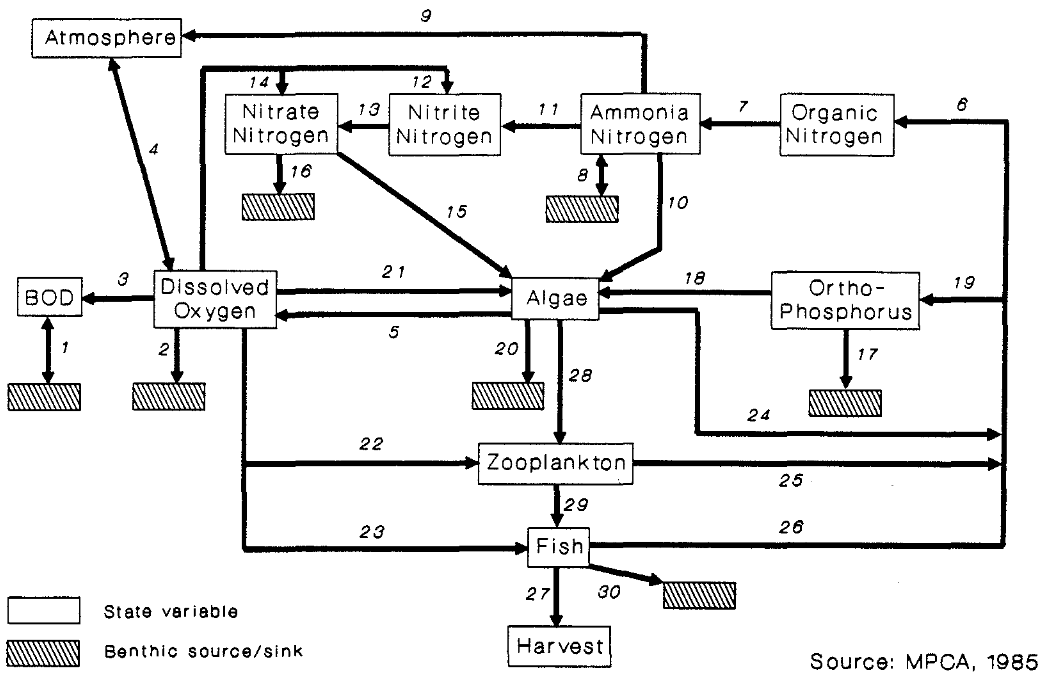
A river WLA study establishes the quantitative relationships between waste load discharges and water quality impacts. Using these relationships, incremental changes in effluent loadings can be compared to the incremental changes expected in the concentration of specific constituents in the receiving water. This information is used by the MPCA to identify the maximum permissible loads that can be discharged into a receiving water by all dischargers without violating water quality standards. WLA studies are performed with the use of water quality models that simulate the natural processes affecting each reach of the river being studied.

The model utilized for the lower Minnesota River WLA study in 1985 and 1986 was RMA-12, a one-dimensional, steady state version of the QUAL II model as refined by W.R. Norton of Resource Management Associates (Norton, 1977). This model combines the basic mathematically conceptualized DO reactions involving organic sediments, algal respiration and nitrification with the mass balance equations involving stream convection and eddy diffusion, local stream morphology, and water quality constituents of each individual stream discharge or sink and their change over time. Figure 5 displays the range of interactions replicated by the stream water quality model RMA-12. Time dependent reaction kinetics for physical, chemical, and biological reactions are initiated separately for each constituent. Use of this version of the QUAL II model allowed low stream flow conditions to be more accurately simulated through a redefinition of the nitrogen cycle that allowed direct uptake of ammonia-nitrogen by algal biomass.

A different model has been used for allocation studies on the Mississippi River. The RMA-12 model used on the Minnesota does not effectively simulate the processes at work in the "reservoir" system of the Mississippi that occur in the reach above Lock and Dam No. 2 known as the Hastings Pool. Hydroscience, Incorporated, developed the AESOP model in 1979 for the MWCC to simulate the interactions between DO, phytoplankton, CBOD, and the nitrogen and phosphorus cycles at work within the Mississippi River. This model was successfully calibrated using data from the August 1976 and winter of 1977 low flow surveys (Hydroscience, 1979 and MPCA, 1981).

Great care must be taken in calibrating a water quality model to insure that it accurately represents the natural processes affecting water quality within each reach of the specific river being evaluated. Data used in modeling to predict future background water quality conditions is typically the median of measured data, so that the corresponding output provided by the model represents the anticipated typical or median response of the river. WLA studies of rivers within the TCMA have all been calibrated with the use of current low flow water quality survey data and the historic flow and water quality data base available for each river. DO-CBOD models are best calibrated under low flow, low temperature (winter) conditions when the complicating effects of a larger phytoplankton population are minimized. Phytoplankton-nutrient models are best calibrated under low flow, high temperature (summer) conditions when instream plant and animal growth is most favorable. During summer low flow periods, maintenance of acceptable levels of instream water quality is highly dependent upon phytoplankton for their contribution of DO, when other natural reaeration mechanisms are at their lowest levels of contribution.

Figure 5
WATER QUALITY INTERACTIONS FOR THE STREAM QUALITY MODEL RMA-12



Stream Flow

Water quality standards must relate directly to the quantity of flow in a stream; the greater the streamflow, the more pollutants it can assimilate without violating water quality standards. Similarly, the lower the streamflow, the higher the probability of diminished water quality. Industry and power generation facilities requiring a constant supply of cooling water recognize the value of sites along streams with high minimum flows. It is estimated that there are less than 200 rivers in the United States with minimum flows in excess of 50 cfs. The TCMA is located at the confluence of three of those rivers; the Mississippi, Minnesota, and St. Croix Rivers (Nemerow, 1974).

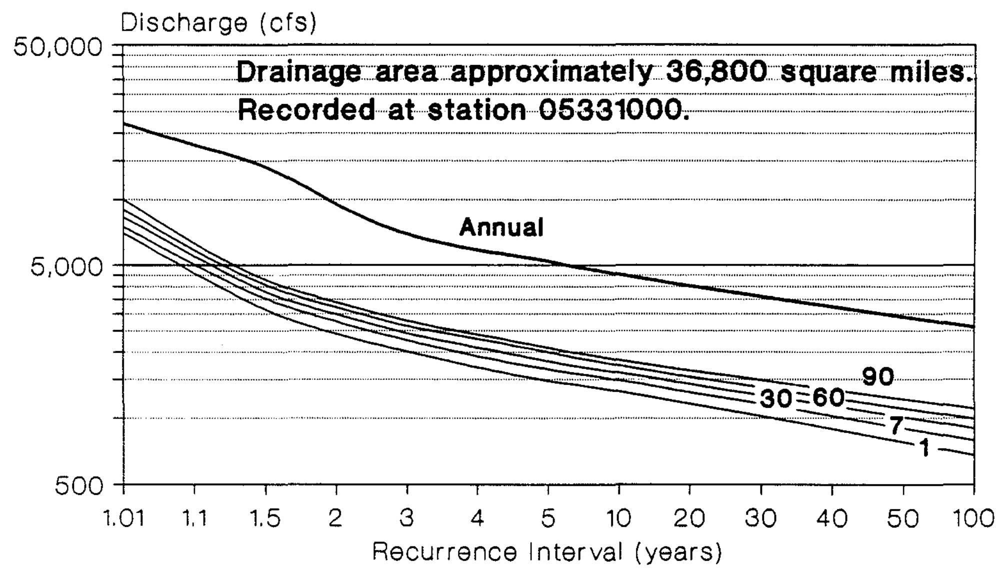
Stream flows fluctuate seasonally in response to changing meteorological conditions. Maximum TCMA stream flows typically coincide with spring snowmelt during March and April. Rains during late spring and early summer can either maintain these higher spring flows or create temporary periods of elevated streamflow throughout mid-summer. Flow rates usually taper off during the summer, continuing to fall to a yearly low flow during late winter. Most violations of in-stream water quality standards occur during summer periods of concurrent low stream flow, high water temperatures, and highest levels of water demand. Incremental increases in temperature have a two-fold effect of increasing biochemical deoxygenation rates, and reducing the concentration of oxygen that water is capable of maintaining in solution. Low stream flows also decrease the dilution potential for toxic pollutants such as ammonia and chlorine.

Low-flow-frequency curves are the primary tools used to determine availability of streamflow for human use. Curves of this type are derived by determining the lowest average flow for periods ranging from one to 365 consecutive days in a given year. These data are compiled for each year of record and then analyzed to determine the statistical frequency of various magnitudes of flow. Figure 6 depicts typical historic low-flow curves for periods of 1, 7, 30, 60, 90, and 365 days (annual) at the St. Paul gaging station on the Mississippi River (Council, 1973).

Minnesota Rule Part 7050.0210 requires that point source effluent limitations adequately protect stream water quality at flows equal to and greater than the established minimum 7Q10 flow for the critical months. The 7Q10 flow represents a 7-day average low flow which statistically recurs once in each 10-year period or has a 10% chance of occurring in any given year. NPDES permit effluent concentration limitations are still required to be met during periods when receiving stream flows fall below established 7Q10 values, but the legal responsibility of maintaining the minimum established acceptable stream water quality criteria is not applicable. Sufficient habitat volume remains in rivers at the 7Q10 flow rate to maintain fish and other aquatic life.

Figure 6

Figure 6
MAGNITUDE AND FREQUENCY OF LOW FLOWS FOR THE MISSISSIPPI RIVER AT ST. PAUL



Based on period 1895, 1897, 1901-1905, 1907-1967.
Source: Metro Council, 1973

The MWCC operates an automatic monitoring system in cooperation with the U.S. Geological Survey's (USGS) nation-wide continuous stream flow monitoring program involving major streams in the TCMA. The 7Q10 flow for each stream reach is a calculated value that is constantly undergoing change over time. Updated 7Q10 values are statistically recomputed as current flow data is added to the established data base. In addition to flow data, the monitoring system operated by the MWCC and the USGS continuously measures and records stream temperature, pH, DO, and specific conductance. These parameters provide a data record that can be used to observe water quality fluctuations due to pollutant discharges and the natural daily parameter oscillations that are a result of the photosynthetic cycle of aquatic plants (Corps, 1990).

When a WLA study indicates conventional secondary treatment levels are unable to maintain stream water quality, the stream or segments of the stream are designated as being "water quality limited", requiring more stringent levels of treatment for dischargers under specific, critical stream conditions. These advanced levels of treatment are typically only seasonally required, being applied to the specific time periods during which the stream is least able to assimilate pollutants in waste loads. Although the lowest 7Q10 flows historically occur during the winter season for local streams, the months during which more stringent limits are applied to local dischargers are the months of June through September. This time period corresponds with the period of peak biological activity and greatest daily fluctuations in DO. Allowing the resumption of a less stringent secondary level of treatment during the remainder of the year, if determined by MPCA to adequately protect water quality in the river, can dramatically reduce capital and operating costs for a WWTP (MPCA, 1981).

The MPCA has established effluent standards criteria that may be applied to advanced wastewater treatment facilities without any allowance for instream dilution. These criteria may be the only future alternative for some MWCC facilities where continued expansions are anticipated to be necessary, and the projected effluent assimilative capacity of receiving stream flows would be inadequate to protect their relegated water quality standards. To meet these criteria, a wastewater treatment facility would need to be designed and constructed to consistently meet a more restrictive effluent $CBOD_5$ limitation of 5 mg/l, in addition to all other currently applicable effluent limitations. This level of treatment has not been evaluated to date for any MWCC treatment facilities.

Water Quality Parameters

The quality of water is determined by analytically measuring the concentrations of its various constituents, and assessing the effects caused by the presence of those substances. All surface waters contain dissolved and suspended materials. Some of these materials serve as nutrients, supporting the growth of microscopic phytoplankton (plants) and zooplankton (animals). Knowing the following characteristics of a surface water is necessary in order to define its potential beneficial uses.

Dissolved Oxygen

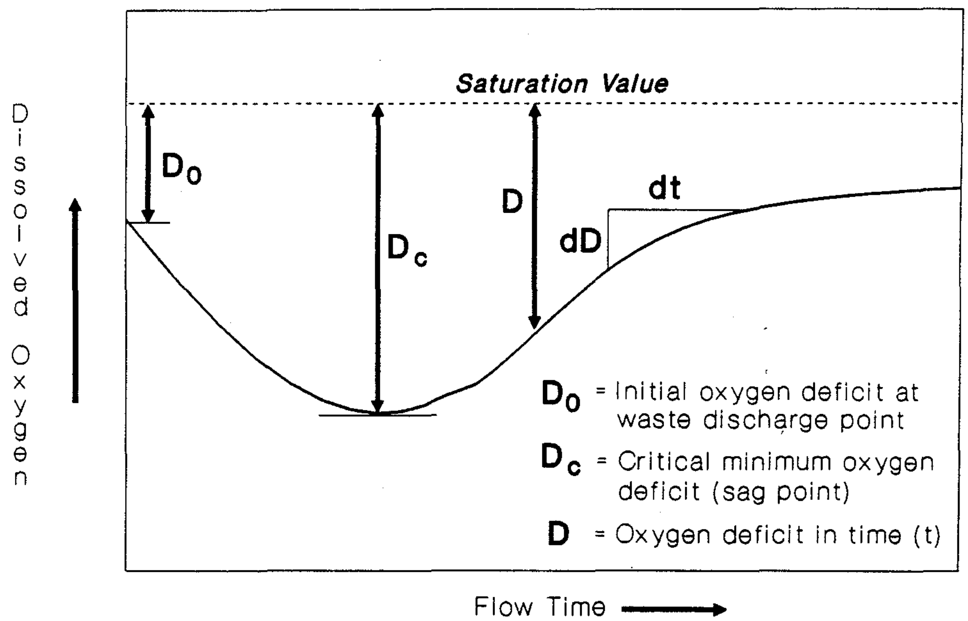
DO is historically considered to be the primary indicator of water quality. It manifests a stream's general health as well as its capacity to support a balanced ecological system. Streamwater DO is the chemical constituent most frequently measured in observing the effect of organic pollution on streams. This determination is accomplished through a controlled test utilizing the natural biological processes of decay, in ascertaining the water's biochemical oxygen demand (BOD). When pollutants are discharged into a stream, their organic material components exert an oxygen demand in the stream. In certain situations, inorganic materials (like sulfides and ferrous iron) present in pollutants can also exert an oxygen demand in the stream. The oxygen requirements to satisfy these demands are obtained from the oxygen dissolved in the river water. If the demand for oxygen exceeds the amount available, the stream's DO can be exhausted, resulting in anoxic conditions in the stream. Typically, bacteria will utilize the oxygen in nitrates first, after DO is exhausted, and then they will use the oxygen from sulfates, resulting in the production of hydrogen sulfide. These reactions can cause foul odors, the death of aquatic life, and other nuisance conditions. The stream criteria having the greatest effect upon the level of DO during periods of low stream flow are its temperature, pH, CBOD, and concentrations of ammonia nitrogen and ortho-phosphorus. These and several other supporting criteria and constituents will be discussed later in this paper (Nemerow, 1974).

The list of oxygen sinks in any stream is a long one. Included on the list are: 1) organic matter in the continuously flowing water; 2) slime growths on rocks, debris, shorelines, and other surfaces over which the water flows; 3) the sediment oxygen demand of river bottom deposits, dead phytoplankton, and bottom-dwelling organisms; 4) temperature increases that cause oxygen vapor loss and an increase in microbiological metabolism; 5) fish and other aquatic organisms' respiration needs; 6) organic contamination from tributary streams; 7) salinity; and 8) nonpoint sources of pollution. Typical oxygen providers in a stream include reaeration due to the physical reaction at the air-water interface; plant photosynthesis; temperature decreases, which result in an increase in oxygen saturation potential and decrease in microbiological activity; and dilution from uncontaminated, oxygenated tributary streams (Nemerow, 1974).

At constant temperature, the demand rate for oxygen by (pollutant) organic matter in a stream will decrease as the distance (flow time) from the point of pollutant injection increases. Figure 7 indicates the effects of an organic waste discharge upon instream DO levels. All pollutants do not "demand" oxygen at a uniform rate, however. Candy manufacturing plant wastes for example, have a high sugar (carbohydrate) content and typically exert a large immediate oxygen demand. Carbohydrates are the primary building blocks of plant proteins and plant and animal supporting tissues, and can be easily and quickly assimilated. On the other hand, a waste from a paper pulp mill containing predominantly cellulose will exert a slower oxygen demand in a stream because most plankton lack the enzymes necessary to digest cellulose as a food source (Nemerow, 1974).

Turbulence at the air-water interface permits oxygen to dissolve in water that is not saturated with oxygen. Although nitrogen is approximately four times more abundant than oxygen in the Earth's atmosphere (78% versus 21% by volume), oxygen is more than twice as soluble in water as nitrogen. The amount of oxygen water will absorb depends upon the water's temperature, salinity, and pressure. Table 4 lists the respective DO saturation values for unpolluted, potable water at standard atmospheric pressure, over a range of actual water temperatures. In general, cold water absorbs more oxygen than warm water; increasing levels of salinity decrease solubility levels; and, increases in atmospheric pressure result in increases in oxygen solubility. Atmospheric reaeration is severely curtailed during periods of extreme cold by the formation of ice over the surface of streams (Cole, 1979).

Figure 7
DISSOLVED OXYGEN-SAG CURVE



Source: Clark, Viessman and Hammer, 1977

Supersaturation of water with DO can occur in a stream in three primary ways. First, it can occur naturally as a result of extreme turbulence at the air-water interface. Second, production of oxygen by photosynthetic activity (during the day) of a sufficient population of phytoplankton can exceed the total daytime level of oxygen consumption (i.e. algal cells generate about 1.5 times the oxygen they consume). This type of natural oxygen supersaturation in rivers and lakes is the most common. Lastly, water can be supersaturated with DO by artificial means involving the turbulent cascading of water through either atmospheric air or an enriched oxygen atmosphere within a confined space. The latter method will be specifically discussed later in the paper relative to the MWCC Seneca WWTP's discharge to the Minnesota River.

Levels of in-stream DO greatly affect fish growth and population dynamics. Studies have shown that progressive reductions in the oxygen concentration in streams can result in a reduction in size, a delay in hatching, and an increase in mortality rate of fish embryos. When food availability is not limiting to the growth of juvenile fish in a stream, their growth rate is often dependent upon the DO concentration, as long as temperatures are favorable for growth. Optimal food consumption and growth rates of fish tend to occur near the oxygen saturation level in a stream. As DO levels progressively decrease, the efficiency of food conversion by fish becomes impaired, eventually reaching a point where growth is prevented entirely. Different species of fish have different threshold impairment levels. In-stream DO levels typically are a primary controlling factor in defining the spacial distribution of different species of fish (EPA, 1973).

Table 4

OXYGEN SATURATION AT STANDARD PRESSURE AND ACTUAL WATER TEMPERATURES

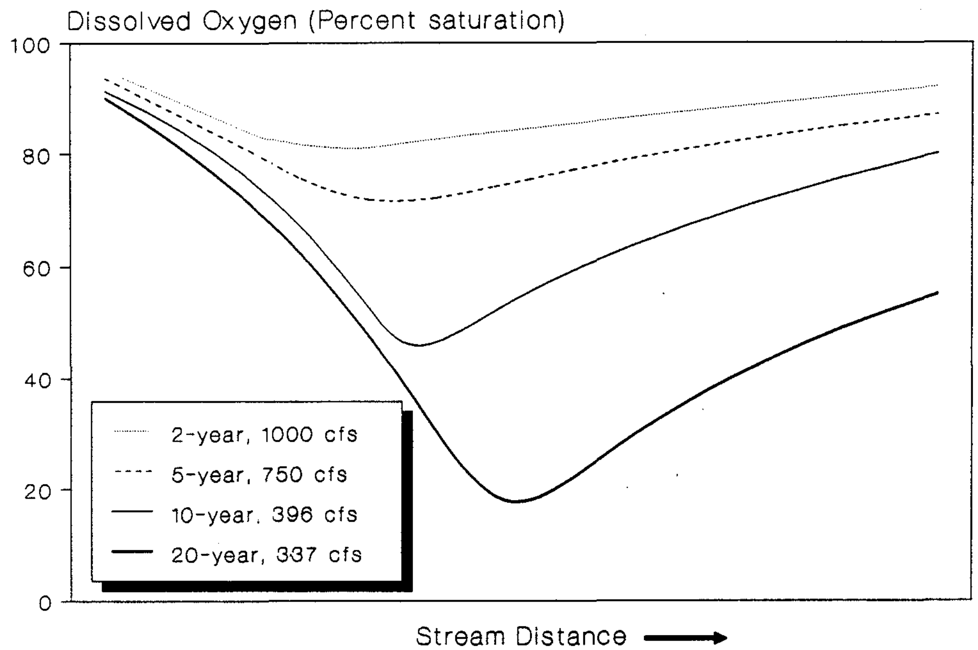
Temperature °C	Dissolved Oxygen Saturation Level mg/l	Temperature °C	Dissolved Oxygen Saturation Level mg/l
0	14.62	16	9.95
1	14.23	17	9.74
2	13.84	18	9.54
3	13.48	19	9.35
4	13.13	20	9.17
5	12.80	21	8.99
6	12.48	22	8.83
7	12.17	23	8.68
8	11.87	24	8.53
9	11.59	25	8.38
10	11.33	26	8.22
11	11.09	27	8.07
12	10.83	28	7.92
13	10.60	29	7.77
14	10.37	30	7.63
15	10.15		

Source: EPA, July 1989

Figure 8 contains a set of typical DO profiles that could be observed in a hypothetical stream during a summer drought period with flow rates declining from 1000 cfs to 337 cfs. The weekly average low flow of 1000 cfs is anticipated once every two years (7Q2); 750 cfs, once every five years (7Q5); 396 cfs, once every 10 years (7Q10); and 337 cfs, once every 20 years (7Q20). The 7Q20 flow is just 59 cfs less than the 7Q10 flow, but produces an instream DO depression that almost depletes the oxygen in the stream. Therefore, as flows continue to decline in a stream, DO levels can diminish at an accelerated rate, as these profiles indicate (Nemerow, 1974).

During the extreme low flow period in the summer of 1988, morning sampling indicated DO was present in the St. Croix River near Prescott at an average concentration of over 97% of saturation. In the Minnesota River during this same period of time, DO was present near Jordan at a concentration of 93% of saturation. Near its confluence with the Mississippi River, however, DO was only present at an average mid-morning concentration of 56% of saturation, an average of 4.6 mg/l. During this three month period in 1988, less than 20% of the DO measurements in the Minnesota River near its mouth were greater than 5 mg/l. During this same time period, mid-morning DO measurements ranged from 91% to 121%, averaging 102% of saturation, within the Mississippi River at Anoka. As flow left the TCMA, the instream DO measurements ranged from 79% to 123%, averaging 98% of saturation. Instream Mississippi River DO measurements below the confluence of the Minnesota River exhibited mid-morning instantaneous averages of 74% of saturation. The greatest amount of DO variability in the Mississippi River during the summer low flow period in 1988 was observed in the instream pool above Lock and Dam No. 2. DO ranged from 46% of saturation before effluent oxygenation was instituted at the Metro WWTP in early June, to daily maximum levels exceeding 200% of saturation as a result of the presence of optimum conditions for intense algal activity (MWCC, March 1990 and Corps, 1990).

Figure 8
DROUGHT FLOWS AFFECTING OXYGEN SAG



Source: Nemerow, 1974

BOD

The BOD test is the most widely used method by scientists for evaluating the biochemical demand for oxygen within a stream. The BOD value of a water sample represents the amount of oxygen in mg/l that would be required by bacteria to aerobically decompose organic matter present in the sample in a given period of time at a uniform stated temperature. The biochemical oxygen demand of pollution in a stream is exerted by three classes of materials: 1) carbonaceous organic material usable as a source of food by aerobic organisms; 2) oxidizable nitrogen derived from nitrite, ammonia, and organic nitrogen compounds which serve as food for specific bacteria; and 3) certain chemical reducing compounds including ferrous iron, sulfite, and sulfide which will react with molecularly dissolved oxygen. All three of these classes of materials have a direct, but varied bearing upon the oxygen balance in a stream (Nemerow, 1974 and APHA et al., 1989).

The determination of the amount of oxygen necessary to completely stabilize a given pollutant, termed its ultimate CBOD ($CBOD_u$), may require a period of incubation of up to several weeks. Figure 9 shows the BOD exerted and DO depleted, as carbonaceous and nitrogenous biological reactions progress with time. For the purposes of practicality and uniformity, a five day period is used as the laboratory standard test length for water samples, carried out at a controlled temperature of 20° Centigrade (C). At a normal summer temperature of 20° C, practically the entire ultimate oxygen demand has been met by biochemical oxidation of the pollutant within 20 days. At 30° C it may be possible to assimilate the pollutants in as few as 13 days, but at 10° C, the reduced metabolic rate will extend the period necessary to completely stabilize the waste to approximately 32 days (Hammer, 1975).

A sample of polluted water having a $CBOD_u$ value of 20 mg/l would consume 20 mg/l of DO over the extended, temperature-dependent period of time necessary to completely decompose all of the organic matter in the sample. The impact of pollution on a stream can be evaluated by comparing the amount of total DO in mg/l that bacteria will consume per mile as it flows downstream during the biodegradation process, to the total amount of DO that will be available to the bacteria within the stream within that same stream reach. An increase in the pollutant load to a stream typically stimulates the growth of bacteria that oxidize the waste. If the concentration of the organic pollutant load is too great, all of the DO within the receiving stream can be utilized by the bacteria. The resultant lack of oxygen can take a tremendous toll upon the higher forms of aquatic life in a stream, and result in a septic environment devoid of zooplankton and fish (Clark et al., 1977 and MPCA, 1981).

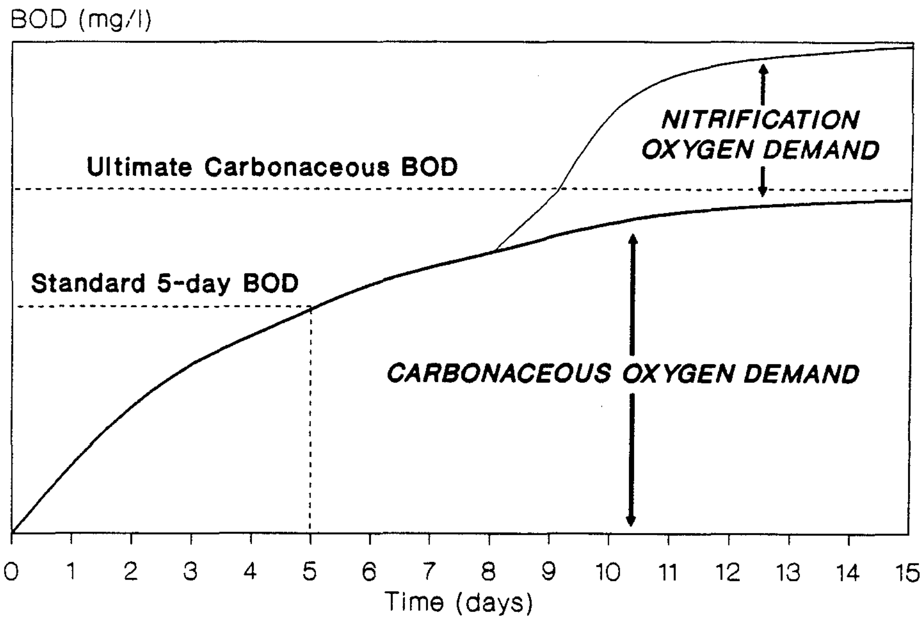
During the extreme low flow period in the summer of 1988, the average $CBOD_5$ measured in the St. Croix River near Prescott was 2.3 mg/l. $CBOD_5$ values measured in the Minnesota River during the same time period averaged 4.7 mg/l near Jordan, and 3.4 mg/l near the confluence with the Mississippi. Also during this same time, the average $CBOD_5$ in the Mississippi River near Anoka and as flow left the TCMA were both approximately 5 mg/l (MWCC, March 1990).

SOD

Sediment oxygen demand (SOD) values are difficult to accurately assume and time-consuming to obtain. This form of oxygen demand results from accumulated deposits of biologically oxidizable suspended solid waste materials that have settled to the stream floor; living or dead phytoplankton (typically algae) that have settled to the bottom and have begun to decompose; and, zooplankton that live in the bottom sediments and consume dissolved oxygen from the water above. SOD rates are typically very site specific and can differ even within the cross-section of a stream.

A progressive downstream increase in SOD is experienced within TCMA river reaches in response to the contribution of organic load from both point and nonpoint sources that settle out onto the river bottoms, and the effect the lock and dam structures and their resultant pools on the Mississippi have in reducing in-stream flow velocities. These processes are particularly observable when flow rates are very low (MPCA, 1981).

Figure 9
HYPOTHETICAL BIOCHEMICAL OXYGEN DEMAND REACTION



Source: Hammer, 1975

Plankton

The plankton community is composed of a mixed group of tiny plants, animals, and bacteria that float, drift, swim, or attach themselves to fixed objects in an aquatic environment. The numbers and relative diversity of plankton present are governed to a great extent by the amounts and kinds of nutrients available. Plankton constitute much of the base of the food pyramid upon which all of the higher forms of aquatic life depend. Plankton and other aquatic organisms are therefore used to determine, as well as affect, the quality of water. In the natural environment, the composition of a mixed population of plankton is in constant flux in response to changing ambient conditions. As one or more species decline in number, others grow in prominence. As a result, the composite growth rate of the entire population changes with time to reflect the growth rates of the predominant species. Predation by zooplankton, whose numbers also can fluctuate wildly as a result in food supplies and environmental conditions, introduces yet another factor that complicates the overall system of population dynamics (Cole, 1979 and MPCA, 1981).

Photosynthesis is a natural process by which algae and all other types of green plants utilize the energy in sunlight to synthesize carbohydrates and oxygen from carbon dioxide and water. It involves a highly endothermic reaction, requiring a large supply of energy. The process is precipitated by the presence of chlorophyll, a green pigment present in algae that enables the algae to absorb energy from the sun's light waves. Aquatic organisms lacking chlorophyll are unable to manufacture starches, carbohydrates, or oils from inorganic matter, and are dependent upon algae and other green plants (directly or indirectly) to preform these organic substances for them. In the absence of sunlight, algae convert to the process of respiration, where oxygen is absorbed and carbon dioxide is released, or the reverse of photosynthesis. Respiration is performed by all typical bacteria, fungi, yeasts, protozoa, crustacea, and animals, regardless of the presence of sunlight. The amount of oxygen and carbon dioxide in an aquatic environment often depends upon the relative rates of photosynthesis and respiration being carried on collectively by the algae, bacteria, and other organisms in that environment. Algae make many important metabolic activities and chemical changes possible through their release of oxygen during daylight hours. The presence of oxygen helps to prevent malodorous septic conditions by favoring the activities of aerobic rather than anaerobic bacteria. Oxygen release by algae is the primary source of oxygen renewal in flowing streams (EPA, 1977).

A food chain represents levels of metabolism in an aquatic community. Energy is transferred through the food chain in a pyramid fashion such that each higher level has less energy than the previous one. Thus the biomass at each energy level decreases; the mass of phytoplankton is greater than the mass of zooplankton, and there are more small fish than large ones. Figure 10 portrays two biomass pyramids. The pyramid on the left depicts a situation where inorganic nutrients are in short supply, limiting primary production of green plants. The populations of zooplankton and fish are thus held in check by restricted food sources. The pyramid on the right depicts a situation where an abundance of plant nutrients can increase the standing crop on all levels of the biomass pyramid. In this situation, an imbalance can be created in the normal succession of the aquatic food chain. When not inhibited by nutrient deficiency, weed beds may flourish, and phytoplankton production can either exceed the consumptive demands of zooplankton or be composed of nuisance varieties that the zooplankton will not eat (Clark et al., 1977).

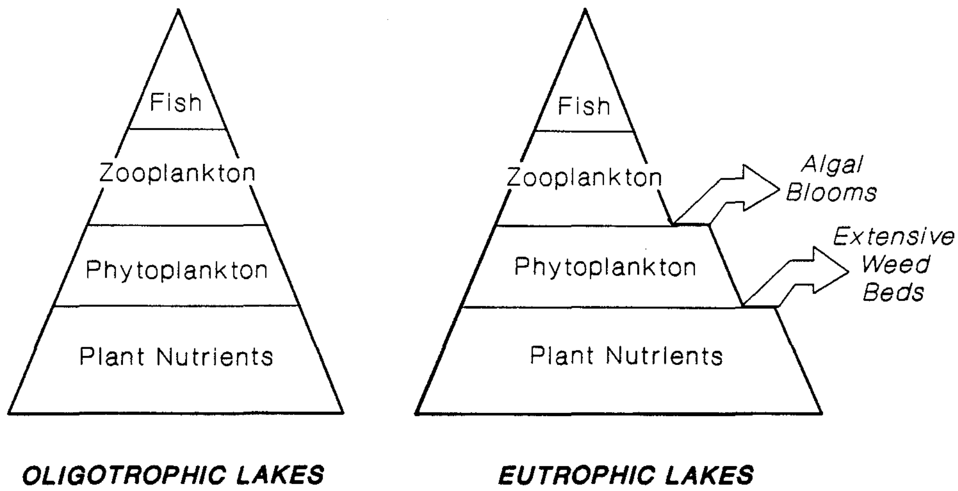
A dramatic increase in the population of one or more members of the phytoplankton community within a body of water over a short period of time is termed a bloom. Rapid reproduction occurs when nutrient levels, water temperature, and other factors encourage optimal phytoplankton growth conditions. Following this period of rapid growth, the algae may experience an extensive dieoff, or collapse. Upon death, algal cell walls rupture, releasing a rich source of nutrients, dominated by nitrogen and phosphorus. Bacterial populations will then often respond with their own rapid increase in growth, due to the sudden increase in the availability of food. If bacteria deplete the water of oxygen and start to denitrify, high concentrations of ammonia nitrogen may be released, often turning the water a milky white color. The toxic effects of high ammonia concentrations and very low DO levels can prove to be fatal for a variety of aquatic life (USGS Water Summary, 1990).

As river flows decline, an increased density of fish is forced to survive in a shrinking habitat that may be unable to support the entire population of aquatic life. A reduction takes place, primarily among the immobile species that become stranded in off-channel areas that are desiccating, or those that are unable to survive in their altered habitat. Macroinvertebrate organisms that feed on bottom deposits do well, while those that filter their food from the water column as it flows by them tend to decline in numbers. Periphyton however, are organisms that attach themselves to submerged objects in rivers, and typically experience luxuriant growth during summer low flows in response to higher temperatures, lower current velocities, and lower levels of turbidity and suspended solids (Corps, 1990).

Diatoms and green algae are normally dominant during periods of cooler water temperatures and higher flows. On the other hand, blue-green algae typically dominate mixed populations of phytoplankton during low flow conditions of late summer. They are considered the "weed species" of phytoplankton because they propagate almost unchecked by the controlling effects of predation by zooplankton and fish.

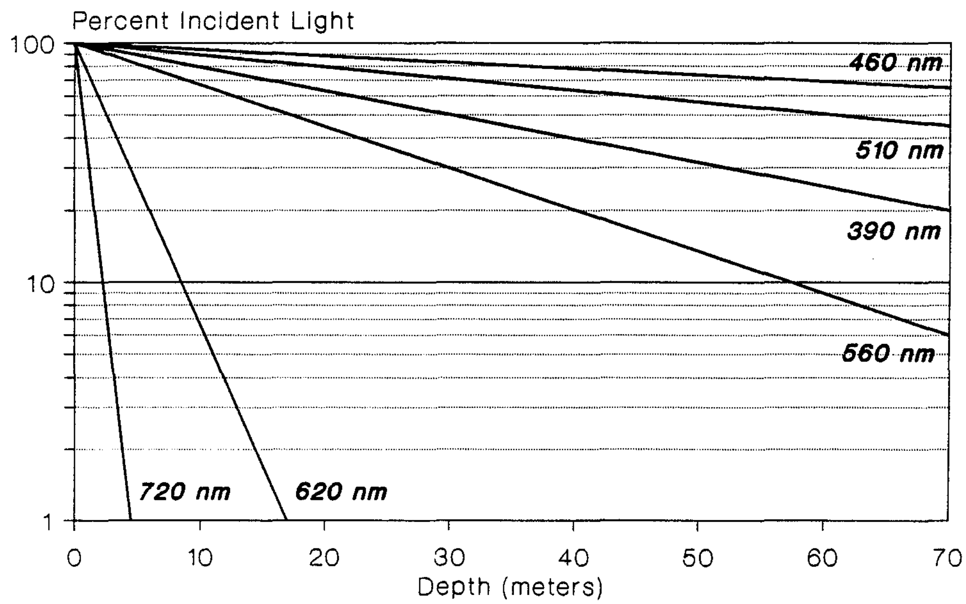
Changes in water quality exert a selective action on the flora and fauna that constitute the living population of water, and the effects produced in them can be used to establish biological indices of water quality. Changes in water quality may affect the amount of oxygen and nutrients present, or cause the water to become toxic to some types of organisms. Chemical and physical measurements of water samples tend to measure only the cause of changes in water quality, while biological tests deal primarily with the effects of the change. Identification of the types and numbers of living organisms present from reach to reach in a river on a seasonal and yearly basis can be used to indicate changes in the water quality of a stream. One such indication of improved water quality within the St. Paul reach of the Mississippi River was the return of the Hexagenia mayfly in vast numbers during the latter 1980s. This native river organism had disappeared from the area over thirty years ago as a result of stress from in-stream pollutants. While not considered to be cause for rejoicing by TCMA motorists, the presence of this particular mayfly is considered to be a positive sign in terms of Mississippi River quality (Council, 3/90 and EPA, 12/77).

Figure 10
BIOMASS PYRAMIDS FOR OLIGOTROPHIC AND EUTROPHIC LAKES



Source: Clark, Viessman and Hammer, 1977

Figure 11
VERTICAL PATHS OF SELECTED WAVELENGTHS THROUGH DISTILLED WATER



Source: Cole, 1979

Chlorophyll-a

Water quality goals are often based upon established levels of phytoplankton chlorophyll concentration. High levels of chlorophyll can affect the usability of a body of water for water supply, aesthetic enjoyment, and recreational activities. Chlorophyll is often used as a comparative indicator of the phytoplankton activity in streams.

Chlorophyll absorbs solar energy and converts it into chemical energy to power the oxidation-reduction reactions known collectively as photosynthesis. Solar radiation is composed of myriad individual rays, each with its own wavelength and characteristic frequency. The longest ultraviolet rays transition to visible violet at a wavelength of approximately 350 nanometers (nm), and visible red light transitions to the shortest infrared light at a wavelength of approximately 750 nm. Chlorophyll vigorously absorbs red and violet waves and reflects the intermediate greens and yellows, which is why plants appear green to the eye. As solar radiation penetrates surface water, it diminishes exponentially. As can be see in Figure 11, the longest rays of incident light, visible red rays, are rapidly absorbed in the shallower water, while shorter rays in the visible violet range penetrate much deeper below the water surface. About 65% of the visible red rays are absorbed within a meter of the water surface. Some members of the phytoplankton community are capable of dwelling selectively near the water surface, maximizing their ability to intercept solar radiation (Cole, 1979).

Plants contain an assortment of pigments, each absorbing energy from rays of differing wavelength. Pigments absorbing short rays pass some of their energy to those absorbing longer waves, but not vice versa. Chlorophyll-a, found in all photosynthesizing plants except bacteria, is the final energy recipient. Chlorophyll-a absorbs light with wavelengths of about 435 nm (violet), and the longest wavelength light of all chlorophyll pigments, in the 670 to 680 nm (red) range. A relatively constant relationship exists between the degree of photosynthetic activity occurring in a body of water and the amount of chlorophyll-a present in the water. By mechanical disruption of a water sample, the chlorophyll-a from both dead and living phytoplankton in the sample can be solubilized and measured. That data can be used to infer the comparative qualities of bodies of water. In general, the higher the chlorophyll-a concentration, the lower the water quality (Cole, 1979).

Phytoplankton can account for a large percentage of the light absorbed while passing through the water column by creating a self-shading effect. They also result in an increased level of turbidity in a stream. Riverine phytoplankton levels are generally considered to be low when chlorophyll-a levels are less than 50 μg/l, and high to eutrophic when greater than 200 μg/l. Within the range of measured chlorophyll-a of 50 to 200 μg/l, algae can diminish the amount of light reaching the subsurface from 33% to 67% (Hydroscience, 1979).

Lower river flows, especially during the summer season, typically result in several hydraulic conditions that favor algae growth and chlorophyll-a production, including longer detention time in pooled areas, enhanced light availability in less turbid waters, and less turbulent mixing. Algal blooms that develop in the pooled areas of TCMA streams during extreme low flow periods typically generate the largest measured levels of instream chlorophyll-a. Concentrations measured in Spring Lake exceeded 250 μg/l during the 1976 low flow survey, but remained under 200 μg/l during the more acute 1988 low flow period (Hydroscience, 1979; MWCC, August 1989; and MWCC, March 1990).

During the 1988 summer low flow period, the total chlorophyll-a concentration measured in the St. Croix River near Prescott averaged 20 μg/l. During the same time period, instream measurements near Jordan in the Minnesota River averaged 97 μg/l, and near its confluence with the Mississippi River, measurements averaged 57 μg/l. However, measured values on the Minnesota near the Black Dog Power Facility at RM 8.5 averaged 102 μg/l during this same period of time, indicating a probable contribution of phytoplankton to the bottom sediments prior to confluence with the Mississippi. Also during this time, chlorophyll-a concentrations averaged 56 μg/l in the Mississippi River near Anoka, and 74 μg/l in the flow as it left the TCMA. Maximum observed values of 180 μg/l were observed during both June and August in the pool above Lock and Dam No. 2 near RM 815.6 (MWCC, March 1990).

pH

Pure water (H_2O) is composed of an equal number of hydrogen ions (H^+) and hydroxide ions (OH^-). The concentration of hydrogen ions in a solution is a measure of its degree of acidity or basicity. The pH scale ranges from 0 to 14. Values below a neutral level of 7 are increasingly acidic, and values above 7 are increasingly basic. A change of one pH unit represents a tenfold change in the hydrogen ion concentration; for example, a pH of 6 has 10 times the hydrogen ions of pH 7, and 100 times the hydrogen ions of pH 8. The majority of natural waters have a pH somewhat above 7, along with the presence of carbonate and bicarbonate salts. Dissolved gases such as carbon dioxide, hydrogen sulfide, and ammonia also influence the pH of a solution. The pH values of most rivers and lakes with productive fish populations range from about 6.7 to 8.6 (Eckblad, 1978).

An important chemical effect of photosynthetic activity, through its continuous removal of dissolved carbon dioxide during the daylight hours and dissolved oxygen during periods of darkness, is its resultant effect on hardness and pH of the streamflow. As carbon dioxide is removed from a stream, an alteration takes place in the relative amounts of soluble (unbound) carbonic acid, intermediately soluble (half bound) bicarbonates, and the nearly insoluble (bound) monocarbonates, often causing some of the latter to precipitate. This series of chemical changes produces a change in the total hardness of the water. Changes in carbon dioxide and hardness in turn, alter the pH of the water. The pH rises as a result of daytime algal photosynthetic activity, and decreases at night as a result of algal respiration. These diurnal fluctuations in water characteristics complicate water treatment operations by necessitating compensating changes in the dosages of chemicals to maintain consistent water quality for human consumption (EPA,1977).

During the extreme low flow period in the summer of 1988, pH levels measured during the mid-morning in the St. Croix River averaged around 8.1 near Prescott. In the Minnesota River near Jordan, they also averaged 8.1, but dropped to an average of 7.9 near its confluence with the Mississippi during the same period of the day. Mid-morning pH levels averaged 8.6 near Anoka on the Mississippi River, and 8.8 as flow left the TCMA. The drop in pH levels in the Minnesota appears to have been due primarily to the effects of dilution by WWTP effluents having a pH in the 7.0 to 7.5 range. In the Mississippi River, the measured increase was most likely due to instream algal activity (MWCC, March 1990).

Temperature

Biological activity is governed by chemical reactions that are significantly influenced by temperature. All living organisms can be divided into two broad divisions: "warm-blooded" forms, like mammals and birds, whose body temperatures are maintained at a uniform level independent of their environment, and "cold-blooded" forms whose body temperatures approximate that of the environment and vary accordingly. The latter group includes algae, bacteria, plants, and animals, all adapted to various thermal conditions. The relationships in van't Hoff's law, a chemical law that applies to some physiological processes, holds true for stream bacteria and phytoplankton. The law states that the rate at which biological processes proceed is increased nearly two-fold with each 10° Centigrade (C) increase in temperature, as an almost linear function of temperature. Therefore, if sufficient nutrients are available, an algal population may grow rapidly and bloom at the optimal temperature for that species, typically followed by a decline in its population (Reid, 1961).

Many species of organisms are unable to remain physiologically active throughout the wide temperature range of their environment, and will form "resting stages", or spores, which exhibit a wider range of tolerance than their active forms. Similarly, fish are often categorized as being "cold-water" or "warm-water," depending on the temperature tolerance of their developing eggs or preferred growth environment (Reid, 1961).

An increase in temperature causes a decrease in the saturation value of oxygen in water, as indicated previously in Table 4. During the winter, water temperature in streams in the TCMA will approach 0° C, and will hold approximately 14.6 parts per million (ppm) oxygen at 100% of saturation. On the other hand, at 27° C, a typical midsummer temperature, the same water will only hold approximately 8.1 ppm oxygen at 100% saturation. This represents a reduction of about 45%. When we consider water's reduced capacity to hold oxygen in solution occurs at a time when dilution (stream flow) is at its lowest level, and metabolic rate and population of oxygen consumers in the stream are at their highest, it is easy to visualize the high level of concern behind the predictions and accumulation of actual data during periods of extreme summer low flow for an accurate understanding of a stream's ability to assimilate pollution.

Under low temperature conditions, the effects of phytoplankton are minimized due to their reduced metabolic rate. The dominant mechanism impacting the level of DO in a river then is the decomposition of organic material in the bottom sediments, and within the water column as a result of its presence in WWTP discharges (Hydroscience, 1979 and Nemerow, 1974).

The temperature of wastewater as it enters a WWTP is typically very close to the temperature of the underground collection system through which it has flowed for the several hours or days that it has taken to arrive at the WWTP. Due to the exposure of river water to the atmosphere, however, its temperature exhibits much larger seasonal swings. The temperature differences between effluent discharged from WWTPs and water in the receiving river is often in excess of 5° C (Stefan, 1982).

River water temperature data collected during the 1970s at the USGS continuous temperature monitor at RM 840 on the Mississippi River indicates that the highest temperatures in that stream are typically encountered during the latter two weeks of July, while the lowest summer flow conditions are more likely to occur during September. The median summer temperature during that period was 23° C, and ranged from 14 to 29° C (MPCA, 1981).

During the extreme low flow period in 1988, a high water temperature within the St. Croix River near Prescott of 26.7° C was measured on August 16th. Temperature readings in the Minnesota River were measured at a high of 30.9° C on August 17th near Shakopee, but no higher than 28.0° C near confluence with the Mississippi, due to the contribution of the cooler WWTP effluent flows. A high temperature of 27.7° C was measured in the Mississippi River near Anoka during this period on August 1, 1988. Within the TCMA, the highest temperature recorded on the Mississippi was 29.3° C near the Robert Street Bridge in St. Paul on August 2, 1988. The highest temperature measured as flow left the TCMA was 29.0° C on August 16, 1988 (MWCC, March 1990).

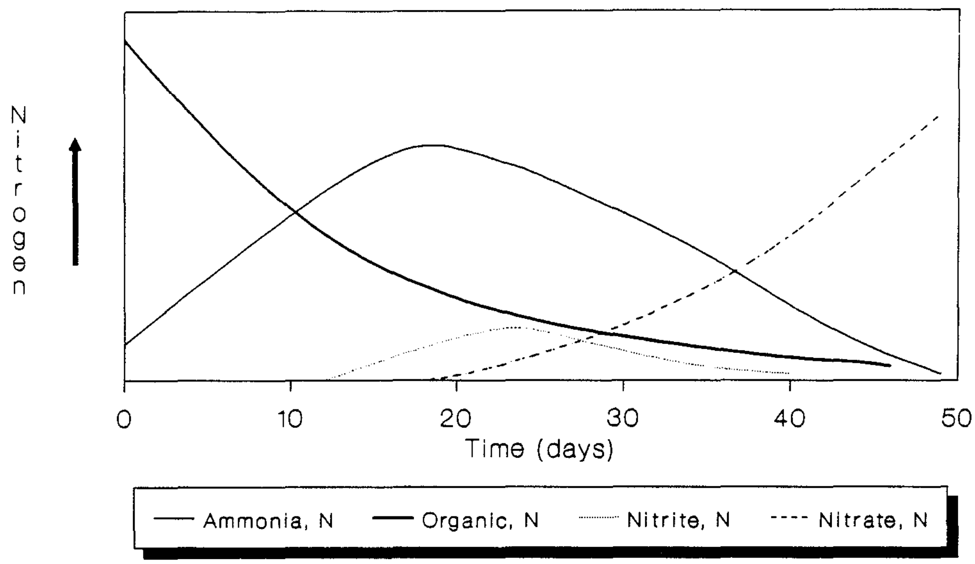
Nitrogen

Nitrogen is an essential constituent of all plants and animals, present principally in proteins. Nitrogen, by chemically gaining or losing electrons, can exist in seven different states of valence. Some valence changes can be brought about by bacteria, and will be either positive or negative, depending upon whether aerobic or anaerobic conditions prevail. Typical forms of nitrogen that may be present in a stream sample include organic, ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^{2-}). The atmosphere serves as a reservoir from which nitrogen is constantly removed by the action of electrical discharge (lightening), and nitrogen-fixing bacteria and algae. During electrical storms, large amounts of nitrogen are oxidized to N_2O_5 that combine with water to produce nitric acid (HNO_3), which is carried to the earth in the rain (Sawyer and McCarty, 1967).

All nitrogen present in organic compounds (compounds containing carbon) may be considered organic nitrogen. Most are derivatives of ammonia, in the form of proteins or their degradation products: polypeptides and amino acids. Animals and human beings are incapable of utilizing nitrogen from the atmosphere or from inorganic compounds to produce proteins. Thus, we and other animals are dependent upon plants, or other animals that feed upon plants, to provide protein that is used primarily for growth and repair of muscle tissue. Nitrogen compounds are released in the waste products of the body during life. Urine contains nitrogen resulting from the metabolic breakdown of proteins that are hydrolyzed rapidly by the enzyme urease (also present in urine) to create ammonium carbonate. Animal feces contain appreciable amounts of unassimilated protein matter (organic nitrogen) that is converted to ammonia by the action of saprophytic bacteria (bacteria that derive their nourishment from dead or decaying organic matter), under either aerobic or anaerobic conditions (Sawyer and McCarty, 1967).

Stream tributaries are common nonpoint source recipients of large amounts of animal urine and feces. These materials enter either by direct deposition by animals within the stream channel if they are not isolated by fencing, or by rainfall or snowmelt runoff into the river tributaries in areas where berms have not been constructed along the banks to channel polluted runoff away from the tributaries. Figure 12 identifies the conversion of organic nitrogen to nitrate nitrogen over time by bacterial action in a typical aerobic stream environment (Sawyer and McCarty, 1967).

Figure 12
CHANGES IN FORMS OF NITROGEN IN POLLUTED WATER UNDER AEROBIC CONDITIONS



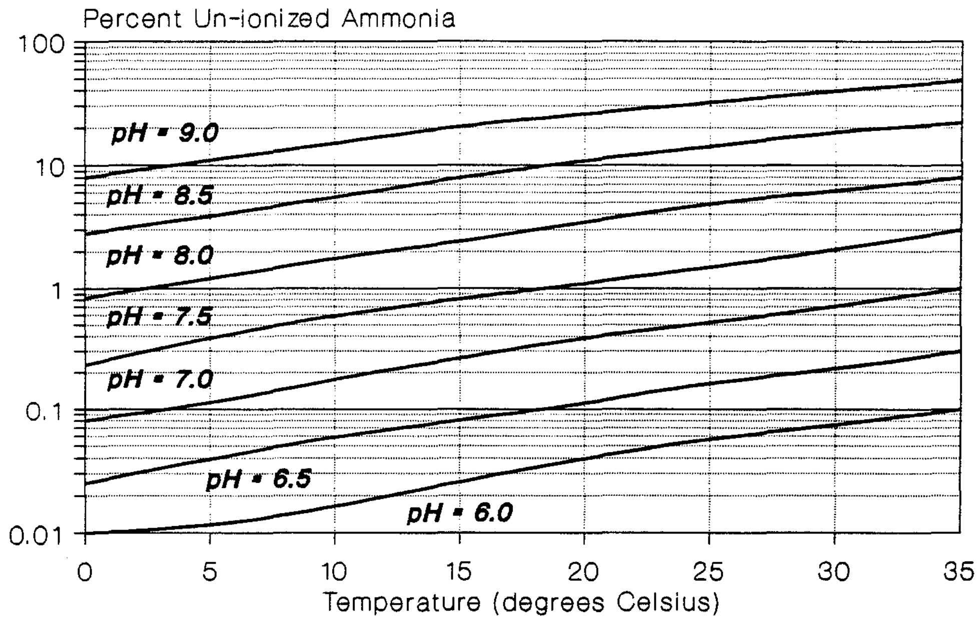
Source: Sawyer and McCarty, 1967

Ammonia exists in two forms in equilibrium in an aqueous solution: un-ionized (NH_3) and ionized ammonium (NH_4^+). Upon contact with water, a portion of the ammonia present reacts to form ammonium. The distribution of each form is highly sensitive to changes in ambient pH first and temperature second, according to the relationship displayed in Figure 13. There is an approximate ten-fold increase in the un-ionized ammonia concentration for each unit increase in pH. Un-ionized ammonia can be highly toxic to fish and other aquatic organisms. When pH and water temperature increase, as typically occurs during summer low flow periods, the concentration of un-ionized ammonia will increase even though the total ammonia nitrogen concentration may have remained constant.

Ammonia concentrations in TCMA rivers show an apparent correlation with increasing spring flows, suggesting contributions from nonpoint sources. This situation is particularly prevalent on the lower Minnesota River. During late fall through early spring, lower pH and cooler temperatures of water in streams effectively minimizes the fraction of instream ammonia that is un-ionized, ensuring that minimum water quality standards are maintained. For this reason, wastewater treatment plants typically are not required to carry out in-plant nitrification during the cooler months of December through April. During warmer months, the discharge of total ammonia to streams must be limited in order to maintain the un-ionized fraction below toxic levels. Wastewater treatment plants providing only secondary levels of treatment typically provide minimal removal of ammonia, and can be primary contributors of ammonia to a stream. Therefore, monthly limitations for allowable levels of effluent ammonia have been established for the major WWTPs in the TCMA. The levels are established as functions of the ambient conditions of each effluent's receiving stream: flow, pH, temperature, and the loading of ammonia from all other sources. Current water quality standards in Minnesota limit in-stream un-ionized ammonia to 40 μg/l. During periods of extreme low flow during late summer, the potential for instream ammonia toxicity increases as algal activity raises pH, water temperature is at its yearly high, and the resultant un-ionized ammonia fraction is largest. Ionized ammonium is able to chemically bond tightly to soil colloid surfaces and the interlayers of clay particles that are present in the water column and bottom sediments of streams (MPCA, 1985).

Figure 13

PERCENT UN-IONIZED AMMONIA IN AMMONIA-WATER SOLUTION AT VARIOUS PH/TEMP VALUES



Source: Hydroscience, 1979

During the summer low flow months in 1988, sampling of un-ionized ammonia nitrogen levels in the St. Croix River revealed no toxicity problems, with average readings near Prescott of less than 3 μg/l. Minnesota River readings during the same time frame also averaged less than 3 μg/l near Jordan, but averaged approximately 65 μg/l by the time flow reached the Mississippi River. Discharge of ammonia from WWTPs along the lower Minnesota resulted in measurement of toxic levels (> 40 μg/l) of un-ionized ammonia from Savage to the mouth of the river, from the end of June through most of October. In the Mississippi River near Anoka and Prescott, levels averaged 6 μg/l for un-ionized ammonia. Isolated occurrences of toxic levels were measured during early June and late July of 1988 at different locations in the Mississippi River through the TCMA. The large total ammonia loading from the Minnesota River, however, was diluted to non-toxic levels when it flowed into the Mississippi, and was subsequently consumed by phytoplankton within the Spring Lake area during the 1988 extreme low flow period (MWCC, March 1990).

Nitrate nitrogen usually occurs in relatively small concentrations in unpolluted surface waters, the observed world average being about 0.3 mg/l. Higher nitrate concentrations generally correspond to periods of higher river flows during early summer in the TCMA, reflecting the effects of surface runoff. Nitrification is the aerobic process involving the sequential bacterial oxidation of ammonia, first to nitrite, then to nitrate, by nitrosomonas and nitrobacter bacteria, respectively. Since this process requires oxygen to occur, the level of DO in a stream can be seriously reduced during the long residence times required for the growth of the slow-growing nitrifying bacteria. The speed with which these reactions take place in a stream is directly related to the number of nitrifying bacteria in the stream. Nitrosomonas bacteria use ammonia nitrogen as a food source, converting it to nitrite. The nitrobacter in turn utilize nitrite nitrogen as a food source, converting it to nitrate nitrogen. Independent of the nitrifying bacteria, phytoplankton are able to utilize nitrogen in all three of these chemical states as a food source. The optimum conditions for nitrification include a pH range between 8.4 and 8.6 and a temperature range between 25° and 28° C. Nitrifying bacteria will typically be at their highest population and activity levels during late summer when these instream pH and temperature conditions are most probable in TCMA streams. The process is also enhanced in rivers when they are shallow and contain high concentrations of suspended particulates that provide sites for the nitrifying bacteria to reside on (Sawyer and McCarty, 1967; MPCA, 1985; and Eckblad, 1978).

Denitrification is a reduction process that takes place under anaerobic conditions that are the reverse of those observed during nitrification. Nitrates are reduced to nitrites, which are then reduced to ammonia by a few types of bacteria, or most often to nitrogen gas, which then escapes to the atmosphere. Denitrification proceeds best in anaerobic environments, including natural areas like the hypolimnion (bottom waters) of lakes, swamps, marshes and wetlands. Nitrification/denitrification processes are utilized in wastewater treatment by creating controlled environments that encourage the growth of many types of bacteria to coexist and carry out these processes to biologically remove nitrogen from wastes. Typically, ammonia and organic nitrogen are first biologically converted to nitrites and nitrates in aerobic treatment processes, then the waste is placed under anaerobic conditions where denitrification oxidizes organic matter present for energy to drive the bacterial reactions that reduce the nitrite and nitrate to nitrogen gas (Sawyer and McCarty, 1967 and Cole, 1979).

Nitrate nitrogen, when present in public drinking water supplies in concentrations exceeding 10 mg/l, is a tremendous public health concern. Water containing nitrate nitrogen exceeding that level is capable of causing methemoglobinemia (blue-baby syndrome) in infants, which can lead to death. The nitrate is absorbed into the bloodstream where it reacts with hemoglobin to produce methemoglobin, impairing the blood's ability to carry oxygen. This problem is most prevalent in rural settings where water quality monitoring of individual wells typically occurs less frequently than for community wells. Improper nitrogen fertilization practices on agricultural land are a common cause of high nitrate levels, creating plumes of polluted ground water that can move through aquifers toward individual and community wells being pumped for human consumption. Instream nitrate levels approached 1 mg/l in the Mississippi River at Anoka, but reached approximately 9 mg/l in the Minnesota River at Jordan as a result of high runoff flows during May of 1988 (MWCC, March 1990).

Low flow periods during either summer or winter typically exhibit the lowest levels of nitrate nitrogen concentrations in TCMA rivers. This is due to the relative inactivity of the nonpoint source transport mechanisms of runoff, precipitation, and dustfall, and the increased summer uptake levels by aquatic algae. Low flow survey data from the summer of 1988 indicate nitrate nitrogen levels in the St. Croix River near Prescott averaged 0.22 mg/l, having dropped from high spring concentrations in excess of 1 mg/l. During the same time period, nitrate concentrations still remained high during June (declining from a measured high of 9 mg/l in early May to 4.25 mg/l in early June) in the Minnesota River near Jordan, but averaged 0.09 mg/l during July and August. Similar, but slightly lower levels were measured in June near confluence with the Mississippi River, but the average for July and August had dropped to 0.23 mg/l. Instream Mississippi River nitrate nitrogen concentrations near Anoka during June through August of 1988 averaged 0.10 mg/l. Metro WWTP effluent increased the instream concentration to approximately 2.2 mg/l, but by the time flow left the TCMA, increased phytoplankton activity during the extreme low flow period in the Mississippi had effectively reduced its concentration of nitrate nitrogen to an average of 0.53 mg/l (MPCA, 1985 and MWCC, March 1990).

Phosphorus

Phosphorus is absolutely necessary to all life. As a component of ATP (adenosine triphosphate), it performs the genetic functions of storage and energy transfer in each living cell. It is taken up rapidly and concentrated by living organisms. Phosphorus commonly coexists in two forms: orthophosphate and organic phosphate (also referred to as metaphosphate or polyphosphate). The soluble, orthophosphate form is immediately available for uptake by autotrophic plants, typically plants capable of photosynthesis. Because it is so readily assimilated, it is often the growth limiting nutrient for algae in many aquatic environments.

Polyphosphates, also identified as molecularly dehydrated phosphates, gradually hydrolyze in an aqueous solution and revert to the ortho form from which they were derived. This reversion rate is temperature-dependent, increasing with increasing temperatures. Phosphorus is derived from living plankton organisms that excrete particulate organic phosphorus compounds. All biological wastewater sludges and their respective effluent suspended solids counterparts contain phosphorus (and nitrogen) in significant amounts. Natural sources of phosphorus include the leaching of phosphate-bearing rocks and organic matter decomposition. Additional sources are man-made fertilizers and detergents, and domestic wastewater. Phosphorus is typically lost from solution to the bottom sediments when in chemical-overabundance by chemical precipitation and by adsorption onto clay soil particles. It accumulates on the bottom, and becomes available to phytoplankton whenever sediments are disturbed by low flows, zooplankton activity, or chemical hydrolysis (Sawyer and McCarty, 1967; Cole, 1979; and Eckblad, 1978).

The organisms involved in biological processes of wastewater treatment all require phosphorus for reproduction and synthesis of new cell tissue. Domestic wastewater contains amounts of phosphorus far in excess of the amount needed to stabilize the limited quantity of organic matter present, as demonstrated by its presence in plant effluent in appreciable amounts. Industrial wastes on the other hand, often do not contain sufficient quantities of phosphorus for optimum growth of the organisms used in its treatment. In those cases, the deficiency must be offset by the addition of inorganic phosphates. Aquatic bacteria are formidable competitors with algae when phosphorus is in short supply in a stream. The critical concentration for phosphorus, below which growth of algae is impeded, is approximately 0.01 mg/l (Sawyer and McCarty, 1967).

A eutrophic body of water is characterized as being rich in nutrients and high in biotic activity. Typical management strategies with the desire to prevent further eutrophication involve attempts to reduce and control the concentration of phosphorus from inflow sources. Phosphorus is less difficult to control than the other significant nutrient, nitrogen, because blue-green algae, common in eutrophic waters, are able to assimilate the nitrogen they need from the atmosphere.

Within the TCMA during the summer low flow period in 1988, the total average phosphorus concentration measured in the St. Croix River near Prescott was 0.08 mg/l, and the median value was 0.02 mg/l. In the Minnesota River near Jordan during the same period of time, the total phosphorus concentration averaged 0.25 mg/l, and near the confluence with the Mississippi concentrations averaged 0.45 mg/l. Total phosphorus concentrations in the Mississippi River near Anoka during this period averaged 0.1 mg/l, and the downstream average as flow left the TCMA was measured at approximately 0.26 mg/l (MWCC, March 1990).

Dissolved Solids

Dissolved matter in surface water is derived from the soluble minerals in rocks and soils in contact with the water, and from the discharge of point and nonpoint sources of pollution to the body of water. Water entering a stream from a ground water reservoir generally has been in prolonged contact with solid mineral matter and contains a higher concentration of dissolved solids than water that has reached a stream via direct runoff from rainfall. As a result, water in a stream normally has the greatest concentration of dissolved solids in late summer, when the stream is receiving all, or most of, its natural source-water from stored groundwater seeping into the stream during rainless periods. Evaporation and transpiration are also at their peak during summer high temperature periods, which cause instream dissolved solids concentrations to increase. Samples of Mississippi River water obtained at a USGS sampling station just upstream from Hastings in the TCMA in August of 1988 during the height of the drought period, contained an average total dissolved solids (TDS) concentration in excess of 400 mg/l. In comparison, the average August TDS value over the 1980-1987 period of record was just over 300 mg/l (USGS, 1990).

The densities of both river water and WWTP effluent are a function of their TDS concentration and temperature. TDS values are typically much higher in WWTP effluents than in river water because of inputs into the wastewater collection system by industrial and domestic users. Chloride in the form of the ion Cl^-, is typically the major inorganic anion in both water and wastewater. TCMA rivers typically contain a chloride concentration of about 50 mg/l, while WWTP effluent concentrations will average in excess of 200 mg/l. The higher concentration of chloride ion in wastewater can be explained by common human use of sodium chloride ($NaCl$) as a dietary supplement, and its ability to pass relatively unchanged through the human body's digestive system (Stefan et al., 1984).

The amount of TDS present in water is a consideration in its suitability for human consumption. In general, only waters with a TDS of less than 500 mg/l are recommended for consumption. Waters with a higher solids content tend to disturb the human digestive system. Wide variations in the total salinity, or in the concentrations of individual dissolved salts in a body of water can put a great deal of stress upon some species of aquatic life. When the osmotic pressure is sufficiently high due to the presence of large concentrations of salts in solution, water may be drawn from gills and other delicate external organs, resulting in considerable damage to cells, or even death in selected fish. High concentrations of many kinds of pollutants present this danger apart from any other toxic or corrosive effects they may also exhibit (Eckblad, 1978 and Sawyer and McCarty, 1967).

The TDS concentration averaged approximately 150 mg/l in the lower reach of the St. Croix River, and approximately 570 mg/l in the lower reach of Minnesota River during the 1988 summer low flow period. During the same period of time, the concentration of TDS averaged 220 mg/l in the Mississippi River near Anoka, and approximately 270 mg/l as flow left the TCMA (MWCC, March 1990).

Turbidity

Turbidity is the term used to describe the degree of opaqueness produced in water by suspended particulate matter of various particle size and composition. Materials typically contributing to turbidity include humus, silt, organic debris, colloidal matter, plants and animals. The damping effect of light by suspended particles that causes solar radiation to scatter and be absorbed rather than transmitted in straight lines through the water, can significantly reduce potential photosynthetic activity in a stream. The standard method of determining turbidity is with the use of a nephelometer turbidimeter. Nephelometric Turbidity Units (NTUs), are a measure of the intensity of light scattered at right angles to the path of incident light as observed by photo-electric detectors. The water quality standard for the maximum acceptable level of turbidity in TCMA Rivers is 25 NTUs. This value is representative of the measured median turbidity in the Minnesota River during typical summer low flow periods (MPCA, 1985 and Reid, 1961).

Higher levels of turbidity typically result in lower relative phytoplankton populations in streams due to a reduction in the amount of light penetration. High concentrations of particulate matter also absorb heat from the sun, causing the temperature of water in the stream to increase.

Turbidity values averaged approximately 3 NTUs on the St. Croix River near Prescott during the 1988 summer low flow period. Turbidity on the lower Minnesota River averaged 20 NTUs near Jordan, and averaged 21 NTUs near its confluence with the Mississippi. During the same period of time, readings on the Mississippi River near Anoka averaged 10 NTUs, and as flow left the TCMA, turbidity readings averaged under 9 NTUs (MWCC, March 1990).

Suspended Solids

There are a variety of solids, commonly termed suspended solids, which do not dissolve in water but remain in suspension. Whether solids remain in the water column or settle out in a stream is primarily a function of their specific gravity and the flow velocity. There are no state stream water quality standards for total suspended solids (TSS). Since turbidity and suspended solids are well correlated, the established standard for turbidity is considered sufficient to control this pollutant parameter. There is however, an NPDES standard for the maximum allowable concentration of 30 mg/l TSS that may be discharged from point sources of pollution into streams. Excessive concentrations of TSS may promote sedimentation behind dams, within channelized reaches, or within downstream reservoirs, and may markedly decrease the aesthetic value of a stream. The presence of suspended solids has been shown to decrease feeding by zooplankton (O'Conner, et al., 1975, and MPCA, 1984).

TSS concentrations measured in the St. Croix River near Prescott during the 1988 summer low flow period averaged approximately 3 mg/l. During the same time period, TSS values on the lower Minnesota River near Jordan averaged approximately 68 mg/l and near its confluence with the Mississippi, 55 mg/l. Similar readings obtained for Mississippi River flow near Anoka averaged 30 mg/l, and as flow exited the TCMA, TSS values averaged 20 mg/l (MWCC, March 1990).

Fecal Coliform Bacteria

The potential of water to spread massive epidemics is a matter of public record. The contraction of typhoid fever and other waterborne enteric diseases by humans has historically resulted in the loss of many lives. The number of fecal coliform bacteria present in a water body is used as an indication of the bacteriological quality of water and the health risk associated with using the water for human consumption or contact recreation. Coliform bacteria reside in the intestinal tract of both humans and animals, and are excreted in numbers in the order of about 50 million per gram. Untreated domestic wastewater generally contains over 3 million coliform bacteria per each 100 milliliter (ml) sample (Hammer, 1975).

Coliform bacteria themselves are harmless, but are used as indicator organisms for pathogenic bacteria (i.e. Salmonella) and viruses, since they originate from similar human fecal discharges. Pathogenic bacteria can be responsible for causing enteric diseases in humans. Laboratory analyses for pathogenic bacteria are difficult to perform, and are generally not quantitatively reproducible. The die-off rate of pathogenic bacteria is greater than that of coliforms outside of the intestinal tract of humans and animals in a surface water environment, justifying the use of coliform bacteria in determination of drinking water quality standards for the probability of ingesting pathogens. The Minnesota drinking water standard for the total number of coliform organisms present in the water for it to be considered fit for human consumption is a maximum of 1 per 100 ml of sample. That standard does not preclude the possibility of intestinal infection, but it presents a practical economic degree of acceptability (Hammer, 1975; Clark, et al., 1977; and MPCA, 1990).

The extension of the use of coliform bacteria in determining the quality of water for uses other than purposes of human consumption are less well defined. These bacteria can originate from any one or a combination of animal (cold- or warm-blooded) wastes, human wastes, or soil erosion; with no simple way of distinguishing between the human and animal bacteria. Nonpoint source pollution involving soil erosion can contribute significant numbers of coliform bacteria to a stream.

The maximum coliform concentration considered acceptable for body-contact water uses in Minnesota is 200 organisms per 100 ml of sample, and for general recreation uses is 1000 organisms per 100 ml during the May 1 through October 31 recreation season. These values are not based upon positive epidemiological evidence, for example, that bathing beaches with higher coliform counts are associated with the transmission of enteric diseases, but should be considered conservative from a public health risk standpoint. Most illnesses that develop as a result of contact with contaminated surface water cause infections of the skin and respiratory passages, with only about one tenth related to the transmission of gastrointestinal disorders (due to pathogenic bacteria). Thus, the coliform standard serves two completely different purposes; the drinking water standard prevents the potential mass transmission of pathogens in epidemic proportions, and the body-contact standards minimize the risk of disease transmission only by their assumed affinity to water-associated diseases of the skin and respiratory passages (Hammer, 1975).

Treatment processes utilized to reduce coliform and associated pathogenic bacteria to meet effluent standards are commonly referred to as disinfection facilities. The most common disinfection method used involves contact of the bacteria with a chlorine solution for a minimum specified period of time. Disinfection's bactericidal action results from a chemical reaction between HOCl and the bacterial or viral cell structure, inactivating required life processes. The MPCA has specified a maximum allowable concentration of total residual chlorine (TRC) in the stream following complete dilution of continuously discharging effluents of 6 μg/l to prevent potential chlorine toxicity in the receiving stream. The seasonal low flow in most receiving waters does not reliably provide adequate dilution of chlorinated effluents to protect aquatic life from chlorine toxicity problems. Therefore, in order to ensure compliance with water quality standards during those periods, the addition of dechlorination facilities has occurred at most plants to detoxify the discharge following disinfection. This is achieved by addition of yet another chemical, typically either sulphur dioxide or sodium metabisulfite, that can also be toxic to aquatic life in the receiving stream if improperly introduced. These disinfection chemicals are typically stored in gaseous form and require extreme care in handling by treatment plant staff, due to their potentially toxic effects on humans, if misused. A disinfection method that is improving, technologically, and becoming more cost-effective and reliable, utilizes ultraviolet (UV) radiation. The exposure of coliform and pathogenic bacteria to specific wavelengths and concentrations of UV light damages their intracellular genetic code, preventing replication. When properly sized and maintained, systems using this method of disinfection have proven to be as safe and reliable as those utilizing chemical addition (Hammer, 1975 and MPCA, 1985).

As a result of disinfection, MWCC wastewater treatment plants contribute less than one percent of the total number of fecal coliforms present within the TCMA segment of the Mississippi River during the long term summer season. In excess of 80% of the total measured amounts were estimated to have historically entered the river as a result of the operation of a system of combined sewer overflows (CSOs) on the Mississippi River. A heightened interest in use of the Mississippi River for recreational and developmental uses, both in the Metro Area and continuing downstream to Lake Pepin, as well as state water quality regulations, led to a reduction in the planned time frame to complete the ongoing CSO removal program from 40 years to 10 years. Total separation of TCMA sewers is scheduled for completion by 1996 (MPCA, 1984).

CSO flows are a water quality problem that decrease the aesthetic value, increase the fecal coliform and associated pathogenic bacteria concentrations, and increase suspended solids concentrations and turbidity in the Mississippi River, if not first diverted through a WWTP for treatment prior to stream discharge. The sanitary sewer portion of CSO contributes to a DO deficit that can persist within the receiving stream for up to two days following rainfalls greater than 0.1 inch per day. Modeling also indicates that a DO deficit of up to 3 mg/l may be created in the Mississippi River as a result of the CSO from a 0.7 inch rain. Therefore, during a low streamflow period, CSO due to a rainfall event creates a pulse of lower DO and higher BOD water that moves through and downstream from the TCMA (MPCA, 1984).

The average number of fecal coliform colonies counted during the summer low flow period in 1988 per 100 ml sample in the St. Croix River near Prescott was 21. During the same summer period, an average of 42 colonies were observed in samples from the Minnesota River near

Jordan, and an average of 55 colonies were observed near its confluence with the Mississippi. Mississippi River sampling during the same three month period indicated an average of 82 colonies in flow near Anoka, and an average of 66 colonies per 100 ml sample were observed instream as flow left the TCMA. The median values were lower than the presented averages in each stream, due to occasional values (averaged in) that were much higher than typical measured values (MWCC, March 1990).

Toxics

Polychlorinated biphenyl (PCB) and mercury contamination are the primary toxic contaminants found in TCMA streams. PCBs present a serious threat to human health and the environment. Since their introduction in 1929, PCBs have been used in a variety of commercial and industrial products such as transformers, capacitors, paints, inks, paper, plastics, adhesives, sealants, and hydraulic fluids. The Monsanto Corporation, the sole domestic manufacturer of PCBs, has now imposed restrictions on their production and has essentially eliminated all uses except those involving closed electrical components. Because of their widespread use in the past and their resistance to degradation, PCBs are widely dispersed throughout the environment (Corps, 1980).

Periodically since 1976, the Minnesota Department of Health (MDH) has issued warnings about eating fish taken from certain lakes and rivers in Minnesota. The advisories have been based primarily upon measured contaminant levels of PCBs and mercury in fish tissues. PCBs tend to accumulate in the fatty tissue of bottom-dwelling fish like carp that often disturb and consume contaminated sediments in their search for food. When contaminated fish are consumed by humans, the carcinogenic PCBs can affect the functioning of the liver and nervous systems, and cause skin disorders.

Although the production of PCBs was curtailed in 1971, they are still found in stream sediments, ground water contaminated as a result of improper disposal practices, air samples, wastewater, and other locations due to mishandling. Aroclor 1016 is a commercial variety of PCB that the MWCC has observed in similar concentrations in monitoring data for each of the flows entering the TCMA from the St. Croix, Minnesota, and Mississippi River watersheds, indicating contamination to be a widespread problem.

Ongoing monitoring programs suggest contamination levels may be decreasing. State and federal regulations requiring proper disposal of existing PCBs may be responsible for diminishing in-stream concentrations. The trend may also relate to deposition of uncontaminated sediments on top of the contaminated bottom sediments, their flow out of the TCMA watersheds (and further down the Mississippi River watershed), variations in flow of contaminated ground water plumes, or a number of other factors (MPCA, 1984). Twelve species of fish found in these three streams in the TCMA however, have been identified by the MDH to still potentially contain concentrations of PCBs or mercury that could accumulate within the human body to unhealthy levels.

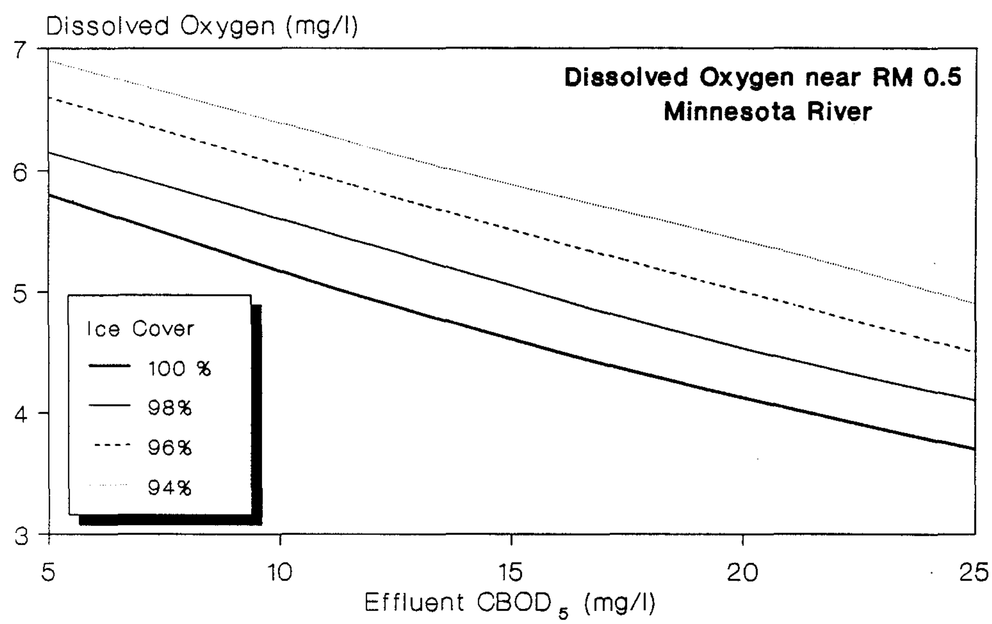
Similar concentrations of PCBs were detected within the flow of the St. Croix, Minnesota, and Mississippi Rivers as they entered the TCMA during sampling in September of 1988. PCBs as well as pesticides were detected within fish tissues and bottom sediments of all three streams during summer and fall sampling in 1988, indicative of historic instream contamination (MWCC, March 1990).

Stream Low Flow Phases

The high-flow and low-flow phases of a stream significantly effect the level of human activity that occurs either in or along the stream. High-flow phases are typified by spring floods resulting from snowmelt runoff and flash floods due to high intensity rainfall events. High-flow phases result in the greatest amounts of property damage and nonpoint source pollution. Low flow phases are characterized by periods with limited water inflow into a stream, and can be observed in winter and summer-fall seasons. Low flow concerns include whether there is sufficient flow in the stream to safely assimilate wastewater flows, provide public water supplies, allow for stream navigation, provide cooling water for power generation, allow irrigation of adjoining cropland, and promote recreational activities. Different degrees of low flow periods exist, including seasonal low flows, yearly low flows, 7Q10 flows, and historic low flows.

Winter low-flow phases occur yearly in varying degrees, depending upon climatic conditions and the size of the stream. A period of extreme low temperatures, when coupled with a very low flow-phase, can result in complete surficial ice coverage preventing reaeration, or complete solidification and flow stoppage of very small streams. Figure 14 shows the predicted DO response to ice coverage and changes in WWTP loadings in the Minnesota River near its confluence with the Mississippi under future conditions. In this figure, one can observe that as the river approaches a state of complete ice coverage, incremental increases in ice coverage can result in significant reductions in reaeration capabilities. Stream solidification can result in the elimination of dilution water for proper wastewater assimilation.

Figure 14
YEAR 2000 WINTER DO CONCENTRATION VS CBOD LOADING AT VARIOUS ICE COVERAGES



Source: MPCA, 1985

Historic low-flow phases occurring in the summer-autumn season are tied inextricably to drought events. Low flows during this season are usually selected as the critical design streamflows in determination of the maximum amount of pollutant discharge that may be assimilated by a stream without violating a baseline set of water quality standards.

Drought

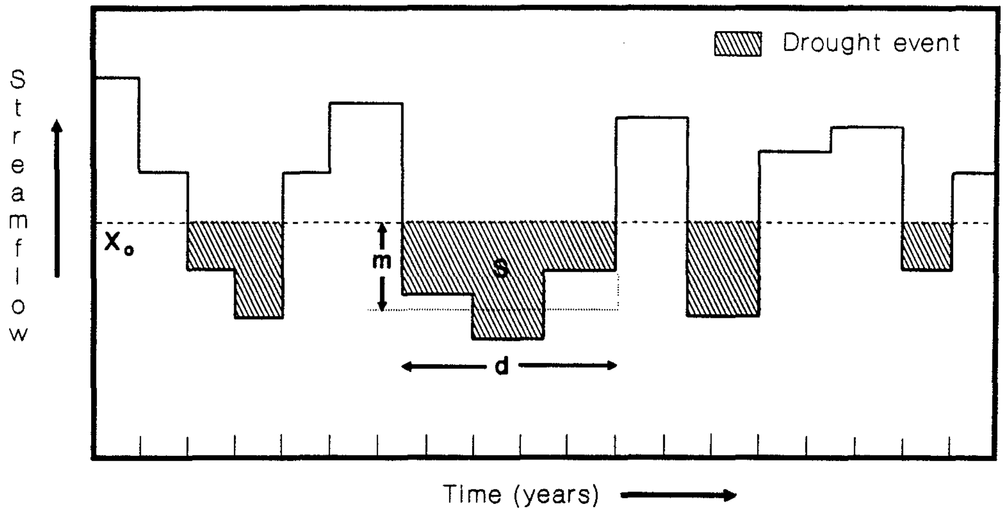
From a streamflow standpoint, a drought is characterized as any year or consecutive number of years during which average annual streamflow is continuously below the long-term mean annual runoff. A drought can similarly be related to other factors including precipitation, soil moisture, ground water levels, and Palmer Indexes. As shown in Figure 15, a drought event is considered to be composed of three components: severity (cumulative flow deficiency below the mean annual flow), duration (length of time flow is continuously below the mean annual flow), and magnitude (average annual deficiency below the mean annual flow). Notable multiyear droughts that have affected the TCMA occurred in the 1930s; 1950s; mid-1970s; and most recently, in the late 1980s (Sadeghipour and Dracup, 1985).

The major factor in the onset and perpetuation of droughts is the global circulation of air in the upper atmosphere, which is controlled by the arrangement and intensity of pressure cells. The most severe drought can end almost overnight with a change in the predominant airmass brought about by a reorientation of the upper air-pressure regimen. The onset of a drought is usually a subtle process. The first effects are observed by the agricultural community and homeowners in the form of low soil-moisture levels caused by below normal rainfall. The additional irrigation and lawn watering that ensue increase the demand for water from both surface and ground water reservoirs. Higher temperatures and stronger winds that are commonly associated with drought further aggravate soil-moisture depletion. When soil moisture is reduced, replenishment of groundwater reserves, even from rainstorms of moderate intensity, tends to be restricted because soil-moisture demand must be satisfied before water can percolate through the surficial soils and into ground water reservoirs.

The available water supply during drought years includes the precipitation during those years, and the surplus water from more humid years that has been held over as soil moisture, groundwater, and surface water, stored in reservoirs, lakes, and wetlands. Drought severity used to be evaluated largely on the basis of its impact on agriculture in the form of damage to crops and other vegetation, to livestock and wildlife, and to soil cover. Today however, municipal and industrial demands are heavier and more widespread, requiring droughts to be evaluated in much broader terms (Nace and Pluhowski, 1965).

Drought is only one of many causes of water shortages. Other causes include overdevelopment of water reserves, lack of storage and distribution facilities, improper design of distribution facilities, poor management of water supplies, and poor watershed management. Rapid growth of population and industry in the TCMA will continue to intensify the problems associated with shortages as a result of drought. Several of these problems are dealt with in greater detail in working papers 2, 3, 4, and 8 in this technical report series. Reaction to drought too often is exemplified by the flow chart in Figure 16. Once in this loop, planning for the future, approval of financing, and providing facilities to alleviate atypical drought conditions in the future are thwarted. While little can be done to prevent the recurrence of droughts, much can be done to alleviate their effects-- provided facts on their intensity, duration, and frequency are known, if mitigation measures are put into place prior to the arrival of the next, possibly more severe drought (Matthai, 1979 and Lindskov, 1977).

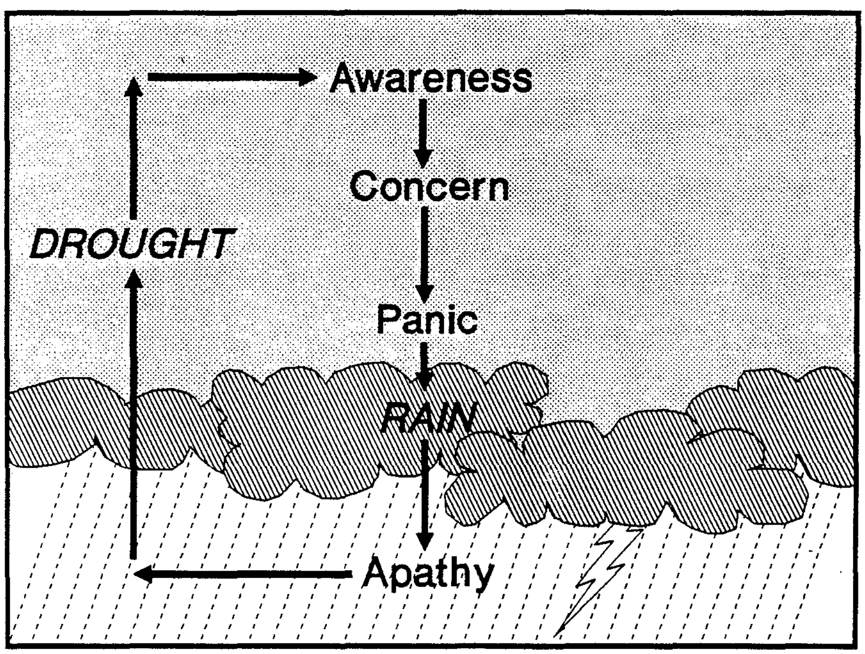
Figure 15
FUNDAMENTAL PARAMETERS OF DROUGHT EVENTS



s = Drought severity
m = Drought magnitude (avg)
d = Drought duration
X_0 = Mean annual flow

Source: Water Resources Bulletin, June 1985

Figure 16
PROGRESSION OF DROUGHT PERCEPTIONS



Source: USGS Prof. Paper 1130, 1979

The drought experienced in the TCMA from 1987 through 1989 arrived on the heels of the wettest five-year period on record in the TCMA. Over that period, precipitation averaged more than 9 inches above normal yearly accumulations. The Crow River at Rockford, the Minnesota River at Jordan, and the Mississippi River at both Anoka and St. Paul all experienced average May flows in 1986 that exceeded recorded flow data for the 50 preceding years. Record high lake levels were also a common occurrence as a result of this extended period of above-average precipitation. The lowest average daily flow measured at St. Paul on the Mississippi River during July through September of 1986 was 19,800 cfs. The flow levels during that period were the highest summer-season flows on record for that gaging station. By the fall of 1986 however, precipitation had begun to diminish in both the TCMA and Mississippi Headwaters region to between 50 and 75% of average expected amounts. As this trend continued through the fall of 1989, flows in the Mississippi River at St. Paul ultimately dropped below its established 7Q10 value for 48 consecutive days during June through August of 1988. Similar critical low flows were experienced in the Minnesota and other TCMA rivers. Figure 17 compares the historical average to recorded average flows in the Minnesota and Mississippi Rivers during both the high precipitation period of 1982 through 1986, and the low flow in 1987 and 1988 (USGS, 1988).

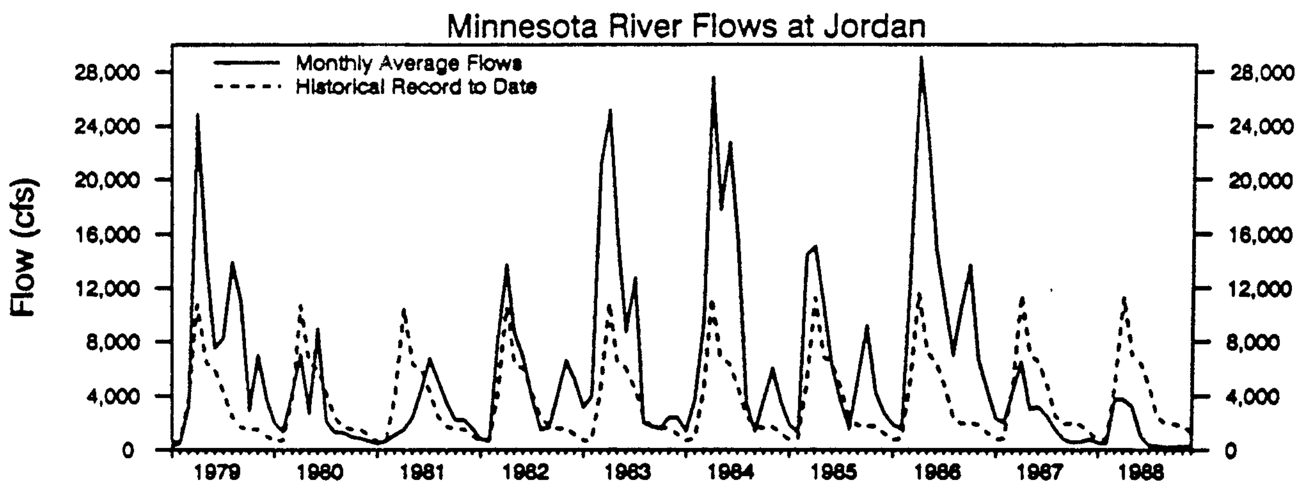
Analysis of USGS streamflow records obtained during the prolonged drought of the 1930s indicates that inflow sources to the Mississippi River, both within the TCMA and upstream to its headwaters, may not be as dependable in their contribution to instream flows through the TCMA during future periods of drought as they were through our most recent drought. We may have been extremely fortunate through the relatively short drought of 1987-89 to have just experienced the wettest five-year period on record within this portion of the Upper Mississippi River watershed. From 1982 through 1986, soil moisture levels increased, surface water levels rose, and ground water levels rebounded in response to increased amounts of natural recharge and decreased withdrawals for water supply uses (Schoenberg and Mitton, 1990).

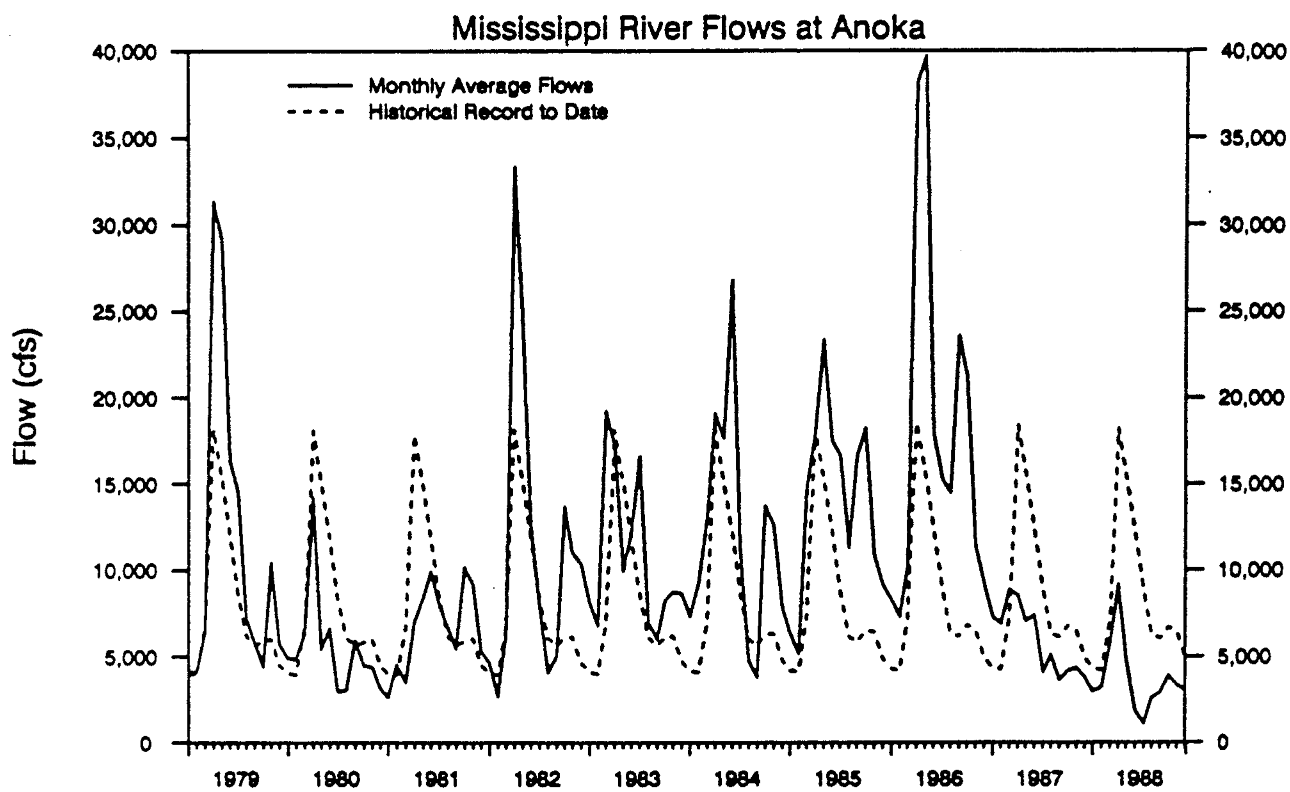
Further study of the dependability of inflow to the Mississippi River from the Headwaters area through the TCMA during past recorded drought periods is necessary to project minimum amounts of inflow we may expect during future drought occurrences. Typically, the duration of a future drought would exceed the most recent one experienced in 1987-89. Soil moisture, surface and ground water levels should also be expected to be lower at the outset of a future drought, characterizing more ordinary climatic conditions.

Flow augmentation has been suggested as a means of low flow maintenance within the Mississippi River. If specific flow augmentation alternatives are to be considered viable during future drought periods, we must be sure that they will be adequate to overcome the losses due to outflow through stream reaches where this phenomenon can be anticipated to recur, based upon the historical record. Oversight may be necessary in the future of the water sinks that historically have provided inflow to stream reaches where those inflows could be critical for baseflow maintenance, or to prevent outflow during future periods of drought. Potential flow augmentation sources must also be evaluated for their capacity for carry-over storage. During a multiyear drought, the increased demands are typically felt during its latter stages. An inadequate augmentation source, or one over-utilized during the early stages of drought, might then be unavailable when most needed.

Figure 17

MONTHLY AVERAGE FLOWS FOR THE MINNESOTA AND MISSISSIPPI RIVERS IN THE TWIN CITIES METROPOLITAN AREA 1979-1988





Source: MWCC, 1988

Mississippi River Low Streamflow Concerns

Low streamflow concerns exist for all streams within the TCMA, but the Mississippi River bears the most responsibility for continued service to area residents in all of the use categories. Lock and Dam No. 2 and the upstream pool it creates on the Mississippi River maintain a constant water surface elevation within the Minnesota River channel for several miles above its confluence with the Mississippi during yearly low flow periods. The following is a discussion of streamflow users and uses that may be compromised during periods of low flow.

Federal Controls

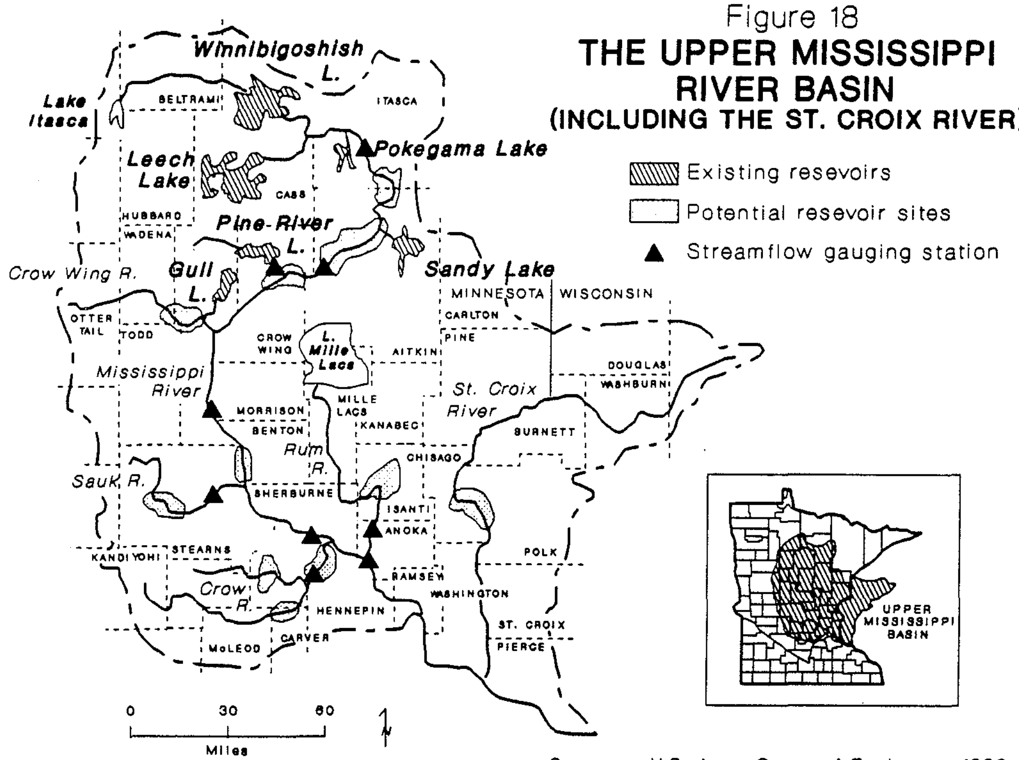
The U.S. Army Corps of Engineers (Corps) has ultimate legal control of the use of federal project waters at the Mississippi Headwaters Lakes projects. The six-reservoir headwaters lake system shown on Figure 18 includes Lakes Winnibigoshish in Itasca and Cass Counties, Leech in Cass County, Pokegama in Itasca County, Big Sandy in Aitkin County, Pine River in Crow Wing County, and Gull in Cass and Crow Wing Counties. Lakes Leech and Winnibigoshish contain approximately 75% of the total capacity of the six lakes (Corps, 1990).

These reservoirs have a combined surface area of over 370 square miles and a combined storage volume of approximately 1.6 million acre-feet (521 billion gallons) of water. Construction of the dams at each of the six Mississippi River headwaters lakes was authorized by the River and Harbor Acts of June 14, 1880 and August 2, 1882. Construction began in 1881, and the Corps of Engineers completed the headwaters reservoirs project in 1913. The primary purpose of construction of the six dams was to provide flow augmentation for Mississippi River navigation within and downstream from St. Paul (Corps, 1990).

The area surrounding the headwaters lakes was occupied by the Minnesota Chippewa people at the time of construction of the dams, and the Chippewa leaders were concerned about the effects of widely fluctuating lake levels on the wild rice and other resources. Thousands of acres of wild rice grow in shallow, interconnected flowages whose water levels are controlled by dam operation. The rice seeds ripen over time, so beds are harvested by canoe many times over during a harvesting season that ranges from mid-August into October. Harvesting is severely restricted by drops in reservoir levels during this period that render many beds inaccessible. Continued minimum daily releases of water at the dams can result in significant losses, even in years not marked by drought. Increased lakeshore development for both recreation and resort purposes, and downstream agricultural development have occurred that have also translated into a desire for the maintenance of stable lake levels by all project area residents (Corps, 1990).

The need for water releases from the six lakes for navigation was greatly reduced after completion of a 9-foot channelization project on the Mississippi River during the 1930s. For continued commercial navigation purposes, the headwaters project dams are most needed during low flow conditions. The House Committee on Rivers and Harbors passed a resolution on June 7, 1945, requesting review of the headwaters lakes water control operation. Several interim studies have been completed in response to that resolution in an attempt to identify and resolve reservoir related problems. The most recent report, a Low Flow Review issued in October of 1990, essentially recommends that the St. Paul District Engineer continue to use the existing regulation plan and have complete and independent responsibility and authority for water control of all six headwaters dams, within specific constraints established by Congress and higher U.S. Army and

Figure 18
THE UPPER MISSISSIPPI RIVER BASIN (INCLUDING THE ST. CROIX RIVER)



Sources: U.S. Army Corps of Engineers, 1990; UMRCBS, 1970.

Corps of Engineers Command. In fulfilling his duties, the St. Paul District Engineer consults with the state of Minnesota Department of Natural Resources (DNR), the Minnesota Chippewa Nation, and other interested parties, concerning the water control operation of the six headwaters dams. The District has no formal agreements with other agencies regarding the regulation of any of the headwaters lakes.

Routine low flow releases from the headwaters lakes system total 270 cfs. Due to their location, 20 to 24 days of travel time are required for water released from these reservoirs to flow the approximate 400 miles to the TCMA.

State Controls

In 1973, the Minnesota Legislature established five priority classes of water use. While the effects of the most recent drought that extended through 1988 were still fresh in everyone's memory, the original priorities of the water appropriation Rules were modified by the 1989 Legislature. Current priorities from highest to lowest are as follows:

1) Domestic water supply, excluding industrial and commercial uses, and essential power production that meets contingency planning requirements (requirements during a widespread drought when other power suppliers within the supply grid may be having difficulty meeting demands);

2) Water use that involves consumption of less than 10,000 gallons per day (gpd);

3) Agricultural irrigation and processing of agricultural products;

4) Power production in excess of the use provided for in the contingency plan requirements; and

5) All other uses, involving consumption in excess of 10,000 gpd, including non-essential uses of public water supplies.

Minnesota Rules Part 6115.0620 requires that a permit be obtained from the DNR for appropriation of water in excess of 10,000 gpd or 1 million gallons per year. There were 59 active permits for water appropriation from the Mississippi River between the Winnibigoshish Dam and Lock and Dam No. 2 near Hastings on record during the recent drought period (Corps, 1990).

The 1988 drought increased the priority for drought planning by many agencies with jurisdiction in Minnesota. The governor appointed a drought task force to outline the activities and responsibilities of various parties affected by low stream flow during each phase of the drought. The Metropolitan Council short-term water supply plan focused upon getting a process in place that would provide for an immediate response to drought-related problems affecting the TCMA. Drought phases in the process are triggered by a combination of factors, including precipitation deficiencies, declining streamflows, the Palmer Drought Index, frost depths, lake and reservoir levels, and groundwater conditions. The streamflow factor is specifically tied to the lowering of flows in the Mississippi River at RM 871 in Anoka below benchmark levels for periods exceeding 72-hours. Table 5 represents all phases of the Drought Coordination Matrix, describing actions that can be taken by state and federal agencies, public water suppliers, industrial users, and agricultural and self-supplied interests. The Corps has assumed the coordination and public information/involvement activities for the team of agencies (Corps, 1990 and Council 2/90).

In spite of the tremendous volume of water stored in the six Headwaters reservoirs, increases in the routine volume of 270 cfs of water released will likely not occur. The Corps would consider, but not automatically begin, emergency releases when flows at Anoka drop below the critical flow of 554 cfs. This critical flow would allow minimum flow needs for the Minneapolis Water Works (132 cfs), St. Paul Water Utility (70 cfs), the Upper St. Anthony Falls (USAF) lock (350 cfs), and consumption at the High Bridge and Riverside power facilities (2 cfs). Since emergency-release-flows would take approximately three weeks to reach the TCMA, the Corps reserves the right to time that ultimate decision of exactly when to make the release, on the basis of current factors at that time. The flow of 554 cfs would not however, provide sufficient instream flow to assimilate wastewater discharges to the Mississippi River without probable violations in water quality standards (Corps, 1990).

Water Quality/Waste Assimilation

Drought conditions are usually considered to exert the greatest degree of stress upon the quality of water in a stream. For this reason, they exemplify the best conditions in which to determine the assimilative capacity of a stream for pollutants. Under such conditions, dilution is at its lowest, the decay coefficient is highest for pollutant materials exerting BOD, and the oxygen saturation concentration is lowest due to high water temperatures (Eheart, 1987).

Table 5
AGENCY DROUGHT COORDINATION MATRIX

Condition and Program Phase	State and Federal Actions	Public Water Suppliers	Industrial (Local Actions)	Agricultural and Private
NORMAL CONDITIONS: * Water quantity is adequate for normal purposes; water quality is acceptable under normal management. * Normal releases from reservoirs. * Normal precipitation/weather patterns/Hydrologic conditions	* Develop precipitation, streamflow, ground water, and water quality monitoring programs. * Conduct state and regional water studies and coordinate recommended actions. * Assist public water suppliers and local government in developing emergency water management plans. * Establish public education program. * Emergency planning is needed in a generic sense.	* Develop Emergency Water Management Plans. * Develop additional storage and treatment facilities; evaluate distribution system. * Adopt standby rates, other necessary ordinances and codes, and establish mutual aid agreements, interconnections, conservation education, etc.	* Develop Individual Emergency Water Management Plans. * Develop additional wastewater storage. * Develop alternative water storage, and conservation measures. * Purchase standby equipment and install permanent equipment as necessary for recycling.	* Develop emergency water management plans. * Evaluate need for irrigation. * Enlarge ponds, purchase tanks, drill wells, install conservation devices and livestock watering tanks, etc. * Evaluate agricultural water use and find where conservation could be used. * Evaluate domestic water use and install water-saving devices, etc., to reduce stress on supply source.
DROUGHT WATCH: * Lower than normal precipitation, declining streamflows and groundwater levels. * Palmer Index, Frost, Reservoir and lake levels, snow/water content, streamflow, groundwater condition result in a 30, 60, 90 day outlook that is deficient.	* "Drought task force" initial meeting (see agency list). * Intensify selected monitoring activities. * State initiates an awareness program via media, etc.	* Monitor water sources and daily water use for specific purposes and anticipate user demand. * Monitor potential conflicts and problems.	* Monitor water source and daily water use for specific purpose and anticipated demand. * Monitor water quality.	* Monitor water sources and daily water use for specific purposes and anticipate demand.

Condition and Program Phase	State and Federal Actions	Public Water Suppliers	Industrial (Local Actions)	Agricultural and Private
<u>CONSERVATION PHASE: 1000 cfs</u> * Water quantities/water quality deteriorating or conflicts among users. * Agency/utilities appeal to public for voluntary conservation. * Public awareness program. * Closely monitor drought indicators. * Monitor NWS 30, 60, 90 day weather and precipitation projections. * Monitor NWS streamflow projections.	* More frequent "task force" meetings to exchange water supply and water quality data and discuss actions. * Monitor systems and users having past problems and monitor plan implementation. * Respond to local and individual appeals for assistance. * State agencies issue orders to water suppliers and/or dischargers. * Public information about conditions. * Public water conservation education/encourage.	* Implement "conservation" phase at plan triggering point. Potential conservation measures include curtailment of outside uses, education, and pricing. * If conservation goal is not obtained, implement restrictions. * Notify MDNR of source conflicts.	* Institute re-cycling, cut back production, store wastewater, alter production schedule per emergency industrial water management plan during a drought. * Notify MDNR of source conflicts.	* Continue conservation of domestic supplies. * Notify MDNR of source conflicts. * Implement water conservation measures for agricultural uses.
<u>RESTRICTION PHASE: 750 cfs</u> * Insufficient supplies to meet all demands. * Allocation suspensions taking place. * Continued decline in water supply and/or water quality. * Utilize drought indicators. * Utilize NWS 30, 60, 90 day weather and precipitation projections. * Closely monitor NWS streamflow projections.	* Same responses as in Conservation Phase and State implements mandatory restrictions. * State Contingency Actions accomplished (example: ease NSP thermal permit). * Consider emergency releases from reservoirs above the low flow plans.	* Implement "restrictions" phase at plan triggering point. Restrictions could include banning of some outdoor water uses, per capita quotas, cut-backs to non-residential users. * Notify MDNR of source conflicts.	* Institute additional cut-backs in production, storage of wastewater, or changes in production schedule, etc., per emergency industrial management plan or Commissioner's orders for suspensions. * Notify MDNR of conflicts.	* Same response as in Conservation Phase. * Follow MDNR allocation restrictions on irigation.
<u>EMERGENCY PHASE: 554 cfs</u> * Severe water supply or water quality problems. * Highest priority water suppliers not being met. * Threatened or actual power "brownouts" * MAPP (NSP power pool) resources threatened. Strict monitoring of drought indicators. * Strict monitoring of weather and streamflow projections.	* Governor responds to critical situations by declaring an emergency. * MDEM implements emergency operations plan. * State agency mediates conflicts. * Consider Corps PL-99 authorities. * Implement emergency releases from reservoirs above low flow plans.	* Provide bottled water and sanitation supplies to users. * Make hospitals, firefighting, etc., priority. * Initiate hauling of water. * Comply with State Commissioner's Orders.	* Comply with governor's Emergency Declarations. * Coordinate emergency action with local government. * Implement hauling water for sanitation, domestic uses.	* Request local government assistance in obtaining water for domestic purposes, and in supporting livestock. * Implement hauling water, etc., in cooperation with local governments.

Source: Corps, 1990

A strict water quality basis does not exist for the use of the 7-day, 10-year low flow (7Q10) as the design stream flow in developing wasteload allocations. While use of the 7Q10 flow is considered to be for the protection of water quality, its use nationally as the most common legal index for pollution control and abatement, including Minnesota's Pollution Control Agency, is because historic 7Q10 data tends to be the most readily available streamflow statistic (Biswas et al., 1984).

In 1980, the water quality data available for TCMA streams was ranked as one of the more complete data assemblages in the country for water quality management planning purposes. However, the scope of the water quality management field has now been broadened to include monitoring and control of stormwater discharges and surface runoff from nonpoint discharge sources. As the influent loadings at metro area wastewater treatment facilities continues to increase in response to increases in the sewered population, discharge effluent limitations are also becoming increasingly more restrictive and inclusive. One effect of these changes is the ever increasing need for additional stream data to more accurately model natural stream processes (EPA, 3/80).

Public Water Supplies

The Minneapolis Water Works and St. Paul Water Utility rely on Mississippi River water as their sole and primary sources, respectively, in their service of potable water to all or part of 18 TCMA cities. Although the Mississippi River is affected by numerous pollution sources above Anoka (near RM 871), the location of the Minneapolis and St. Paul water treatment facility intakes are both above the two most significant sources of diminished quality water to the Mississippi River in the TCMA. Those two sources are the Minnesota River at RM 844 and the MWCC Metro WWTP at RM 836.8.

The Minneapolis Water Works withdraws water from the Mississippi River to supply the cities of Minneapolis, Columbia Heights, Hilltop, Golden Valley, New Hope, Crystal, and portions of Bloomington and Edina. The water is withdrawn at approximately RM 858 in Fridley and treated prior to distribution at the Water Works facilities located in Fridley and Columbia Heights. The withdrawal capacity is approximately 200 million gallons per day (mgd) (310 cfs) and treatment capacity is approximately 170 mgd (260 cfs). The intake structure is located on the river bottom, at an approximate maximum elevation of 795.8 feet. At river flows below 1000 cfs, water level in the area of the intake is controlled by the elevation of the crest of the USAF dam at RM 848. Under normal circumstances the USAF dam crest is between 796.5 and 796.8 feet, but adding flashboards to the dam would allow the crest to be raised to 799.2 feet in an emergency situation. Flow into the pool above the USAF dam would have to be less than the volume of water being withdrawn by the Water Works for pooled water behind the dam to drop below the top of the intake structure, thereby jeopardizing drinking water supplies. This situation would also cause result in no flow out of the pool, an unacceptable situation for all subsequent downstream River uses. The historic flow record has not registered a flow that low within this reach of the Mississippi River to date. Intake hydraulic design constraints would control flow withdrawal capabilities at Mississippi River flows below 310 cfs (Council, February 1990 and Corps, 1990).

The St. Paul Water Utility withdraws about 70% of its total water demand from the Mississippi River near RM 863, about five miles upstream from the Minneapolis Water Works intake, and pumps it into the Vadnais chain of lakes. The utility also draws water from the Rice Creek chain of lakes (Centerville and Peltier), from four ground water wells, and from direct runoff water into the Vadnais chain. Water is then withdrawn, treated, and distributed to supply the cities of St. Paul, Lauderdale, Falcon Heights, Roseville, Arden Hills, Little Canada, West St. Paul, Maplewood, Mendota Heights, and a portion of St. Anthony with potable water. The Utility is able to discontinue Mississippi River withdrawal and rely on its supplemental lake and ground water sources to meet all of its needs for periods of up to 30 days. Since river water passes through the Vadnais chain of lakes prior to treatment and distribution, short term Mississippi River water quality fluctuations due to low flow do not create immediate water treatment problems for the Utility.

Potential water supply problems that could occur during low stream flows that might affect each of the utilities include exposure of their intake structures above the stream surface; slow moving, untreatable chemical or nuclear spill plumes passing over the intakes requiring their temporary closure; or treatment facility or distribution equipment failure. The St. Paul Utility is also vulnerable to problems in the two lake chains from which they withdraw, and potential ground water contamination or drawdown difficulties at their well site.

Potential water quality problems as a result of low stream flows are typically related to taste, odor, or turbidity of the treated water. Treatment process adjustments may be made on a daily basis, but may be more imposing during summer low flow periods due to both increases and rapid fluctuations in the phytoplankton population and their resultant effect upon the chemical characteristics of water in the streams (and lakes). The Minneapolis Water Works experienced treatment difficulties during low river flow periods in the summer of 1976. Decomposition products were present in the Mississippi River as a result of the dieoff of algal blooms upstream of the TCMA. Presence of those products imparted annoying taste and odor qualities to the water supply that persisted, even after supplemental treatment with potassium permanganate (Hansen, 1983).

As a direct consequence of the MWCC Anoka WWTP discharge of treated wastewater above the Minneapolis and St. Paul water supply intakes, the plant is slated for phase-out during 1992. Its flow will be diverted to the Metro WWTP for treatment. The Anoka facility currently discharges its treated effluent into the Mississippi River near RM 871, approximately eight miles upstream from the closest water supply intake structure, operated by the St. Paul Water Utility. Plans for phaseout of this plant began approximately ten years ago, when determination was made that rerouting of the flow was preferred over upgrade and expansion of the plant to continue discharge of effluent above the public water supply intakes. The more stringent effluent permit limitations that would have been required at an upgraded Anoka plant precluded its consideration as an alternative to the chosen phase-out alternative.

Navigation

Locks

A Mississippi River barge is typically 35 feet wide and 195 feet long. Unloaded, its draft (depth of its keel below the water line) may be only 1.5 to 2 feet; when full, the draft can be 8 to 8.5 feet. "Barge tows" consist of 1 to 15 individual units and travel at speeds of 7 to 8 mph, or about 11 feet per second (fps). Tugboats operating on the navigable TCMA rivers typically have twin engines and range from 4000 to 6000 hp. Smaller switchtugs, used to move individual barges, are typically powered by a 1000 hp engine. Conceptually, the stream power of the flowing river can be compared with the power of a tug. To equal the amount of work done per linear foot of river by a 5000 hp barge tow traveling at 11 fps, a river with the characteristics of the Mississippi near the Metro WWTP flowing at a near-7Q10 flow of 2000 cfs would have to travel an equivalent distance of 169 miles. This basic power comparison is made simply to stress the major impact upon river mixing of barge tows and tugs at very low summer flow rates (Stefan, 1982).

Minnesota River tows typically consist of one power unit and two to four barges, transporting primarily bulk grain or grain products. During peak shipping periods, the average time between passage of towboats is less than four hours. Commercial traffic is expected to increase in the future (MPCA, 1985).

The commercial navigation locks on the Mississippi River require a certain amount of river flow to operate. Lock operation does not consume water. Upstream water is used to fill the lock each time a vessel enters from downstream, raising the vessel to the upstream water level. In completing the cycle, a vessel may then enter the lock from upstream, and water in the lock is discharged out of the lock into the downstream flow, lowering the vessel to the downstream level. The Upper and Lower St. Anthony Falls Lock and Dams, and Lock and Dam No. 1 and No. 2 replace what was formerly a natural stream elevation change between RM 853.8 and RM 815.3 of approximately 125 feet. The objectionable effect of these dams has been to reduce flow velocities in the pooled areas upstream from the dams. The reduced flow velocities, especially during low flow periods, result in continuous settling out of sediment and organic matter within the river channel. The settled out organic matter exerts an oxygen demand upon the stream, and settled sediments provide associated nutrients that promote phytoplankton growth in the pooled reaches.

The USAF lock, located in Minneapolis, requires the largest volume of water for a single lockage. It would require a river flow of about 700 cfs if it were to cycle continuously, as fast as safely possible. Fortunately, however, the USAF lock has the least traffic of all of the locks, and a flow of about 350 cfs will provide adequate operation to handle current commercial navigational traffic. USAF lock operation is not expected to detrimentally affect the level of water over the Minneapolis Water Works intake structure (Corps, 1990).

In response to water quality concerns about DO concentrations in the Mississippi River in 1988, the District provided small openings in gates and stop logs at the St. Anthony Falls lock structures, and Lock and Dam Nos. 1, 2, and 3 to provide supplemental aeration. The detectable benefits on the DO levels in the river are small, but the practice is locally beneficial to aquatic life with no operational drawbacks down to river flows of about 750 cfs. At flows lower than 750 cfs, the practice could be restricted in favor of navigational requirements (Corps, 1990).

Channelization

Before construction of the 29 lock and dam structures and channelization of the Mississippi within and south of the TCMA, the river bottoms consisted primarily of wooded islands. The islands often contained hay meadows and small farming areas. Deep sloughs were common, with hundreds of lakes and ponds scattered along the river within the flood plain.

The St. Paul District of the Corps of Engineers is authorized to maintain a 9-foot deep and 300 feet wide navigation channel on 243 miles of the Mississippi River below about RM 855. Their authority has also been extended to include maintenance on the lower 14.7 miles of the

Minnesota River, and lower 24.5 miles of the St. Croix River within the TCMA. The "9-foot" channel description is not quite accurate, since channels are usually overdredged to depths of 11 to 13 feet. The elevation datum used to determine desired channel depths is correlated with the elevations of flow over the dams. Past maintenance of channel depth consisted primarily of dredging, but increased emphasis is being placed on the use of control structures like wingdams, that tend to increase current velocity in the main channel and improve the sediment carrying ability of the rivers in areas historically subject to sediment deposition. Yearly dredging is still necessary in some areas however, on both a routine and emergency basis. Up to one million cubic yards of sediment is dredged each year within the St. Paul district.

Historically, channel dredge material was deposited close to its source, for use as fill for shallow pools or for beach material along the Mississippi and St. Croix in an effort to enhance the attractiveness of these areas for recreational purposes. Until the mid 1970s, wetlands and other shallow pools were looked upon as waste areas whose only value was in conversion to agricultural or developmental use. Recent research now documents the many public benefits of leaving them in their natural state. Current disposal of dredged material typically involves its transport away from the river to transfer sites where it is available for a variety of beneficial uses as construction fill.

The physical act of dredging results in the following immediate negative water quality effects within a stream: an increase in turbidity and suspended solids within the water column, the resuspension of polluted and nutrient-laden materials, and a reduction in instream DO levels in response to exposure of materials having a high organic content. These materials in turn negatively affect the aquatic environment by promoting bioaccumulation of released pollutants, destruction of river bottom communities by physically covering them, blockage of the respiratory surfaces of aquatic organisms, and alteration of established habitats to degrees that are difficult if not impossible to quantify. Fish are usually able to escape all but the bioaccumulation effect, but less mobile life forms like crustaceans, periphyton, and benthic zooplankton are not. Some benthic organisms are able to recover from burial by vertical migration through as much as a meter of settled disposal material if the material is similar to the original substrate. If however, the newly settled material differs from the original substrate, like mud settling over sand, benthic dwellers can smother by being covered with as little as a few centimeters of disposed sediment (Corps, 1980 and MPCA, September 1980).

Channelization is in basic conflict with the natural equilibrium of a stream. Unquestionably, the process results in stream reaches exhibiting enhanced flood protection and increased navigation capabilities, but it can eliminate some natural purification processes. These natural processes involve diversion of floodwaters through historic oxbows and create overland sheet flow across adjacent marshlands and wetlands, maintaining wildlife habitats and depositing nutrient-laden sediments outside the normal stream channel.

Power Generation

A number of thermoelectric generating plants and industries make use of the Mississippi, Minnesota, and St. Croix river flows for the cooling of steam condensers and machinery. The maintenance of full-capacity operation levels at power generation plants is of greatest concern during low streamflow periods because the plants typically require significant volumes of water for noncontact cooling purposes. Open-cycle plants pump water through a condenser and discharge it directly back to the water source, consuming very little water. Plants that operate in either helper-cycle modes, where water is pumped through cooling towers prior to being discharged, or closed-cycle modes, where water is reused for cooling after being run through cooling towers, typically consume several times more water than open-cycle plants. To a certain extent, cooling water can be recirculated in lieu of using additional streamflow when streamflow drops to extremely low levels, but some additional water must be withdrawn from the stream to make up for evaporation losses and to dilute salinity buildup (already at peak levels during late summer) in the cooling water system prior to its discharge back into the stream (Corps, 1990).

Table 6 provides a listing of the power generating plants in the TCMA that utilize streamflow for cooling purposes. Northern States Power (NSP) Company's Sherco and Monticello thermoelectric plants are located (above the TCMA) along the Mississippi River at RM 904.5 and RM 901, respectively. These two plants provide roughly half of NSP's base load generating system capacity. They are both located in freeflowing reaches of the Mississippi River above the Minneapolis and St. Paul water intakes and are dependent upon a flow of between 200 and 250 cfs just to keep their intake structures submerged and functioning. Sherco operates closed-cycle year-round. All other NSP plants in the TCMA operate in either the helper- or open-cycle cooling modes that consume less water during the summer low streamflow period. The Monticello plant is allowed to appropriate up to 645 cfs, but never more than 75% of the river flow. So, when river flow drops below 860 cfs, the plant must begin to recirculate a portion of the cooling tower discharge water to the condenser (Corps, 1990).

The NPDES permits for power generation plants include requirements for thermal assimilation of their discharge within each receiving stream. The requirements vary according to the classification of each particular stream reach, and depend on relative temperatures and flow rates within each respective stream reach to provide an adequate thermal sink for waste heat. Typically, an increase of streamflow temperature by a specific amount over the average monthly temperature of record is allowed, up to a specific maximum water temperature.

Although the 1988 drought resulted in generating limitations for NSP facilities, service to NSP customers was never jeopardized because of a combination of system generation and power purchases. Combined physical (low streamflow) and regulatory (seasonal discharge temperature limits and low streamflow) water use constraints during the 1988 drought at times caused the Monticello plant to be temporarily limited to 70% of its generating capacity. That generation loss of up to 160 megawatts (Mw) occurred during a time of peak system demand, requiring power purchases from other power generation companies at substantially increased costs that were passed on to NSP customers within the TCMA.

MPCA offered to waive NPDES permit requirements and allow NSP to exceed thermal assimilation limitations in their discharge during the 1988 drought period, but NSP declined since replacement generation capacity was available. While this loss was considered a tolerable one by NSP, further streamflow reductions or higher streamflow temperatures that would cause the loss of the entire generation capacity of either Monticello or Sherco, or both under similar peak conditions, would create power shortages for customers. Their shutdown could also be expected to cause severe electrical equipment damage to the NSP system and the entire Mid-Continent Area Power Pool (MAPP), of which NSP is a member (Corps, 1990).

Table 6
NSP MINNESOTA THERMOELECTRIC POWER PLANT SURFACE WATER USE RATES

Appropriation Plant	Generating Capacity (Mw)	Summer Cooling Mode	Maximum Consumptive Use (cfs)	Permit Limit Diversion (cfs)
<u>Miss. R. above TCMA</u>				
•Sherco (Becker)	2200	Closed	47	67*
•Monticello	547	Helper	10	645
<u>Miss. R. below WS Intakes</u>				
•Riverside (Mpls)	326	Open	1	543**
•High Bridge (St. Paul)	360	Open	1	490*
<u>Minnesota River</u>				
•Black Dog (Burnsville)	443	Open	1	633**
<u>St. Croix River</u>				
•King (Oak Park Heights)	571	Helper	14	660

* Converted from gpm limit
** Converted from acre-feet per year limit
WS Water Supply

Source: Corps, 1990

Future low flow events should be anticipated that will necessitate NSP facility operation at capacity levels. This will likely cause thermal permit limitations to be exceeded in lieu of local brownouts that would jeopardize the health and safety of TCMA residents. If flows would continue to drop below the ability of those facilities to withdraw water from the streams, the only alternative would be to cease operation. Supplemental emergency headwaters lakes discharges cannot be solely relied upon because of the estimated three weeks of travel time the extra flows would take to arrive, the uncertainty of whether there would be an emergency headwaters release at all, and the probability that the release would be insufficient to satisfy all NSP facility needs. Additional supplemental streamflow source(s) that would be available during future low flow, emergency situations, should be put in place to prevent damages due to the loss of electrical power to the TCMA.

Irrigation

The DNR has authority to limit consumptive uses of streamflow during drought periods, having exercised this authority to limit or cease withdrawal from the Mississippi River for some uses during the 1988 low flow period. Generally, these limitations are first imposed upon the agricultural and horticultural irrigators. There were 36 permits in effect during 1987 and 1988 for water appropriation from the Mississippi River above its confluence with the St. Croix River for crop irrigation and 4 additional permits for water for golf course and landscaping watering purposes. These 40 permit holders had the combined authority to appropriate approximately 110 cfs from the Mississippi River under normal flow conditions. The next group of users that would experience use restrictions during an extreme low flow period would be industrial users, in an effort to reserve as much flow as possible for municipal water supplies and cooling water for electrical power generation (Corps, 1990).

Surface water appropriation from the Minnesota River for irrigation purposes within the TCMA is unlikely in areas adjoining the river because agricultural soils in those areas tend to be heavy and poorly drained. Any future increase in irrigation water demand along the river's lower reaches will most likely be met by the use of ground water sources (MPCA, 1985).

Recreation

Boating

Each of the lock and dam structures on the Mississippi River has created an upstream pool of water that provides opportunities for recreational use and enjoyment. Recreational boating is limited in some areas however, because channel maintenance to accommodate commercial navigation has resulted in areas that are very shallow, filled with tree stumps, and contain channel structures like wing dams or closing dams that boaters must be able to recognize and avoid. As flows diminish in the river, obstacles become more numerous, but not necessarily visible, and formerly navigable areas can become too shallow in which to navigate. Boat landings on free-flowing reaches of the river can become unusable as water levels decrease due to a drop in the flowrate. Landings located along the pools upstream of river control structures would be accessible even during low flow periods to support continued recreational uses.

Recreational boat lockages at the USAF lock might have to be either severely restricted or suspended during future periods of low flow in order to satisfy the current minimum commercial navigation demand of 350 cfs on the Mississippi River within the TCMA (Corps, 1990).

Fishing

Each species of fish tends to live in a riverine environment that most suits its needed level of water quality. As flows diminish, the size of these respective environments typically decreases, and both the concentration of fish and their level of competition for available food increase. As a consequence, fishing is reported to improve during some periods of low flow. During years following droughts however, some species may be present in reduced numbers as a result of the stresses low flows can exert. Some of the beneficial aspects of occasional low flow years include improved small mouth bass recruitment, sport fishing opportunities in general, and the germination of emergent aquatic plants in adjacent wetlands. The latter utilizes instream nutrients and provides a habitat for small fish (Corps, 1990).

Fishing, swimming, and waterskiing are all limited by the diminished quality of the water in the Mississippi River below the confluence of the Minnesota River at RM 844, and discharge from the Metro WWTP at RM 836. The fishery in the TCMA reach of the Mississippi, long suppressed by poor water quality, is also improving, with small mouth bass, crappie, walleye, sauger, channel catfish, and northern pike increasing in abundance. In spite of this improvement, the visual presence of increased algal populations in the pool behind Lock and Dam No. 2 is thought to be the main reason for decreased use of this reach for many recreational purposes (MPCA, 1981).

The Mississippi River has long been thought of as a water resource of inferior quality for recreational use and development. However, the quality of water in the river is better now than at any time since the early 1900s. Recently initiated revitalization projects along the riverfronts of Minneapolis, St. Paul, and South St. Paul are an indication of the improved perception of the corridor and commitment to it by both private and public entities. The recent influx of permit applications to build new or expand existing recreational marinas along the 74-mile stretch of river from St. Paul to Lake Pepin is a positive sign that there is a renewed interest in utilizing the Mississippi for recreational activities.

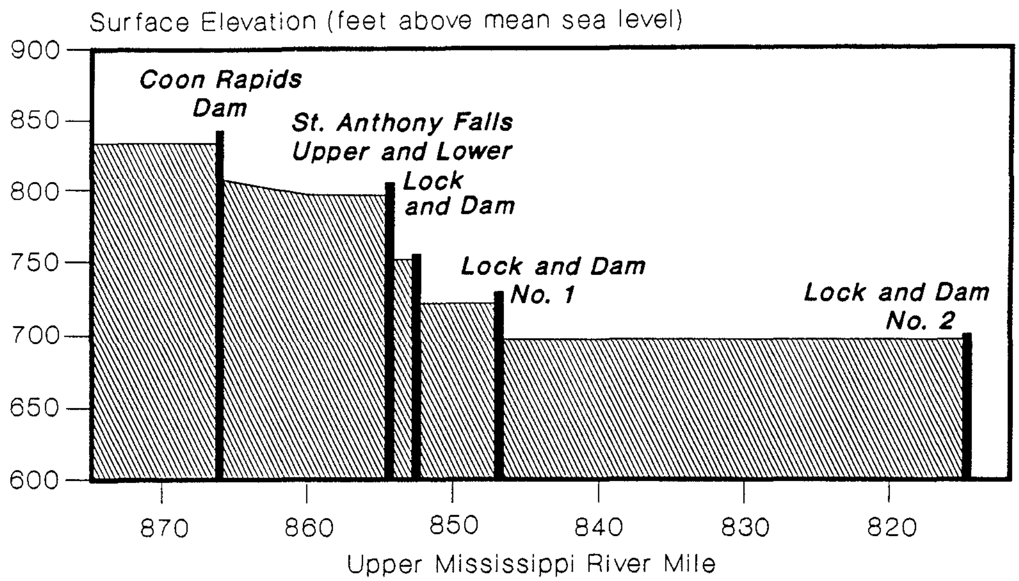
Mississippi River Basin

The TCMA extends from approximately ten miles upstream from Anoka at RM 880 on the Mississippi River, to RM 810, a few miles below its confluence with the St. Croix. Figure 19 shows the effect that the five dams in the TCMA have had in converting the river essentially into a series of controlled backwater pools with constant water surface elevations under average to low flow conditions. The Crow, Rum, Minnesota, St. Croix, and Vermillion rivers all contribute flow to the Mississippi within this 70 mile reach.

Basin Geology

The valley of the Mississippi River south of the TCMA to the Gulf of Mexico is the handiwork of the Glacial River Warren. The Warren drained into the Mississippi most recently through the channel we now know as the Minnesota River, from Glacial Lake Agassiz. At one point during the recession of the glacial front, Agassiz was larger than the combined area of the present Great Lakes. Its depth is estimated to have been up to 700 feet along the glacial margin. The tremendous sediment load carried by the Warren is responsible for the erosion-sculpting of both the Minnesota and Mississippi River valleys in Minnesota. The flow level in Agassiz dropped as its contents drained to the Gulf. As the glacial front continued to recede to the north, the lake began to drain through uncovered channels into Hudson Bay as well. Eventually it ceased to flow into the River Warren. Since that time, reduced flow rates have resulted in the accumulation of over 200 feet of sediment within the Mississippi River channel below the TCMA. Today there is not even enough flow to cover the valley floor (Schwartz et al., 1976).

Figure 19
UPPER MISSISSIPPI RIVER PROFILE



Source: Hydroscience, 1979

Tributaries to the Mississippi River below the TCMA typically have higher gradients than those upstream. As glacial runoff decreased, these tributaries supplied more sediment to the river than it could transport downstream. These tributaries provided much of the now-present sediment base and helped in generating the sand bars that deflected the river's currents, creating its multiple channels, meanders, oxbow lakes, swamps, sloughs, and broad terraces (Schwartz et al., 1976).

The Mississippi River above the TCMA, from its headwaters to its confluence with the Minnesota River, has a much tamer geologic history. Although it too received glacial meltwater while the ice was receding, the flow volume was infinitely small compared to the flow transported through the present Minnesota River valley. The Mississippi originates at Lake Itasca in Itasca State Park in Clearwater County in north-central Minnesota. Its drainage area above the USGS streamflow gage at Anoka is approximately 19,100 square miles. The preglacial surface in this area had an extensive and well-developed drainage system. The St. Croix Valley, along the eastern side of the TCMA, is considered to be a modern analog of the ancestral Mississippi River Valley. The old bedrock river channels of the Mississippi River however, are now filled and covered with as much as 200 feet of glacial drift and river-deposited sediments (Corps, 1990 and Schoenberg, 1990).

Much of the upstream reach of the river has a rock rubble substrate derived from glacial drift deposits. In some of the upstream reaches, the river meanders through bog, with organic materials in its banks and a sandy substrate. Near Aitkin, the river is meandering with a low gradient, lined with many abandoned channel lakes and embayments, a "U"-shaped channel, and cut banks composed of clayey soils. Downstream from Brainerd, the river gradient increases considerably as it flows through bedrock outcrops. From St. Cloud to the TCMA, the river flows through river-deposited glacial sediments within an island-braided channel. The bed is primarily composed of sand, with areas of gravel and cobbles. At the Falls of St. Anthony, the river descends through a narrow gorge where the channel is confined by bedrock and the substrate is composed of sand and gravel. From its confluence with the Minnesota River downstream, the river channel becomes much wider with its substrate dominated by the fine-grained sediment load of the Minnesota (Corps, 1990).

The volume and character of the bottom sediments in TCMA rivers are primarily a function of flow velocity. Activities occurring upstream of the TCMA tend to dominate the local river sediment loads. Study of this problem in 1979 indicated that during a typical summer, about 3% of the TSS load in the Mississippi River resulted from TCMA storm sewer and CSO flows, 3% from the Metro WWTP discharge, 39% from the Mississippi headwaters above the TCMA, and 55% from the Minnesota River (MPCA, 1981).

Classification

The Mississippi is an interstate water whose use classification varies by reach. From north of the TCMA to the Upper Lock and Dam at St. Anthony Falls in Minneapolis, the river carries its highest use classification, a 1C classification, indicating its potential use as a source for drinking water after receiving stipulated levels of treatment. Upstream from the USAF lock and dam, the river is classified as a 2Bd water, considered acceptable as a cool and warm sport fishery water, suitable for aquatic recreation including swimming, and protected as a source of drinking water. Both upstream (to the USAF dam) and downstream from RM 830 within the TCMA, the river is classified as a 2B water, considered acceptable for all 2Bd uses excluding its protection for use as a drinking water source. From the discharge point of the Metropolitan WWTP in St. Paul near RM 835, downstream to the Rock Island RR Bridge at RM 830, the river is classified as a 2C water. A 2C stream classification indicates its expected capability of supporting only rough fish, and whose water quality is not sufficient to promote swimming. The lower quality classification for this five mile reach is a result of the combined effects upon instream water quality of three key long-term sources of diminished quality water to the Mississippi River. Those three sources are the Minnesota River, CSOs, and the Metro WWTP. In addition to all of the classifications given above, the river through the entire TCMA is also classified for use as a 3B, 3C, 4A, 4B, 5, and 6 water (MPCA, 1981 and State, 1991).

Water Quality Impacts

The water quality standard for fecal coliform has a yearly history of violations throughout the TCMA reach of the Mississippi River above the Metro WWTP. This summer standard is most frequently exceeded in the area near and immediately downstream from downtown St. Paul. The severity and frequency of violation becomes relatively insignificant by the time flow reaches Lock and Dam No. 2 near Hastings, however. The persistence of these violations has essentially precluded attainment of the Class 2B use designation of the Mississippi River from RM 835 to RM 830 of being "swimmable". The primary cause of these violations is the intermittent discharge of combined wastewater and stormwater flowing through the same pipe, via the CSOs in

Minneapolis, St. Paul, and South St. Paul. These cities are in their sixth year of a 10-year program to completely eliminate the interconnection of these two conveyance systems. Upon complete separation, the frequency, severity, and the geographical extent of fecal coliform violations will be reduced by an estimated 80%, but not eliminated. The remaining fecal coliform contamination is caused primarily by separated stormwater runoff containing fecal material from sources other than human wastes. The presence of these contaminants will not necessarily pose a public health threat of pathogenic organisms, but will preclude the full recreational use of that reach of the Mississippi for activities such as swimming. Comparing storm sewer and CSO flow data with river data revealed that approximately 84% of the long term summer fecal coliform load was contributed by CSOs, and an additional 12% from separated TCMA stormwater flow (MPCA, 1984).

The river presently receives a fairly steady amount of inflow above the TCMA, sustained by numerous lakes and six headwaters reservoirs, and by bedrock, glacial drift, and outwash deposit aquifers along its entire length. The many headwaters lakes effectively reduce peak flows on the river, but their effective flood protection extends downstream only to about the town of Aitkin. Late summer low flows approximately equal winter low flows. Releases from the headwaters reservoirs over the course of the winter to attain their target drawdown elevations prior to spring runoff add to the normally low winter flows in the river. The cumulative routine low flow rate of release from the six Corps-operated reservoirs is 270 cfs. Flows typically drop to this cumulative level during the latter half of summer during normal climatic conditions.

During drought conditions, flows may decrease to typically expected low flow rates earlier in the summer. When headwaters lake levels drop below an even lower stage in each reservoir, as might occur during a severe long-term drought period, releases are halved to a cumulative 135 cfs. During the 1988 drought, flows released from the headwaters reservoirs were maintained at the 270 cfs level, and comprised approximately 25% of the flow in the river at the Anoka gage with consideration of anticipated losses en route. A record low flow of 842 cfs was observed in the Mississippi at Anoka on July 20, during that 1988 drought period (Corps, 1990).

Negative effects of the 1988 drought upon water quality in the Mississippi above the TCMA, or its ability to maintain aquatic life during that period, were determined to be minimal in all reaches up to the headwaters reservoirs. During low flow periods, inflow from tributaries falls off to a minimum, and food available to aquatic life originates primarily from within the river. It is not known to what degree food for aquatic life would be limiting during extended periods of low flow, below those experienced in 1988. Existing stream water quality models, calibrated at flow rates equal to or above 7Q10 flows, cannot be expected to accurately simulate conditions experienced during 1988, when flows dropped to near 7Q50 levels (Corps, 1990).

Travel time for flow in the river is greatly affected by flow volume. During an August 1976 low flow survey, flow averaging 1550 cfs at St. Paul took about 16 days to travel from Anoka to Lock and Dam No. 2. During an October 1977 flow survey when near-average seasonal flow conditions of approximately 9000 cfs were measured at St. Paul, travel time was a much shorter span of only about 3 days (Hydroscience, 1979).

A review of MWCC sampling data of river water samples taken between RM 871.6 and RM 796.9 to assess compliance with water quality standards for DO, fecal coliforms, turbidity, and un-ionized ammonia nitrogen from 1984 through 1988 indicates a definite yearly trend of improved water quality. Some of the improvements in compliance with turbidity and coliform standards are obviously due in part to greatly diminished nonpoint and storm sewer flows as a result of less than average amounts of rainfall. Years of future water quality data and completion of the CSO elimination program will be necessary during an extended period of normal climatic conditions to accurately evaluate the success of the program. Compliance with standards for DO in 1988 was lower than in previous years due to the low river flows. A comparison of the 1988 DO data to 1976 low flow survey DO data indicates improved river water quality, largely due to improved levels of wastewater treatment. As can be observed in Figures 20 and 21, DO concentrations were significantly higher in 1988, even under more stressful instream conditions, than during the 1976 survey. If not for supplemental aeration of the Metro WWTP effluent, compliance would have been greatly reduced and stress upon aquatic life below the Mississippi's confluence with the Minnesota River would have been much greater (MWCC, 1989 and 1990).

WWTPs

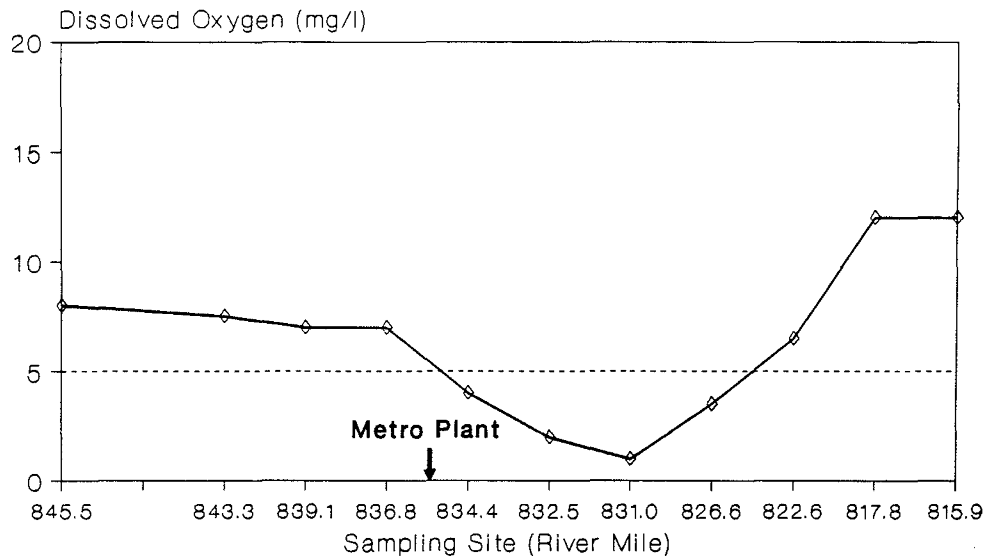
All five WWTPs that discharge treated effluent directly to the Mississippi River within the TCMA are owned and operated by the MWCC (see Figure 2). The Anoka plant is an activated sludge facility, located just above the confluence with the Rum River near RM 871. It provides secondary treatment of wastewater for Anoka, and part of Ramsey and Champlin. The plant was last expanded in 1968 to treat an average flow of 2.46 mgd, and is currently operating at capacity. Phase-out of this plant will occur during 1992, with diversion of its flow to the Metro WWTP. The elimination of this plant from MWCC's system has been planned for a number of years. The alternative would have been to expand and upgrade the existing facility to meet more restrictive effluent limitations in an effort to maintain in-stream water quality through the subsequent reach of the Mississippi River where much of TCMA water supply is withdrawn.

The Rosemount plant provides secondary treatment of wastewater for Rosemount and southern Inver Grove Heights. It is an aerated waste-stabilization pond system, constructed in 1989 to treat an average design flow of 0.72 mgd. Discharge is to Spring Lake at RM 832.2, above Lock and Dam No. 2. Subsequent growth in excess of estimated rates within the facility's service area will require a further increase in its treatment capacity by 1996.

The Cottage Grove WWTP was last upgraded in 1978 and provides secondary treatment of Cottage Grove's wastewater. Discharge is to a water quality limited reach of the Mississippi River at RM 819.6. This plant is projected to reach its design treatment capacity of 1.8 mgd by 2000.

The Hastings WWTP was expanded in 1986 to treat an average annual design capacity flow of 2.34 mgd. Secondary treatment requirements apply to this plant serving the city of Hastings, with discharge to the Mississippi River near RM 815. The treatment capacity of the plant is considered to be adequate through 2010. Dechlorination facilities are currently being added to this plant to meet new, more restrictive limitations on TRC by June 30, 1992.

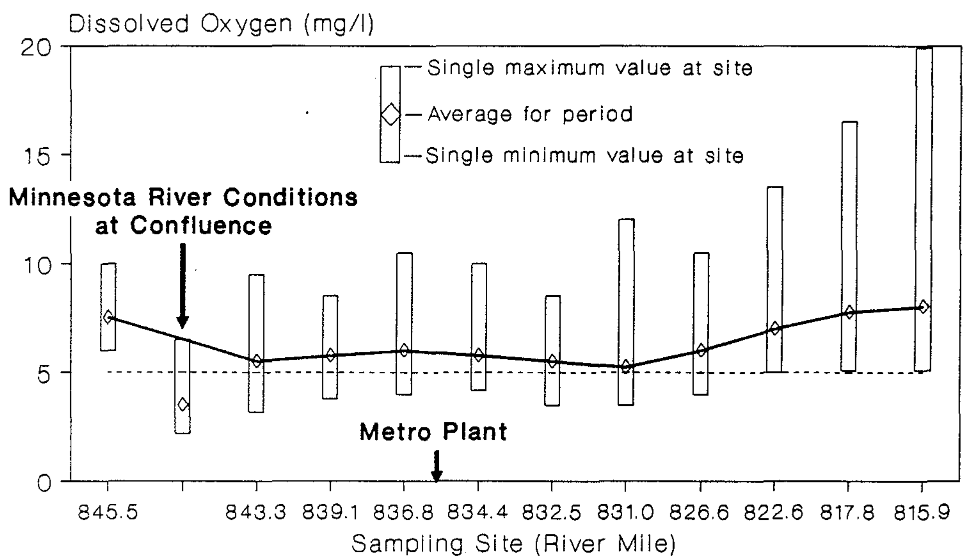
Figure 20
AVERAGE DISSOLVED OXYGEN, 1976
MISSISSIPPI RIVER LOW FLOW SURVEY



For the period Aug. 19 - Sept. 2

Source: MWCC, 1989

Figure 21
AVERAGE DISSOLVED OXYGEN, 1988
MISSISSIPPI RIVER LOW FLOW SURVEY



For the period June 17 - July 1

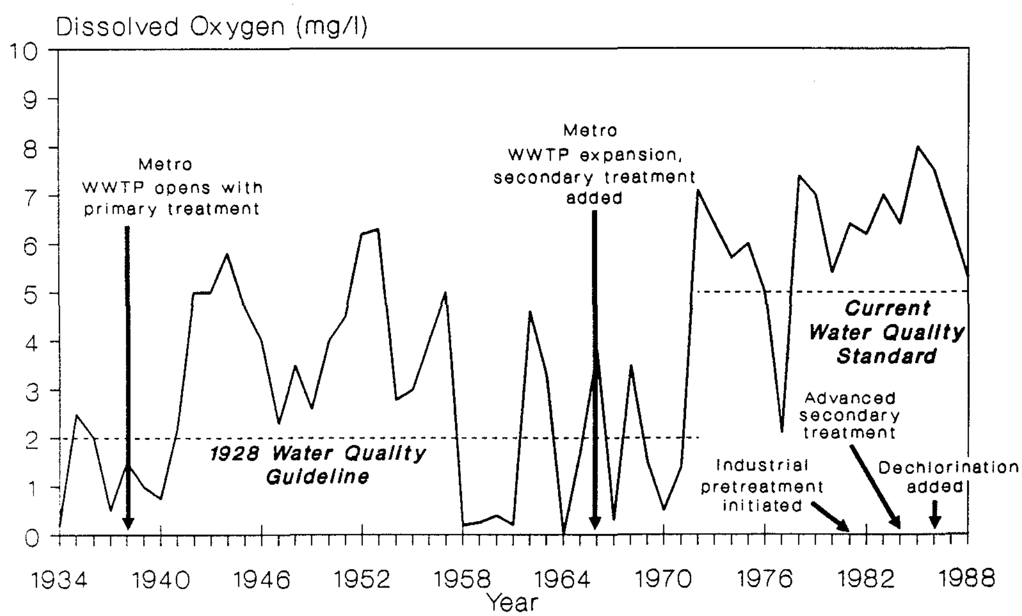
Source: MWCC, 1989

Metro WWTP

The Metropolitan (Metro) WWTP is located just downstream of downtown St. Paul on Pig's Eye Island, at RM 835.1. The Metro plant began providing primary treatment in 1938. Many subsequent upgrades and process modifications have increased its average annual treatment capacity to 251 mgd. Eighty-five percent of the TCMA's wastewater, including flow from Minneapolis, St. Paul, many older suburbs, and some developing communities is treated at the plant. Advanced secondary treatment requirements apply to this facility. It utilizes the step aeration activated sludge process and began providing summer season nitrification in 1984 to convert potentially toxic levels of ammonia to nitrate nitrogen. Dechlorination facilities went on-line in 1986 to reduce the TRC level in plant effluent to non-toxic levels. In 1988, the plant began oxygenation of its effluent in response to an increasing diurnal fluctuation of in-stream DO, and decreasing flow rates in the Mississippi. Figure 22 illustrates the fluctuation of average measured DO concentrations in the Mississippi River near RM 827 during August, from 1934 through 1988. The figure also indicates when major plant modifications went on-line.

The vast majority of the wastewater flow from TCMA industries utilizing MWCC collection and treatment facility system ultimately flows to the Metro plant for treatment. The MWCC's industrial waste pretreatment program currently regulates over 750 industrial users, including industrial sources, waste transport haulers, and generators of leachate and contaminated ground water. The MWCC administers a number of activities within this program to prevent collection system problems, treatment plant upsets, and discharge of potentially toxic levels of heavy metals or trace organics to TCMA streams. The program activities include permitting, inspection, discharge monitoring, high strength charge assessment, and enforcement.

Figure 22
AUGUST AVERAGE DO CONCENTRATIONS FOR THE MISSISSIPPI RIVER AT GREY CLOUD, 1934-88



Source: MWCC, 1990

In addition to the three MWCC treatment plants downstream from the Metro plant, other industrial point source wastewater discharges to the Mississippi River during the 1988 low flow survey period included Ashland Oil at RM 830.3, N-REN at RM 824.5, Koch Refinery at RM 824.2, and 3M Chemolite at RM 817.2. Altogether, these facilities were discharging less than 10% of the flow and loading of most wastewater constituents to the river that were contained in the Metro plant's discharge during that same period of time. These industries are considered to have a minimal effect upon further reduction of river water quality, based upon the most recent WLA study of the Mississippi River. The combined effect of each of these, and any other pollutant contributing facilities upon River water quality will continue to be taken into consideration during future Metro plant WLA studies to establish WWTP discharge limitations (MPCA, 1981).

Aeration of Metro effluent to near saturation levels is accomplished by utilization of an effluent pump station originally designed for use only during flood flows when the main discharge point can become submerged. It functions exceptionally well in boosting in-stream DO levels by the mixing of effluent with air as it cascades down a 40-foot concrete wall to the river. By successfully increasing the plant's typical summer effluent DO concentration of 2.7 mg/l to an attainable minimum of 7 mg/l, use of this procedure can effectively increase the minimum DO concentration that the river will experience in the critical reach below the plant by an estimated 0.6 mg/l. Originally a voluntary river water quality improvement operation, criteria have now been included in the plant's NPDES permit outlining the river flow conditions requiring operation of the effluent aeration system. If the average daily river flow falls to below 7000 cfs at the USGS gage at RM 836.8 in St. Paul and the average daily DO is less than 6.0 mg/l above the Metro WWTP, or less than 5.5 mg/l below the WWTP at RM 826.6 and RM 831 for two consecutive days, then the effluent must be aerated prior to discharge. Summer season river water DO saturation typically ranges between 8 and 9 mg/l, based upon normal water temperatures (MWCC, 5/90 and MPCA, 8/90).

Beginning at approximately RM 834, the river was accurately simulated in its 1981 WLA study as a stratified (two-layered) system in which the upper four feet of water can vary in quality from that encountered in the underlying bottom layer. Between June and August, the effluent from the Metro WWTP is slightly denser than river water and plunges below the water surface in the diverging outlet channel into which it is discharged. It enters the main channel of the river as an underflow. This process can begin as early as May and continue into September. The plunging phenomenon and resultant underflow is controlled by water temperatures and the higher TDS concentration of the effluent relative to the passing Mississippi River water. Once reaching the dredged main channel of the river, vertical mixing takes place through two primary mechanisms: turbulence induced by shear on the river bed and secondary flow due to channel irregularities, and turbulence resulting from barge traffic. At river flow rates below an estimated 5000 cfs, (about one-half the average summer season flow), shear-induced vertical mixing becomes very slow and the mixing zone can become several miles long. Barge traffic however, mixes the stratified waters very effectively. The passage of three barge tows appears sufficient to essentially eliminate most quality differentials. At an approximate observed frequency of one barge tow per hour, the effluent mixing zone extends about 1.3 miles below the WWTP outlet. Under these conditions, barge traffic controls the length of the mixing zone in the summer when river flows are below about 6000 cfs. Above 20,000 cfs, mixing is dominated by shear flow. Between in-stream flows of 6000 and 20,000 cfs, both processes make significant contributions to mixing (Stefan, 1982).

There is very little measurable SOD in the Mississippi River above its confluence with the Minnesota. Below the confluence however, SOD has been determined to gradually increase to Lock and Dam No. 2. The Minnesota River and the Metro WWTP combine to exert the majority of this form of oxygen demand due to reduced flow rates and increased settling of organic materials out of the water column. As Minnesota River WWTP discharges improve in quality in response to stricter effluent limits, and future nonpoint source pollution contribution declines, the negative effects of the lower Minnesota River sediment upon Mississippi River SOD values should diminish (Hydroscience, 1979).

During the August 1976 low flow survey between RM 835 and RM 823 on the river, instream DO dropped to a minimum daily average value of 1.5 mg/l, as previously indicated on Figure 20. The principal causes of the DO depression were the oxidation of organics (CBOD) discharged from Metro, and SOD, accounting for demands of up to 6 mg/l and 2 mg/l, respectively. Algae photosynthesis was a net source of DO in this critical reach during the survey, accounting for 1 to 5 mg/l of surplus DO, partially offsetting the effect of the DO demands of CBOD and SOD. Observed phytoplankton chlorophyll-a concentrations exceeded 200 µg/l in this reach during the study, a level considered indicative of eutrophic conditions (Hydroscience, 1979).

Toxic levels of un-ionized ammonia were present in concentrations of 100 µg/l downstream of the confluence of the Minnesota and in excess of 250 µg/l below the Metro plant in the Mississippi River during the 1976 low flow survey. Current standards limit this component to 40 µg/l. Low flow survey data from 1988 indicate a vast improvement in toxic ammonia levels. Levels in the Mississippi River below the confluence of the Minnesota River averaged about 30 µg/l, and below the Metro plant concentrations averaged approximately 20 µg/l during that survey (Hydroscience, 1979 and MWCC, 1989).

Data collected during the 1976 survey indicate the first stage of nitrification was occurring within the Hastings Pool area. This in-stream reaction further reduced the DO level in the river at that time. Nitrite-nitrogen level fluctuations are uncommon in natural waters, but a significant increase was observed over a period of days within the Hastings Pool during the extreme low flow survey periods in 1976 and 1988. Insufficient numbers of nitrobacter bacteria do not appear to have been present instream during 1976 to further convert the nitrite to nitrate. Since this survey, increased CBOD and ammonia removal efficiencies at the Metro plant have increased the concentration of nitrifying bacteria that will be present in the plant's effluent, assuring their future presence downstream of the plant under similar low flow conditions (MPCA, 1981).

Instream nitrification may be promoted further in the future, in the area downstream of the Metro plant on the Mississippi River, by the discharge of additional seed bacteria from the Blue Lake and Seneca plants on the Minnesota River that will take place after their upgrades are put on line in 1992. However, with lower instream ammonia levels due to higher levels of treatment (in-plant conversion of ammonia to nitrate), and competition by phytoplankton for the remaining instream ammonia for food, the nitrifying bacteria may quickly die off after their limited food supply is exhausted and cause only minimal impact upon instream DO levels. Future WLA modeling by the MWCC to analyze their measured streamflow data, and by the MPCA to develop the limits for the Metro plant's effluent beyond 1995, will utilize current data to more accurately predict to what degree future instream nitrification will affect critical season DO levels (Hydroscience, 1979 and MPCA, 1981).

Ice cover reduces the ability of the Mississippi to naturally reaerate its flow with atmospheric oxygen during winter. Heat sources that increase the size of open water areas during this period of time include power plant and industrial "cooling" discharges, and municipal and industrial WWTP effluents. These sources have minimal effect upon the Spring Lake reach between RM 825 and RM 815, however. This reach is typically 80 to 100% ice-covered during yearly winter low flow periods. Water quality simulations of winter low flow conditions indicate Spring Lake DO levels should remain above the minimum 4 mg/l winter water quality standard that is applied from December 1st through March 31st. Cascade aeration of the Metro plant's effluent would be available if necessary, to supplement DO in the Mississippi River if instream standards below the plant are jeopardized (MPCA, 1981 and 1990).

Tributary Stream Basins

Crow

The South Fork Crow River enters Carver County from the west, near New Germany, and flows in a northeasterly course toward Watertown. It drains an area of approximately 110 square miles in the western and northwestern parts of that county. The river continues to flow northeasterly, through the extreme southeastern corner of Wright County (outside the TCMA), joining the North Fork Crow River to form the Crow River a few miles southwest of Rockford. The Crow then continues to meander northeasterly to the Mississippi River, draining a belt 3 to 7 miles wide, at the western boundary of Hennepin County. The entire Crow River watershed drains approximately 2700 square miles, primarily west of the TCMA. The surficial geology streambed composition of the Crow varies from glacial outwash deposited sands and gravels to silt and clay (USDA, 1968).

The Crow is classified for the following uses: 2B, 3B, 4A, 4B, 5, and 6. All reaches of the Crow River and its South Fork within the TCMA typically contain low flow volumes, and are water quality limited. Their capacity to assimilate organic pollutants varies seasonally, with assimilation capabilities being highest during periods of higher instream flows (State, 1991).

Five WWTPs owned and operated by TCMA rural centers discharge into the Crow and South Crow Rivers. All are required to meet secondary effluent standards. The New Germany, Mayer, and Watertown plants are of waste-stabilization pond design. New Germany and Mayer, designed to treat flows of 0.052 mgd and 0.068 mgd respectively, are permitted to discharge only in the spring and fall. Discharging during these seasons avoids the potential problems that might result if their organic loads were to be introduced during critical summer low streamflow periods. The Watertown plant is also a pond system, designed for a flow of 0.28 mgd, that normally discharges continuously. It is required to discontinue discharge of its effluent during winter periods when flow ceases in the river. These periods typically will last only up to 30 days. Watertown is currently considering replacing its existing plant with a new, expanded facility capable of meeting the advanced secondary treatment limitations necessary to allow continuous discharge of effluent to the South Fork of the Crow River. The Rockford plant, designed to treat 0.361 mgd, employs the activated sludge process and the Rogers plant is a waste-stabilization pond system designed to treat 0.15 mgd. Only modest growth was forecast for these communities over the next 20 years. However, the city of Rogers is currently in the process of upgrading its facility with an activated sludge system capable of treating an average wet weather flow of 0.672 mgd. Although the Crow River enters the Mississippi River upstream of the Minneapolis and St. Paul water supply intakes (about five miles upstream of the Anoka WWTP discharge point), negative water quality effects of these facilities upon the Mississippi River are considered to be negligible by the MPCA, due to the effects of dilution.

Rum

The Rum River drains a watershed of approximately 1360 square miles upstream of St. Francis in northern Anoka County. The source of the Rum River is Mille Lacs Lake, located in both Aitkin and Mille Lacs counties. The lower third of the Rum watershed is comprised of a nearly level area known as the Anoka Sand Plain. It is composed of glacial outwash sand with scattered sand dunes. The sand was deposited by the migrating Mississippi River as it shifted westward with the retreat of a glacial lobe. Following the glacial activity, wind action redistributed the fine sands over the surface of parts of Sherburne, Isanti, and Anoka Counties. The streambed of the Rum is comprised primarily of these glacially deposited rocks and sand.

The Rum is classified for the following uses: 2B, 3B, 3C, 4A, 4B, 5, and 6; and has been designated as a scenic or recreational river segment from the state highway 27 bridge in Onamia (north of the TCMA) to Madison and Rice Streets in Anoka, near its confluence with the Mississippi. The Rum River is considered to be an effluent limited stream, and secondary treatment requirements are sufficient for WWTPs to maintain water quality standards in the river at the present time.

St. Francis, a rural center in northern Anoka County, is served by a three-cell waste-stabilization pond system designed to treat a flow of 0.158 mgd that can either discharge to six infiltration basins or to the Rum River. Special ground water monitoring requirements have been established for this facility to ensure ground water is not contaminated by operation of the basins in this geologically sensitive area. Although the Rum River enters the Mississippi River upstream of the Minneapolis and St. Paul water supply intakes, the negative water quality effects upon the Mississippi River that result from discharge from this facility are also considered to be negligible by the MPCA, due to the large dilution factor.

Minnesota River

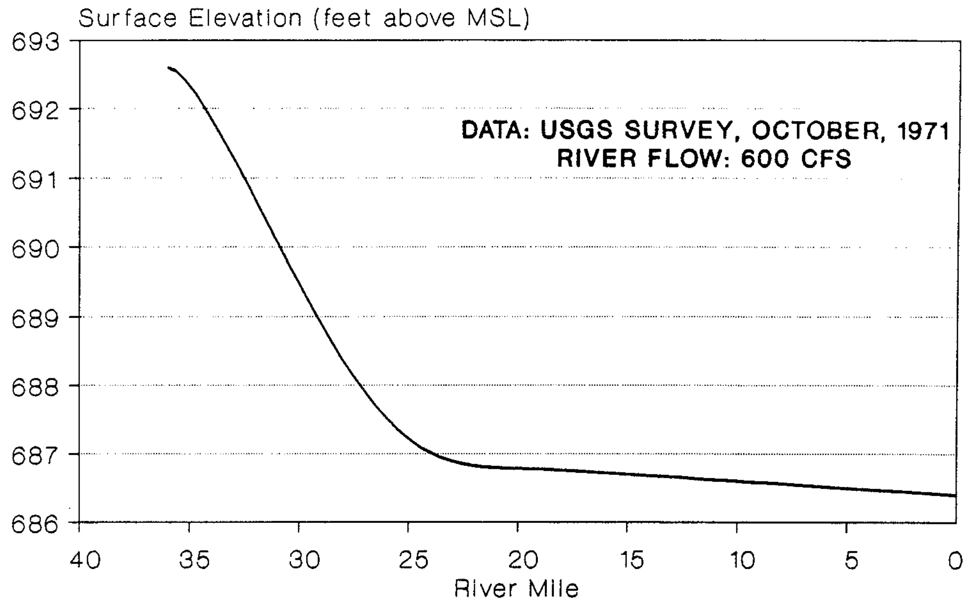
Basin Geology

The Minnesota River originates at Big Stone Lake on the Minnesota-South Dakota border and flows to the southeast. At Mankato the river turns sharply and maintains a northeastward trend to its confluence with the Mississippi River at St. Paul, having traveled a total distance of 330 miles. The Minnesota drains an area of approximately 16,900 square miles, including about 1610 square miles in South Dakota and 323 square miles in Iowa. About 90% of the predominantly rural Minnesota River watershed area is dedicated to agricultural activities. The present Minnesota River occupies only a small portion of the broad river valley that varies from one to five miles wide and from 75 to 200 feet deep. This wide valley was carved out by the Glacial River Warren that carried torrents of meltwater to the Mississippi from Glacial Lake Agassiz during the recession of the most recent glacial ice sheet. From Mankato to St. Paul, the Minnesota Valley has broad terraces of bedrock, sand, and gravel that occur at heights varying up to 150 feet above the present stream. Above the TCMA, the river bed is composed primarily of sand and rock rubble, but within the TCMA the sediment contains increasing amounts of silt and organic materials. The flood plains on the river bottoms adjacent to the present meandering channel contain numerous shallow lakes and wetlands (MPCA, 1985 and Schwartz et al., 1963).Within the TCMA, the Minnesota River is the border between Carver and Hennepin counties on the north, and Scott and Dakota counties to the south. Dramatic changes occur in the character of the Minnesota as it enters the lower 25-mile reach between Shakopee and its confluence with the Mississippi. The combination of the effects of channel dredging and the backwater pool created by the Corps Dam No. 2 on the Mississippi River at Hastings have transformed the river from a shallow, free-flowing stream into a deeper, low-velocity, navigable channel. When Dam No. 2 was placed in operation in July 1931, it raised the water surface at the mouth of the Minnesota River by about one foot, and at Shakopee, about 0.2 feet (MPCA, 1985).

Dredging of the river to improve navigation began approximately 100 years ago. The Corps has extended a channel 9 feet deep and 100 feet wide approximately 14.7 miles upstream from the mouth. Historically, dredging has been performed by private interests to extend the 9-foot channel on the Minnesota as far upstream as RM 21.8. Water surface elevations obtained by the USGS in 1971 when flow in the river averaged about 600 cfs (the median winter season flow) between Jordan at RM 39 and Shakopee at RM 25 revealed an average drop over the 14 miles of about 0.5 feet per mile. As shown on Figure 23, the water surface elevation only drops an additional 0.5 feet in the remaining 25 miles from Shakopee to its mouth, due to the influence of Dam No 2. on the Mississippi River. Figure 24 illustrates the effect of diminishing flowrates on travel time from Shakopee to the Mississippi River. Table 7 provides typical seasonal flow data near Jordan from the period of record of 1936 to 1980, to put their respective travel times into perspective (MPCA, 1985).

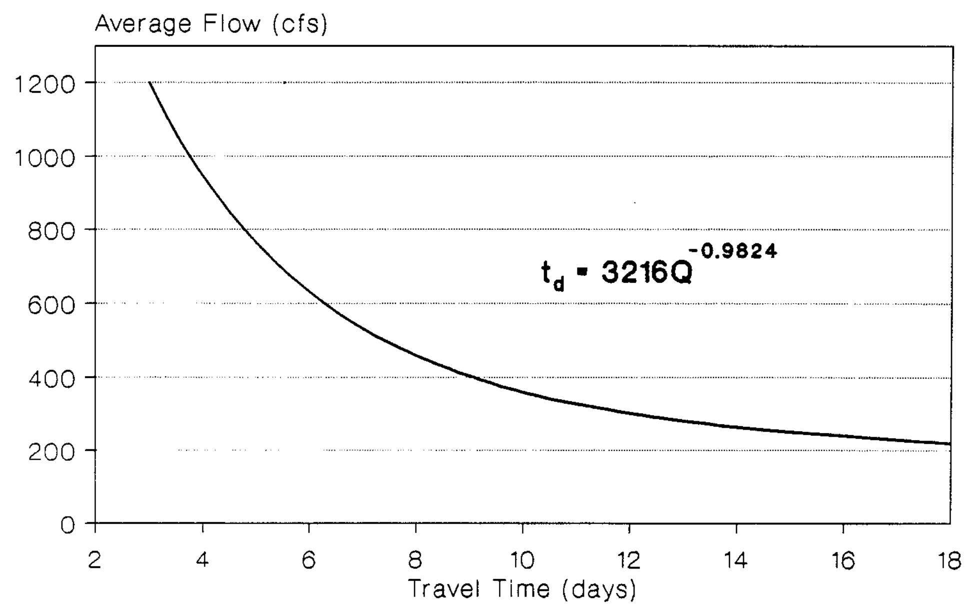
The lower Minnesota River lies within an artesian basin. General ground water movement is toward the river from glacial sediment and bedrock aquifers, discharging via direct seepage, floodplain lakes, springs, and flowing wells. Due to the numerous springs and small tributaries along the Minnesota, inflow is considered by the MPCA to be uniformly distributed along its entire reach within the TCMA. During extended periods of dry weather, natural inflow to the river is mainly from ground water sources. The 7Q10 and ground water inflow rates for various locations on the lower Minnesota that are shown in Table 8 indicate gradually decreasing rates of inflow from fall through spring, representing ground water depletion during the time of year when significant ground water recharge is not occurring. The large summer inflow rate is indicative of ground water recharge from spring snowmelt and early summer rains. The data also show that the lowest 7Q10 flows have historically occurred during the winter season (MPCA, 1985).

Figure 23
WATER SURFACE PROFILE OF THE LOWER MINNESOTA RIVER



Source: MPCA, 1985

Figure 24
LOW FLOW TRAVEL TIME, MINNESOTA RIVER SHAKOPEE TO MOUTH



Source: MPCA, 1985

Table 7

MINNESOTA RIVER LOW-FLOW CHARACTERISTICS** AT JORDAN PERIOD OF RECORD: USGS WATER YEAR 1936-1980

In cubic feet per second (CFS)

Season*	1Q2	1Q10	7Q2	7Q10	30Q2	30Q10	Seasonal* ** Median
Spring	519	221	739	268	2305	740	4677
Summer	564	233	607	247	826	296	2007
Fall	425	166	473	192	581	214	732
Winter	371	161	382	167	413	181	638

* Months having similar flow characteristics were grouped to derive seasonal flow statistics. The analysis required a minimum of three consecutive months per season.

** Statistically derived low flows having a stated duration and recurrence interval, e.g. 7Q10 represents a 7-day average low flow which statistically recurs once in each 10-year period or a 10% chance of occurring in any given year. Similarly, flows with a recurrence interval of two years have a 50% probability of occurring in any year.

*** The 50th percentile or median flow for the period of record.

Spring: March-April-May
Summer: June-July-August-September
Fall: October-November-December
Winter: December-January-February-March

Source: MPCA, 1985

There are no major tributaries to the Minnesota River within the TCMA. The many small tributaries within the lower reach are becoming increasingly urbanized, and the discharge of storm sewer runoff into these tributaries is resulting in the degradation of the quality of water flowing into the Minnesota. Surface water runoff from urbanized areas can carry high concentrations of suspended solids, oxygen demanding materials, nutrients, pesticides, and heavy metals (resulting from auto emissions) from nonpoint sources within the watersheds. Under dry weather and low flow conditions however, tributary flow is minimal and loadings to the river from nonpoint sources become insignificant (MPCA, 1985).

Table 8

SEASONAL LOW FLOW AND INFLOW ESTIMATES LOWER MINNESOTA RIVER

Characteristic	Mankato*	Inflow Rate (cfs/mi)	Jordan	Inflow Rate (cfs/mi)	Shakopee*	Inflow Rate (cfs/mi)	Ft. Snell**
River Mile Index	RM 107		RM 39		RM 25		RM 3
Drainage Area (A), mi^2	14,900		16,200		16,580		16,900
Spring 7Q10 Flow, cfs	196.5	1.05	268.1	1.49	289.0	0.80	306.7
Summer 7Q10 Flow, cfs	124.4	1.80	246.6	2.55	282.3	1.37	312.4
Fall 7Q10 Flow, cfs	113.3	1.16	192.5	1.65	215.6	0.89	235.1
Winter 7Q10 Flow, cfs	92.2	1.10	167.3	1.56	189.2	0.84	207.7

* 7Q10 flow statistics for Water Years 1936-1980

** 7Q10 flow estimated by drainage area adjustment using the following correlation equations:

Spring $Q = 0.05508(A) - 624.1$
Summer $Q = 0.09400(A) - 1276.2$
Fall $Q = 0.06092(A) - 794.4$
Winter $Q = 0.05777(A) - 768.6$

Source: MPCA, 1985

Classification

Upstream from RM 22, the Minnesota River is classified as a 2B water that requires water quality sufficient to permit the propagation and maintenance of cool or warm water fish and be suitable for swimming and all types of aquatic recreation. Downstream from RM 22 to its confluence with the Mississippi, the river is classified as a 2C water, indicating its status as a rough fishery water suitable for boating, but not recommended for swimming. This reduction in classified quality is due primarily to the lower reach's accessibility to barge traffic. In addition to the above classifications, the entire river in the TCMA is also classified for 3B, 3C, 4A, 4B, 5, and 6 uses.

Maintenance of water quality standards in the lower Minnesota River is hampered by pollutant loadings from diverse upstream sources in addition to point and nonpoint sources within the TCMA. Organic and nutrient loads in the river contribute to intermittent violations of the 5 mg/l daily minimum DO and 40 µg/l un-ionized ammonia standards applicable in the TCMA. During an intensive river study in 1980, MPCA sampling revealed that oxygen-demanding organic material from upstream sources accounted for 81% of the CBOD load measured in this lower reach of the

Minnesota. The remainder of the load was attributed to WWTP discharges (13%), industrial sources (2%), and to tributary streams (4%) within the TCMA. Violations of the DO standard were observed during the study, despite recorded river flows being 2.7 times greater than summer low flow (7Q10) design conditions (MPCA, 1985).

Revisions to Minnesota's water quality rules in 1987 included a site-specific DO standard for the lower 22 miles of the Minnesota River that changed the standard of 5 mg/l from an instantaneous minimum to a minimum daily average concentration. This change was considered a relaxation of requirements, recognizing the unique features of this reach of the river, both man-made and natural, and their affect on water quality in general and DO in particular. The change is still regarded as fully maintaining support of this reach's 2C rough fishery use classification (MPCA, 1986 and 1990).

WWTPs

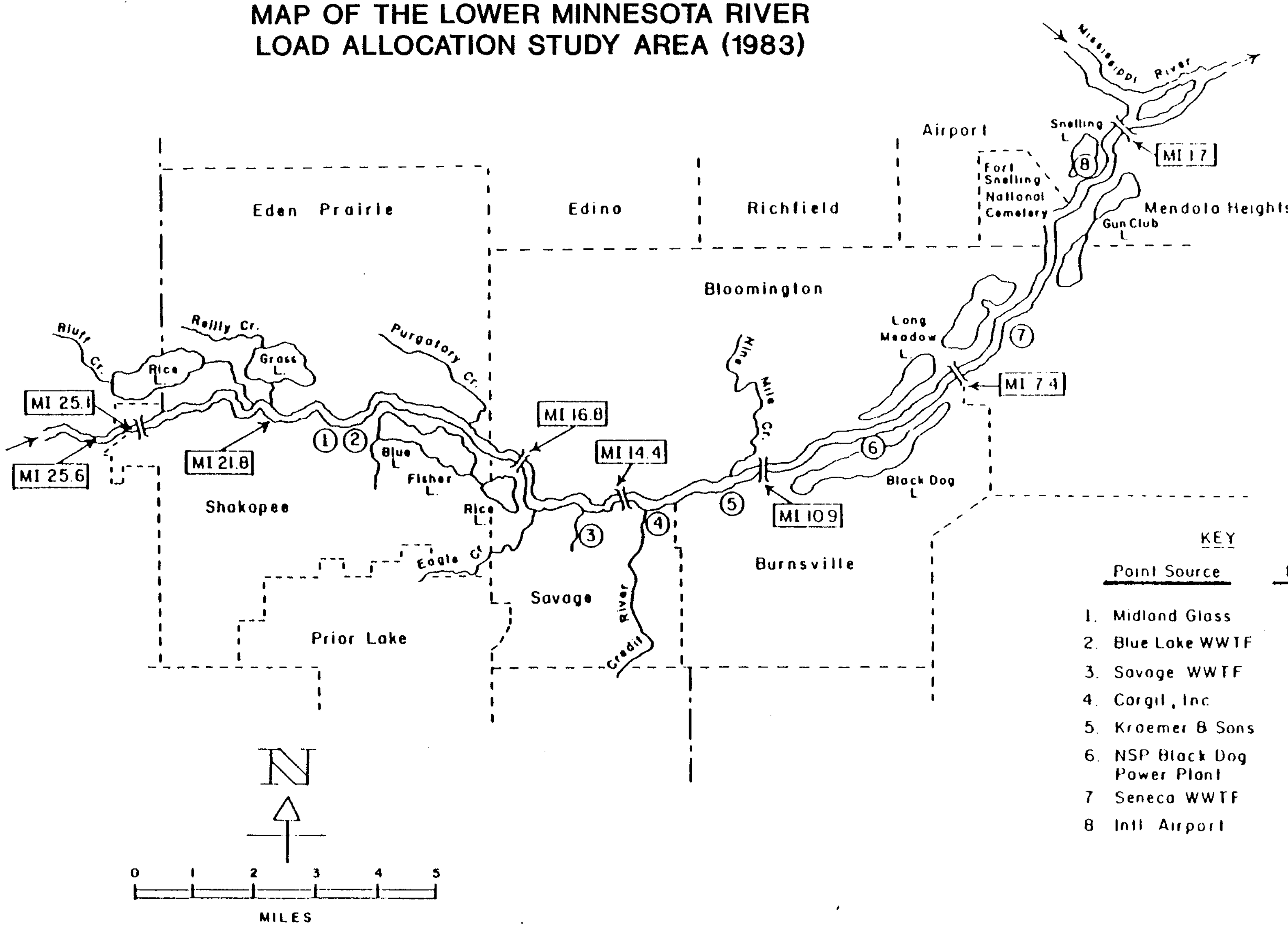
Point sources of pollutants to the Minnesota River evaluated during MPCA's most recent WLA for the river are indicated on the map on Figure 25. Subsequent to the completion of that study, the Savage WWTP (point source 3) has been removed from service, its flow having been diverted to the Seneca plant for treatment. Three MWCC wastewater treatment plants discharge effluent to the Minnesota River. The Chaska plant is located at approximately RM 28, upstream from the other facilities indicated on Figure 25. The plant was expanded in 1988 to an average annual design flow capacity of 1.66 mgd. It utilizes the activated sludge process within a controlled pure-oxygen environment to produce a required secondary treatment quality effluent.

The Blue Lake WWTP, located at RM 20.5, utilizes the activated sludge process to treat wastewater flow from communities around Lake Minnetonka, adjacent Minneapolis suburbs, and the Shakopee and Prior Lake areas south of the Minnesota River. Originally designed in 1972, the plant is currently undergoing an expansion to increase its present average annual design flow capacity of 24 mgd to 32 mgd. When completed in 1992, the upgraded plant will provide a seasonally-required increased level of $CBOD_5$ removal (from 25 mg/l to 12 mg/l), ammonia removal, dechlorination (to prevent instream chlorine toxicity), and effluent oxygenation. The ammonia removal and oxygenation portions of the upgrade are necessary to decrease the plant's probable contribution to exceedances of water quality standards in the Minnesota River for DO and ammonia nitrogen under low flow conditions.

The Seneca WWTP, located at RM 6.5, also provides secondary treatment using the activated sludge process. In operation since 1972, it serves primarily the cities of Burnsville, Eagan, Savage, and Bloomington. This plant is also undergoing an expansion that will increase its present average annual design flow of 24 mgd to 34 mgd. The Seneca plant, scheduled for completion in 1992, is being upgraded to provide advanced secondary treatment to limit effluent $CBOD_5$ to 15 mg/l, provide ammonia removal, and provide effluent dechlorination and oxygenation (MPCA, 1986).

Figure 25

MAP OF THE LOWER MINNESOTA RIVER LOAD ALLOCATION STUDY AREA (1983)



KEY

Point Source	River Mile
1. Midland Glass	20.7
2. Blue Lake WWTF	20.5
3. Savage WWTF	14.8
4. Cargil, Inc.	13.4
5. Kraemer & Sons	11.0
6. NSP Black Dog Power Plant	8.9
7. Seneca WWTF	6.5
8. Intl Airport	3.8

Source: MPCA, 1985

Five municipally-owned WWTPs in the TCMA discharge into the Minnesota River, tributaries, or ditches that flow into the river. The Belle Plaine plant is a waste-stabilization pond system, designed to treat a wastewater flow of 0.396 mgd, that discharges directly to the Minnesota River. Its discharge segment is effluent limited, and secondary treatment is currently adequate to meet water quality standards. Jordan, another freestanding growth center, is served by a plant of similar design, designed to treat 0.541 mgd. It discharges to Sand Creek, a tributary to the Minnesota. This plant is required to meet secondary treatment standards. The rural center of Carver is served by waste-stabilization ponds followed by sand filters. Its facility, designed to treat 0.08 mgd, discharges to the Minnesota River via Carver Creek, and must also meet secondary treatment standards. Two final plants serve rural centers and discharge to Bevens Creek, several miles upstream from its confluence with the Minnesota. The Norwood-Young America plant is a continuously discharging facility designed to treat 0.517 mgd, utilizes the activated sludge process, and is required to meet the more stringent advanced secondary treatment requirements. Hamburg's plant is a waste-stabilization pond system, designed to treat 0.063 mgd, and required to meet secondary treatment limits. The cumulative impact on Minnesota River water quality from these municipal point source discharges is considered by the MPCA to be negligible when compared to impacts from MWCC plants discharging to the river.

The cumulative impact on Minnesota River water quality from industrial point source dischargers within the TCMA is considered by MPCA to be insignificant in comparison to headwater and municipal sources of loading. With projections of municipal WWTPs operating at their future design conditions and secondary treatment levels, industries account for less than one percent of the river's $CBOD_5$ load and less than 0.1% of the estimated total ammonia load (MPCA, 1985).

Water Quality Impacts

Channelization of the lower Minnesota River has resulted in a greater channel depth and slower stream velocities that have substantially reduced its natural atmospheric reaeration potential, and its capacity to assimilate pollutant loadings. Slower stream velocities in the lower reach of the river promote increased settling out of suspended materials to the river bottom. The lower reach also contains a higher concentration of organics than reaches above the TCMA. Inorganic solids, typically soil particles, tend to be laden with nutrients that promote algal growth. As organic solids decompose, they create elevated SOD levels in the slow moving, lower 22 mile reach of the river. These factors were taken into consideration in MPCA's WLA recommendations to establish seasonal effluent limitations for the jointly evaluated Blue Lake and Seneca facilities. The study assumed for simplicity that a common level of treatment would be provided at both treatment plants. Due to the fact that the Seneca plant is located within the zone of the river impacted by the upstream Blue Lake facility, treatment requirements at Seneca depend in part on the level of treatment provided at the Blue Lake plant (MPCA, 1986).

At Minnesota River flows below about 1300 cfs, the water level in the lower 25 mile reach of the river is controlled by the overflow elevation of the Mississippi River Lock and Dam No. 2. Water moves very slowly through the pool behind the dam below that flow rate, and will maintain a nearly constant water surface elevation as flow rates continue to drop. This situation (assuming average seasonal Mississippi River flows) virtually eliminates natural reaeration through turbulence at the water surface within the Minnesota River at flows below 1300 cfs (Stefan et al., 1982 and MPCA, 1985).

In evaluating alternatives that would meet low flow water quality objectives for increased effluent discharge loadings from WWTPs into the lower Minnesota River, the MPCA accepted the equivalency of the provision of additional DO in plant effluents in lieu of a portion of the additional $CBOD_5$ removal that would otherwise be necessary. The added DO in the effluent offsets the impact of additional organic load in the effluents upon the receiving stream's DO reserve. In the case of the Blue Lake and Seneca plants, it was determined to be more cost-effective by the MWCC to provide additional DO to the effluent during the critical summer low flow periods in the Minnesota River than to install costly tertiary filtration otherwise determined to be necessary. Conventional cascade aeration is being constructed at the Blue Lake plant to achieve DO concentrations of 85% (plus or minus 10%) of saturation in the effluent. This level of aeration is not sufficient for the Seneca plant's effluent, however. Historically, the greatest levels of oxygen depletion in the Minnesota occur at its confluence with the Mississippi, during either winter or summer periods of low flow. Seneca's effluent will therefore be aerated by cascade in a confined, oxygen-enriched atmosphere to achieve a DO concentration in excess of saturation. A seasonal, minimum weekly average DO concentration of 6 mg/l will be required at the Blue Lake plant, and 16 mg/l at the Seneca plant when upgrades at these two facilities are complete (MPCA, 1985 and 1986).

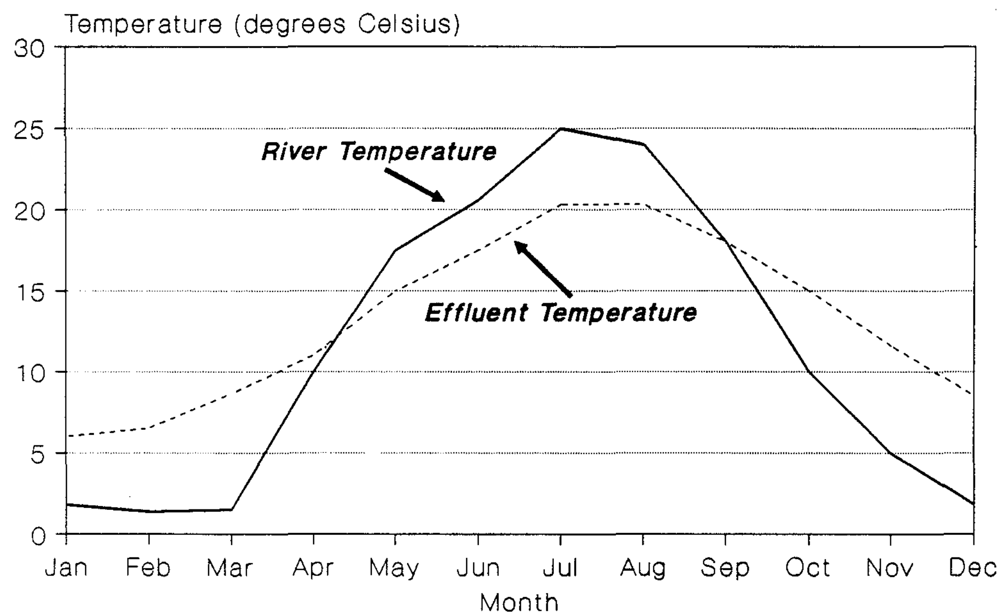
WWTP effluent is of lower temperature and contains a higher concentration of TDS during summer, causing it to be denser than the flow in the Minnesota River. TDS concentrations in the Minnesota typically range between 500 and 600 mg/l, while Seneca and Blue Lakes's effluents average around 700 mg/l and 900 mg/l, respectively. Figure 26 represents the average monthly temperatures of river water and Blue Lake plant effluent, which are similar to those for the Seneca plant. When river flows exceed 20,000 cfs, vertical mixing is much more rapid than horizontal mixing. The effluent disperses relatively quickly in the greater, more turbulent flow. As flow rates diminish, diffusion is slowed down and the mixing zone increases in length. As river flow rates drop below 10,000 cfs, buoyancy, as a result of the temperature difference, causes the effluent to plunge and spread out over the bottom of the river. At flow rates less than 1000 cfs, the effects of buoyancy and transverse spreading are so strong that within less than 300 feet of the discharge point of either the Blue Lake or Seneca plant, the river will stratify and effluent will spread across the river bottom, in both upstream and downstream directions from the outlet. Mixing of river water by tow boats and commercial barge traffic begins to have a significant effect as flow rates diminish. As river flows decrease to extremely low values of 300 to 500 cfs, the effluent mixing zone of the Seneca plant can stretch over 5 miles in length, shortened only by passing barge traffic. Future effluents from Blue Lake and Seneca that will be well oxygenated and supersaturated will be of great benefit to aquatic life in the river by providing a continuous, reliable oxygen source that will not be lost to the atmosphere or readily available at night to respiring algae that dwell near the surface. Typically, the Blue Lake plant effluent is negatively buoyant (heavier than the river water) from May through September, and Seneca's effluent is negatively buoyant from May through August (Stefan et al., 1984, and MPCA, 1986).

Algae in the Minnesota River are typically found to contain more chlorophyll per unit of biomass than algae found in the Mississippi. The ratio of chlorophyll to algae varies from reach to reach and river to river, according to species variations, available light, and temperature conditions. Algae appear to have adapted to the Minnesota River's conditions of increased turbidity and reduced average light intensity by increasing their storage of intracellular chlorophyll to reach their optimal growth. Samples obtained from the Mississippi during the same period of low flow in 1976 indicated relatively lower turbidities which would have resulted in the greater availability of light intensities, providing a possible explanation for their reduced chlorophyll measurements per unit of biomass when compared with comparable Minnesota River algae (MPCA, 1985).

During severe conditions of low stream flow and extended cold weather, the Minnesota River can become completely covered by ice, drastically reducing its natural reaeration capability. The most recent WLA study done by MPCA for the river predicts that under future design flows from these two major plants, secondary levels of treatment ($CBOD_5$ limit of 25 mg/l) during winter operation will maintain DO water quality standards as long as ice covers less than 94% of the river. NSP's Black Dog Power Plant cooling water discharge at RM 8.9, and the two treatment plant discharges currently provide most of the open water during periods of extremely cold weather. The MWCC will observe instream DO readings at a continuous monitoring station near Fort Snelling at RM 3.5 however, and will be prepared to oxygenate the Seneca plant discharge if necessary to maintain instream DO water quality standards (MPCA, 1986).

Figure 26

RIVER AND EFFLUENT TEMPERATURES AT THE BLUE LAKE TREATMENT PLANT



Source: Stefan, et al., 1984

A summer season effluent ammonia limitation of 2.0 mg/l will be in effect for the upgraded Blue Lake and Seneca plants during the months of July through September in an effort to prevent chronic toxicity problems due to its presence in the un-ionized state. Seasonal low flow was determined to be inadequate to sufficiently dilute the chlorine-disinfected effluents of the Blue Lake and Seneca plants to protect aquatic life from chlorine toxicity problems. Consequently, effluent dechlorination has been required as part of the upgrade of these plants to maintain Minnesota River water quality standards (MPCA, 1985).

Routine monitoring data suggest that upstream point and nonpoint sources contribute the majority of toxic substances, including heavy metals and PCBs, that are measured within the TCMA reach of the Minnesota. Elevated levels of PCBs have been measured in fish samples collected over the entire lower 200 miles of the river. The affinity these materials have for sediment makes them difficult to control or eliminate. The most efficient way to prevent their reaching the aquatic environment through WWTP discharges is by the continuation of MWCC monitoring of industrial dischargers in an effort to reduce or eliminate toxic substances at their sources (MPCA, 1985).

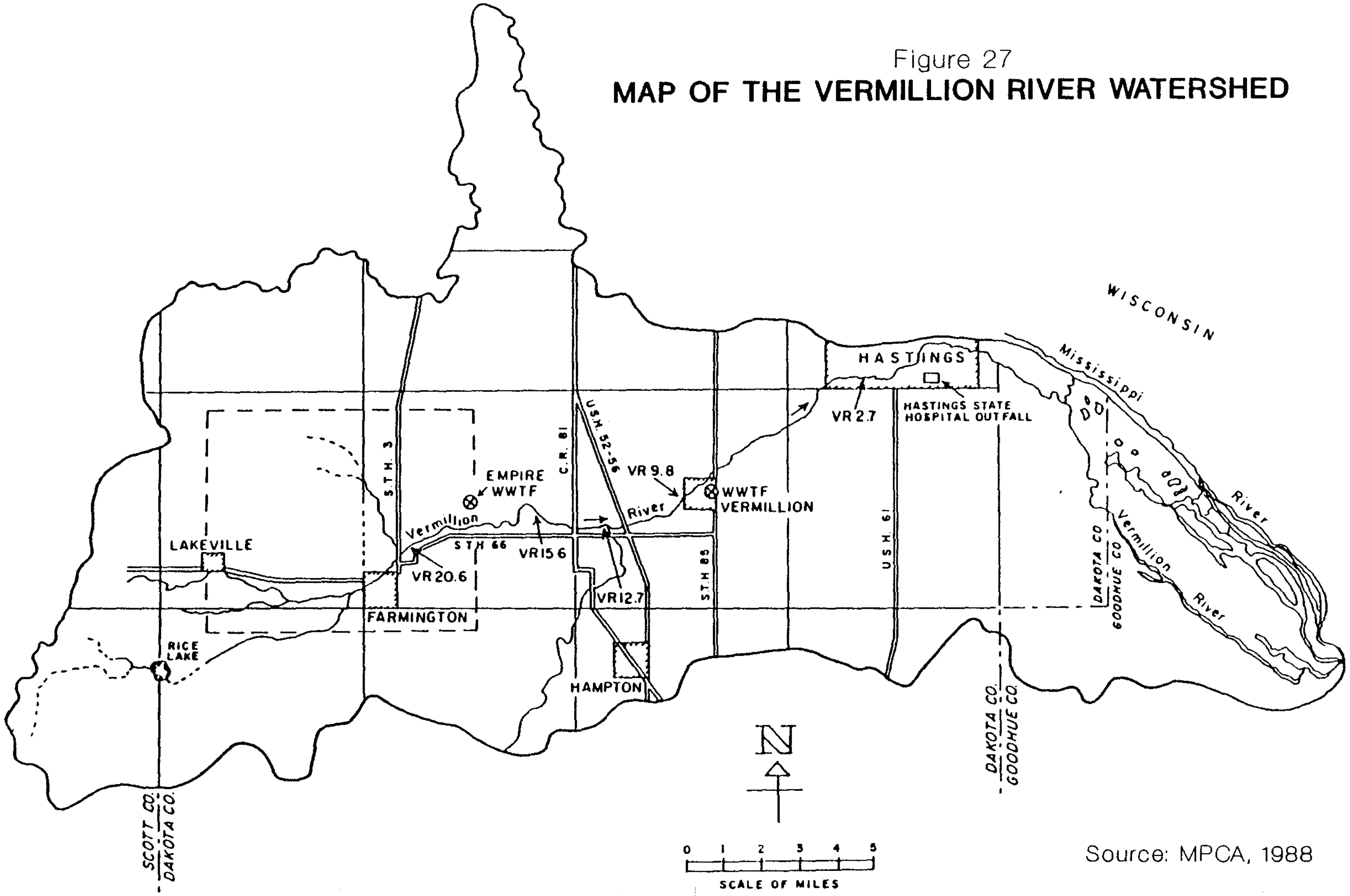
Vermillion River

The Vermillion River drains a relatively small 215 square mile watershed located primarily in northern Dakota County, as shown on Figure 27. Originating in southeastern Scott County, the river flows eastward through approximately 35 miles of gently rolling, predominantly agricultural terrain to its confluence with the Mississippi River just downstream from Hastings. Much of the streamflow originates from ground water seepage into the stream in the upstream and central parts of the watershed. The average stream gradient upstream of Hastings is a gentle 5 feet per mile. A 60-foot natural waterfall and man-made dam at Hastings prevent navigation and fish migration between the Vermillion and Mississippi Rivers. The South Branch of the Vermillion is its only significant tributary, joining the main channel about three miles upstream of the city of Vermillion at RM 12.7 (MPCA, 1988).

The Vermillion is classified for the following uses: 2B, 3B, 3C, 4A, 4B, 5, and 6. It is a low flow, water quality limited receiving stream, with permitted pollution discharge standards that are more stringent than secondary treatment requirements. The Vermillion River's capacity to assimilate organic pollutants varies seasonally in response to changing river flow rates and water temperature. Noncompliance with water quality standards for fecal coliform bacteria occurs both upstream and downstream from the Empire WWTP (near RM 18), indicating probable nonpoint source contamination (MPCA, 1988).

MWCC's Empire WWTP was constructed in 1979 and treats combined domestic and industrial wastewater from the cities of Apple Valley, Farmington, and Lakeville. Accelerated growth in the south suburban areas of the TCMA required an expansion of the plant to increase its existing design flow capacity from 6.0 mgd to 9.0 mgd (13.9 cfs). This expansion is scheduled for completion in 1992. Table 9 provides the seasonally adjusted river flows that are typically available for dilution of WWTP effluent (MPCA, April 1988).

Figure 27
MAP OF THE VERMILLION RIVER WATERSHED



Source: MPCA, 1988

Table 9

VERMILLION RIVER

SEASON	7Q10 (cfs)
Spring	20.2
Summer	12.0
Fall	13.7
Winter	7.6

The design flow of the upgraded WWTP is almost twice the historic measured winter season average 7Q10 flow in the stream. Minnesota Rules established in 1976 required very stringent site-specific discharge limits for the Vermillion River. Subsequent revisions to the rules gave the river uniform consideration under statewide water quality rules, but maintained existing stringent effluent requirements. According to water quality modeling for a WLA study performed by the MPCA, instream DO is potentially most sensitive to treatment plant loading and CBOD decay (dieoff) rates, both of which are a function of the level of wastewater treatment.

Instream nitrification does not seem to generate a significant oxygen demand within the stream below the Empire plant, and only a slight depression in DO concentration occurs downstream from the discharge. Reduction of organic pollution by conventional biological wastewater treatment technologies to the degree required at the Empire plant not only reduces the mass of organics discharged to the stream, but also seems to change the character of the organics. More highly treated effluents contain relatively stable wastes that exhibit lower decay rates, especially when discharged to a stream like the Vermillion that is effluent-dominated under low flow conditions. These slowly decaying organics allow time for the natural assimilative capacity in the Vermillion to stabilize the Empire effluent without severe DO depletions. The Empire plant utilizes an effective cascade aeration structure to continuously raise the effluent DO concentration to near 100% of saturation levels. Modeling projections indicate that even under the most stressful 7Q10 low flow conditions of late summer or winter, effluent from the expanded Empire facility will not exceed minimum water quality DO levels in the Vermillion River if the effluent maintains NPDES Permit limitations (MPCA, 1988).

Three WWTPs owned and operated by TCMA rural centers also discharge into the Vermillion or ditches flowing into the river. The Hampton and New Market-Elko plants are of waste-stabilization pond design, and required to meet secondary effluent standards. They are permitted to discharge only seasonally, in the spring and fall. The Vermillion WWTP utilizes the activated sludge design process, continuously discharging effluent that must meet secondary treatment limits to maintain instream water quality standards in the Vermillion River.

St. Croix

The deep-cut valley of the lower St. Croix River makes up the eastern boundary of Washington County in the TCMA. The river flows out of Wisconsin to the west along central Minnesota's Pine County, and continues south to its confluence with the Mississippi River near Hastings. The St. Croix is a relatively fast moving stream carrying sediment comprised of sand and gravel. This sediment load is deposited where it meets the Mississippi, as flow velocity drops to match that of the Mississippi. This deposition within the Mississippi channel has forced

the Mississippi to back up, spread out, and rise to flow over the deposited material. The backwater or backing-up has caused a natural dam across the mouth of the St. Croix, creating what is known as Lake St. Croix (Schwartz et al., 1976).

The St. Croix is classified from Taylors Falls in Chisago County to its mouth for the following uses: 1C, 2Bd, 3B, 3C, 4A, 4B, 5, and 6. It has been designated as wild and scenic by the U.S. Department of Interior, and scenic or recreational along its entire length by the state of Minnesota. Based upon these designations, the MPCA enforces an anti-degradation policy on the river that does not allow an increase in pollutant loads to the St. Croix over the amounts currently considered to be acceptable for discharge by existing NPDES permits.

The MWCC currently operates two WWTPs that discharge effluent to the St. Croix at Stillwater and Bayport. Both facilities provide secondary levels of treatment through the activated sludge process, with chemical addition for partial removal of phosphorus. The Bayport plant is planned for phase-out by 1994. A pump station and forcemain system will be constructed to pump Bayport flow to Stillwater for treatment. The Stillwater plant is currently being expanded to an average wet weather design flow capacity of 5.8 mgd to accommodate the additional flow and future development. When the Stillwater expansion is completed, it will be required to meet more stringent limits than are currently in place. The expanded plant's effluent $CBOD_5$ limit is being lowered from 25 to 20 mg/l, TSS is being reduced from 30 to 24 mg/l, and total phosphorus from 1.0 to 0.8 mg/l, on a continuous basis. Both of these facilities are currently meeting their discharge requirements.

Sources of Inflow To The Mississippi River During Low Streamflow

Headwaters Lakes

During the period in July and August of 1988 when the TCMA was experiencing the lowest streamflow in the Mississippi River since the 1930s, the six headwaters lakes maintained a routine low flow combined release of at least 270 cfs, as measured at the six respective headwaters dams. Although several downstream uses were curtailed or suspended for a time, sufficient flow was present within the Mississippi River through the TCMA to deter threats to human health and safety as a result of the low flow. Concern about unavailability of potable water or electrical network brownouts as a result of periods of further diminished flow in the Mississippi River must be considered a potential reality in the future and be planned for now, in order to minimize their impacts (Corps, 1990).

The current plan outlining the decision-making process on whether to make emergency supplemental releases from headwaters lakes is determined by the flow at the Anoka streamflow gage. The flow at that gage would have to be projected to remain below the current established minimum flow to support human health and safety (554 cfs), for seven consecutive days to justify a release. Any supplemental release would take at least 20 days to reach the Anoka gage, so the decision of whether or not to release is made more difficult by having to determine exactly when to make the release. Since the potential length of any drought would be unknown, it is desirable to retain as much water as possible in the headwaters lakes for potential future emergency release(s). Each headwaters lake has a minimum designated pool elevation, which when reached, triggers a discharge reduction of 50% for that lake. Remaining headwaters lakes still above their minimum pool level increase their releases to maintain the minimum 270 cfs flow. When water levels in all of the lakes are below the minimum designated pool levels, all discharges drop to one half of their minimum daily release value, resulting in a cumulative release of 135 cfs. This procedure would be followed to maximize the recoverability of all of the lakes by encouraging them all to refill to normal levels during the water year following an emergency supplemental release, to minimize future losses of use (Corps, 1990).

Ground Water

Inflows and outflows occur in the Mississippi River between gaging stations that cannot be attributed to gaged or metered flows. They represent a combination of surface inflow from tributaries, groundwater discharge to the river, discharge from or to bank storage, changes in pool storage, changes in discharge induced by dam operation, evaporation, and inaccuracies introduced by stream gaging. On July 30, 1988, the net increase in instream flow attributed to ungaged inflow between the Lake Winnibigoshish Dam and the Anoka stream gage, as measured and summed from each interim flow gage, was approximately 600 cfs. Figure 28 is a graphic representation of the Mississippi River water budget for July 30, 1988. The influence of withdrawals, return flows, and river regulation at dams is illustrated in the figure. Inflows are listed on the left side of the vertical graph illustrating river discharge, and outflows are listed on the right. The vertical size of the brackets next to the numbered inflows and outflows is proportional to their flow rates. The length of the vertical graph is proportional to the length of the river, and the width is proportional to the volume of river flow (Corps, 1990).

Municipal and Industrial

Contributions to Mississippi River flows above the TCMA from municipal and industrial discharges of well water, for consumption and cooling purposes (not including power generation facilities), approximately equal consumptive withdrawals (Corps, 1990).

Within the TCMA, the contribution directly to Mississippi River flow from MWCC wastewater treatment plants on July 30, 1988 was approximately 355 cfs. Of the total estimated flow contributed by the Minnesota River of 303 cfs, approximately 54 cfs was WWTP effluent discharged from MWCC facilities (Corps, 1990).

TCMA Cooling Water

Contributions to Mississippi River flows of ground water, having been pumped specifically for building air conditioning in the metro area during the July 1988 low streamflow period are estimated to have been approximately 76 cfs (Corps, 1990).

Others

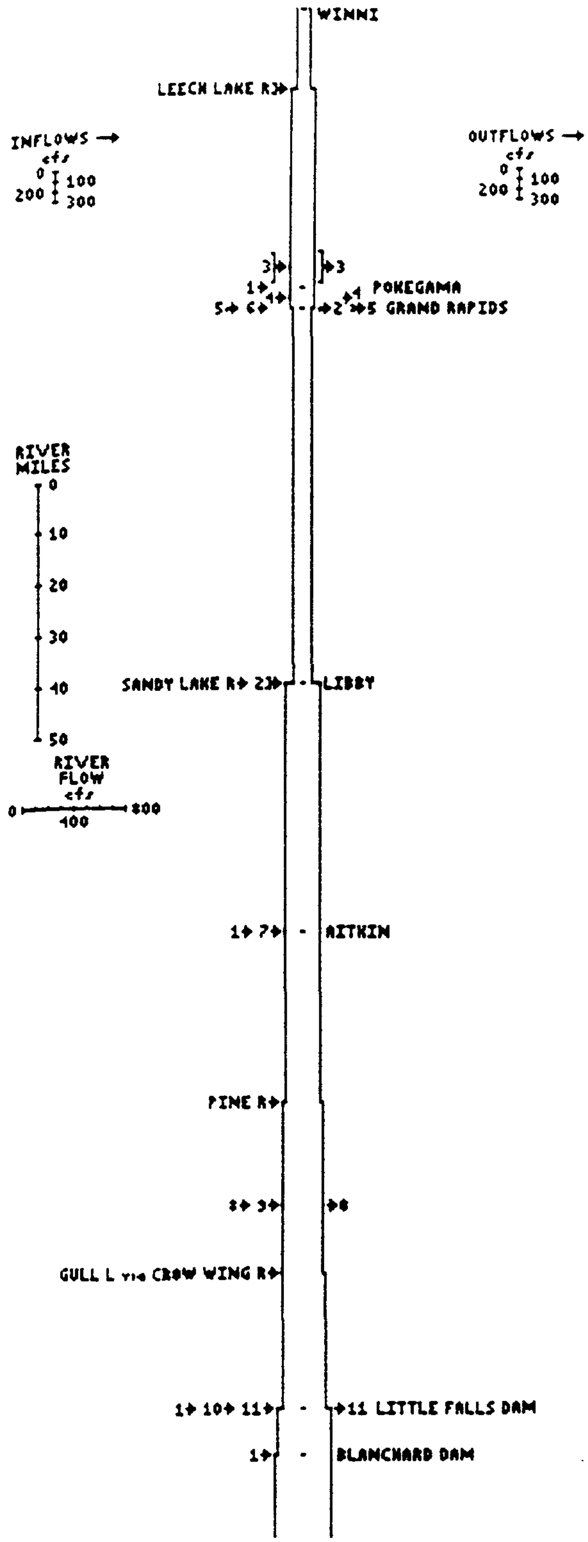
There are 12 water control structures operated by 8 different owners on the Mississippi River between and including Winnibigoshish Dam, and Lock and Dam No. 2. These facilities can create temporary inflow/outflow conditions within the river. Four of the structures are hydropower facilities within the TCMA and the remainder are upstream. Releases from the hydropower dams on the Mississippi River varied during the low flow period during the summer of 1988 as dam operators regulated for hydropower production and maintenance of pool elevations behind the dams. Ordinarily, when streamflow levels are much higher, daily changes in gate settings or hydropower turbine operation at the various dams do not produce large relative changes in river discharge. During low flow periods however, the results were artificially-induced, short-term increases and decreases in river discharge that, as a percentage of river discharge, were in some cases quite significant. Each dam has a specific operating strategy. Daily operation of these dams is informally coordinated by exchange of information between operators, using data on daily releases from the dams, pool elevations behind the dams, and flow data provided by the USGS and Corps gaging systems (Corps, 1990).

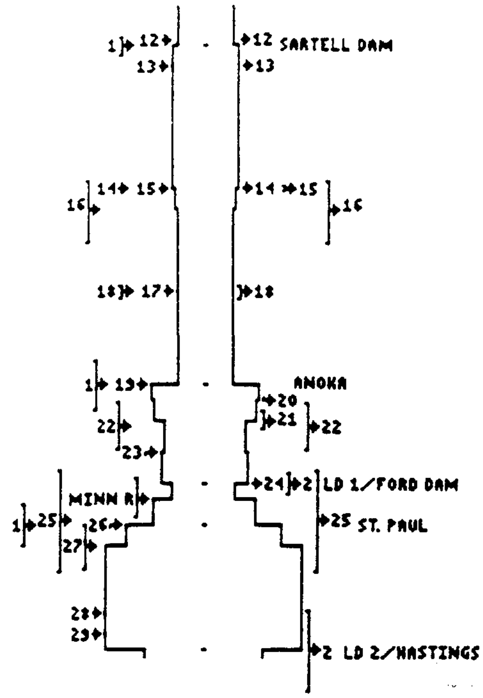
Changes in river discharge that constitute a large percentage change over a short time during a period of extreme low flow can cause significant disruptions to downstream aquatic habitat, water uses like power production that are discharge-sensitive, and downstream dam operation. A clear need exists for more coordinated operation of main stem Mississippi River dams during future low flow periods. The DNR and the Corps intend to assist the operators of the instream dams on the Mississippi River in preparing low flow water control plans that will contribute to more stable river flows downstream from the dams during future periods of low streamflow (Corps, 1990).

Water Quality Problems Associated With Diminishing Streamflows

Water quality conditions in both the Minnesota and Mississippi Rivers are strained by the cumulative effects of extreme low flows, wastewater treatment facility discharges, and high water temperatures. Phytoplankton further modify water quality through photosynthetic activity. The combined effects of constant supplies of sufficient plant nutrients, low flushing rates in pooled portions of the rivers, decreased turbidity due to increased settling, and high water temperatures producing high metabolic rates can promote the development of dense blue-green algae blooms. The associated effects of high air and water temperatures, restricted habitat containing sufficient oxygen, resultant overcrowding, increased concentrations of toxics like un-ionized ammonia, presence of algal toxins, and nightly dips in DO concentration due to algal respiration can combine to impose great stress on fish and other forms of aquatic life. Stressed fish have a diminished resistance to disease and can more easily succumb to various pathogens and parasites (Corps, 1990).

Figure 28
MISSISSIPPI RIVER WATER BUDGET, WINNIBIGOSHISH DAM TO LOCK AND DAM NO. 2, (JULY 30, 1988)





KEY

1 Ungaged inflow
2 Ungaged outflow
3 MN Power Boswell
4 Blandin Wood Prods.
5 Blandin Paper
6 City of Grand Rapids
7 City of Aitkin
8 Potlach Corp.
9 City of Brainerd
10 City of Little Falls
11 Hennepin Paper Co.
12 Champion Intl.
13 City of St. Cloud
14 Barton Sand & Gravel
15 NSP Sherco
16 NSP Monticello
17 City of Elk River
18 United Power Assn.
19 MWCC Anoka
20 City of St. Paul
21 City of Minneapolis
22 NSP Riverside
23 Combined flows (Bldg. AC)
24 Ford Motor Co.
25 NSP High Bridge
26 Combined flows (Bldg. AC)
27 MWCC Metro Plant
28 MWCC Rosemount
29 MWCC Cottage Grove

Source: Army Corps of Engineers, 1990

The incremental reduction of either quality or quantity of streamflow through the area can result in the reduction in the quality of life of TCMA residents. Nuisance algal blooms and fish kills are both obvious indicators of reduced water quality. Increased electricity costs due to the derating of local power generation facilities, restrictions in allowable home water use, and reduced recreational boating access are the result of reduced quantity of water.

Instream Pools

Two in-stream pools of water within the Mississippi River impacted by pollutants discharged from within the TCMA are Spring Lake, upstream of Lock and Dam No. 2 at Hastings, and the downstream Lake Pepin, both identified on Figure 29. Both pools act as sediment traps for the river, as a result of the reduction in streamflow velocities through each of the reaches. Spring Lake has a mean hydraulic retention time of 2.5 days, a mean depth of 8 feet, and a maximum depth of 20 feet. Spring Lake as it appears today was created when water was allowed to accumulate behind Lock and Dam No. 2 upon its completion in 1930. At that time, the lake, once a separate oxbow lake, became a part of the river channel once again. Stump fields within Spring Lake are a sign that much of it is a flooded lowland. As flow velocities drop upon entering the expansive Spring Lake reach, SOD rates increase over the normal progressive increase in rates observed through other TCMA river reaches, in response to the increased deposition of solids, including settled algal biomass.

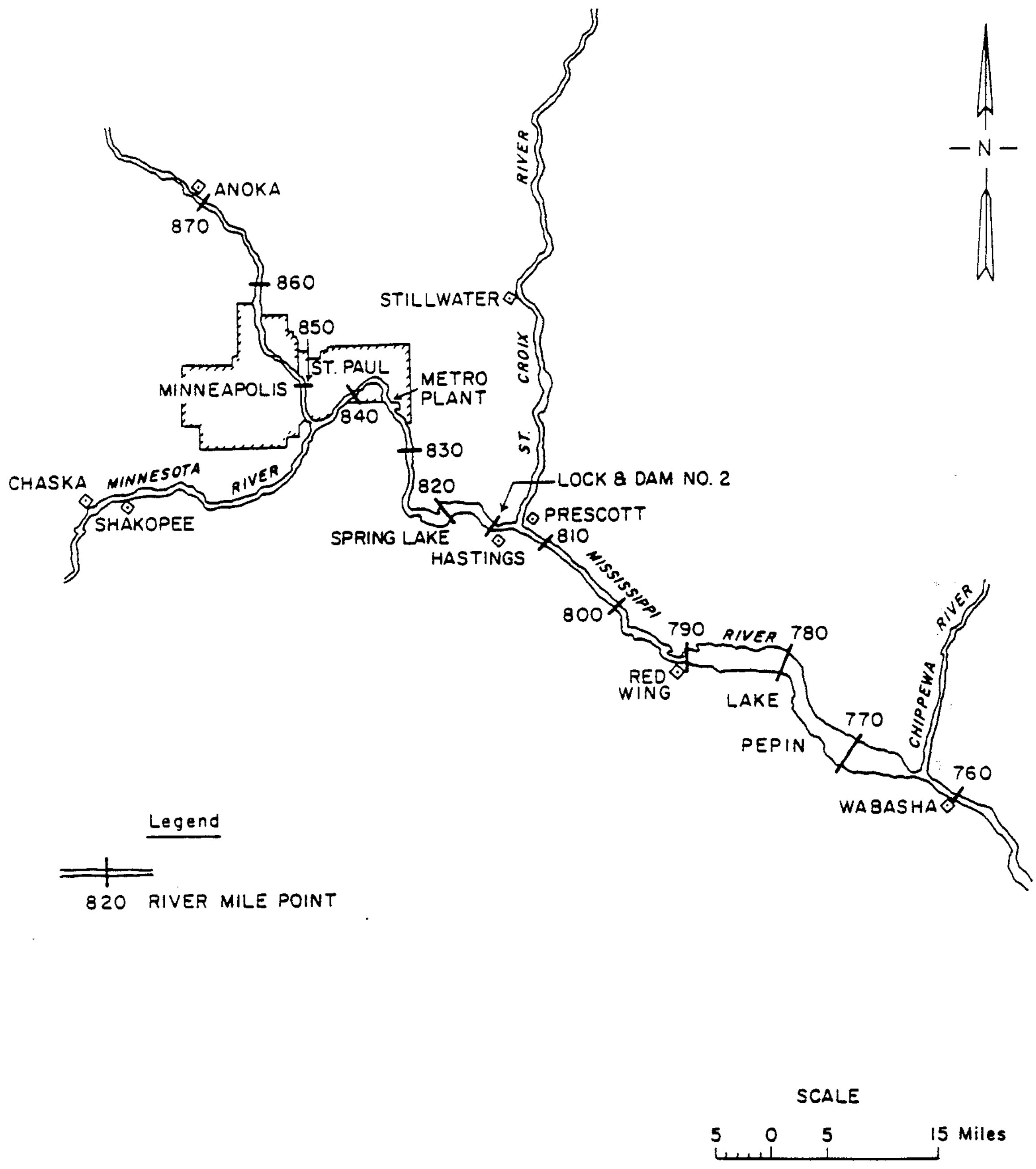
Lake Pepin, located downstream from the TCMA, was formed by delta deposits that accumulated in the Mississippi River channel from Wisconsin's Chippewa River during the post-glacial period when the Mississippi was aggrading. The lake has a mean depth of 16.7 feet, and a maximum depth of around 56 feet. Lake Pepin experienced a number of water quality related problems during the 1988 summer low flow period. Two fish kills and a series of very severe nuisance algal blooms occurred. The fish kills were the likely result of extremely low DO levels, and/or possibly localized elevated ammonia nitrogen levels, both related to extensive blue-green algal blooms in the area and the subsequent decomposition of the blooms upon their collapse (MPCA, April 1989).

The drought-related low flow period of 1988 saw Lake Pepin's typical water residence time of nine days stretch to approximately 60 days. This increased residence time, coupled with the sufficient availability of nutrients and increased water surface temperatures provided optimum conditions for algal growth. The shallowness of Lake Pepin, aided by the resuspension of fine particulate matter laden with adsorbed nutrients (a phenomenon known as internal loading) by wind action and possibly barge traffic, provided an abundance of "food" for apparent unlimited algal growth during that period (MPCA, April 1989).

The phosphorus contribution to the Mississippi River by the MWCC Metro WWTP is being scrutinized for its direct effect upon the trophic condition of Lake Pepin. The current average discharge concentration of phosphorus by the Metro Plant is about 3 mg/l. This concentration translates into an average daily mass discharge of phosphorus of approximately 5000 pounds. Possible effluent limitations of 1 mg/l and 0.4 mg/l are being considered for the Metro plant by the MPCA. Minnesota Rule 7050.0211, subpart 1 (see Table 1) indicates that a maximum concentration of effluent phosphorus of 1 mg/l can be applied to WWTPs whose discharge is substantiated as negatively affecting a downstream lake or reservoir.

Figure 29

MISSISSIPPI RIVER BASIN WITHIN AND BELOW THE TWIN CITIES METROPOLITAN AREA



Source: MPCA, 1984

A phosphorus limitation for the Metro Plant, under high river flow conditions, might have little or no effect on inlake trophic conditions in Lake Pepin. It is less clear what the impacts of limiting effluent phosphorus would be under average to low flow conditions, when volumes of runoff and its associated phosphorus contribution are low (MPCA; 1984, 1989, and 1990).

Ongoing Efforts to Improve Stream Water Quality

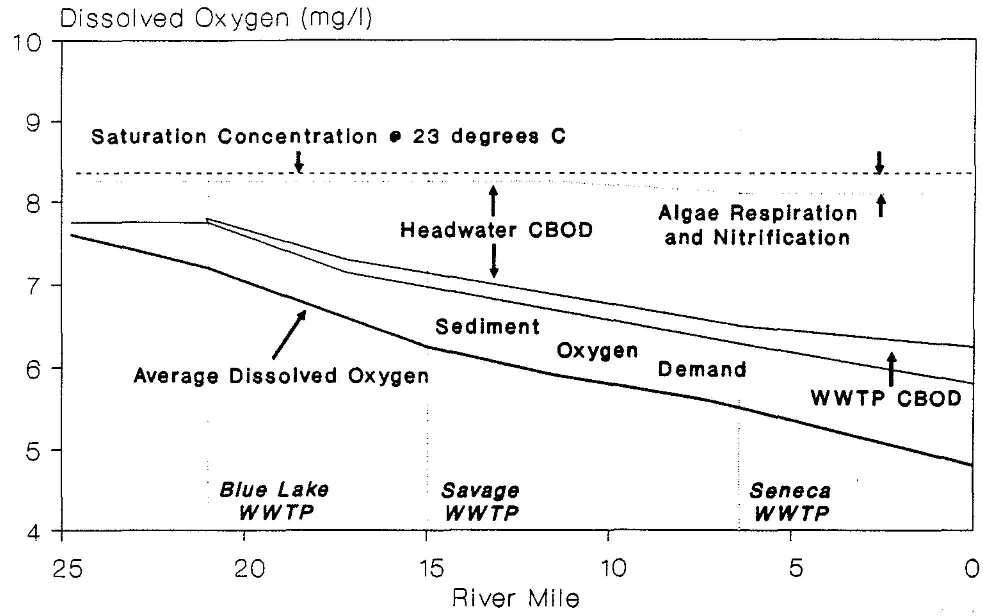
Minnesota River Nonpoint Pollution Reduction Program

The MPCA's WLA analysis of the lower Minnesota River in 1985 and 1986 documented existing water quality problems in the river, and attributed the impairments to a combination of excessive point and nonpoint pollutant loadings. The WLA recommendations involved mandatory reductions to reduce pollutant loadings from both point and nonpoint sources to the Minnesota, as the only perceived course that could achieve river water quality standards. Methods were proposed by the MWCC for reduction of point source loadings from the Blue Lake and Seneca plants that were determined by MPCA to be reasonable and technically able to provide the degree of treatment necessary to meet water quality objectives. Methods to be employed in attaining the associated nonpoint pollutant loading reduction indicated to be necessary to sustain sufficient instream DO to maintain water quality standards were less well defined. The EPA and MPCA have agreed to the 1986 WLA's goal of reducing nonpoint pollution levels by July 1, 1996, to 40% below observed 1980 levels. Figure 30 illustrates the relative significance of major factors that were responsible for the observed DO deficit in the Minnesota River during the MPCA 1980 low flow survey, and why reductions in upstream contributions of CBOD are of such great concern. The Council and watershed management organizations along the Minnesota River, both within the TCMA and upstream, are working cooperatively with the MPCA to determine what methods will best achieve the 40% reduction goal (MPCA, 1985).

The MWCC began a five-year nonpoint source monitoring program in 1988 to assess impacts and control of nonpoint sources of pollution on the Minnesota River within the TCMA. The program involves automatic monitoring of seven Minnesota River tributaries, and subsequent modeling of the collected data. The MWCC intends to continue this program past its initial 1992 deadline, in an effort to more accurately assess the effects of nonpoint pollution and the reduction measures currently being implemented.

Analysis of historic long-term water quality monitoring data for the Minnesota River indicates that nonpoint sources are responsible for more than 80% of the total annual demand for DO through the biochemical oxidation of instream organic matter as measured at Shakopee. Over one-half of this BOD load is carried by the river during the spring months when both streamflow and runoff are typically highest. During the warm summer months, the nutrient-rich river supports increased levels of phytoplankton growth, continually creating new biomass that exert an increasing level of oxygen demand upon the river. Much of this nutrient-rich suspended organic matter then settles out within the TCMA's slow moving, pooled reach of the river. The oxygen demand exerted by this accumulation of bottom sediment materials can significantly affect the capacity of the Minnesota River in its assimilation of WWTP effluent (MPCA, 9/82).

Figure 30
COMPONENTS OF DISSOLVED OXYGEN DEFICIT, MINNESOTA RIVER, AUGUST 12-15, 1980



Source: MPCA, 1985

The MWCC Minnesota River monitoring program observed the following instream water quality parameters at Jordan, as a result of a two-day rainfall event in June of 1990. The total suspended solids load carried within the Minnesota River during those two days was 67,000,000 pounds. This value compares to a 30,000 pound discharge of solids to the Mississippi River by the Metro plant during the same time period. The chemical oxygen demand (COD) within the Minnesota River was 40 times greater, and the BOD was 10 times greater than in the Metro plant effluent to the Mississippi River during this same period of time. The Minnesota River flow contained a loading of 94,000 pounds of phosphorus at Jordan during the two-day rainfall event. The corresponding discharge of phosphorus from the Metro plant was 10,000 pounds during the same time period.

Success in nonpoint pollution source control efforts in rural areas carries with it the obvious benefit of the maintenance of soil particles and their associated nutrients at their sources, for future agricultural use. The reduction of nonpoint source pollution levels may also defer application of more stringent effluent limitations upon point sources of pollution during the critical summer low flow periods, even though the desired accomplishment of maintenance of water quality standards within the Minnesota River might not be achieved through the application of those limitations.

Blue Lake and Seneca WWTP Modifications

The Blue Lake and Seneca WWTPs both currently provide secondary wastewater treatment utilizing the activated sludge process. Expansion and treatment upgrades are in progress at both facilities to provide for additional growth within their service areas, and to meet the increased levels of treatment determined to be necessary by MPCA to achieve and maintain established water quality standards in the Minnesota River. The expansion of these two plants was designed to serve a 2010 total service area population of approximately 452,000. The most recent WLA study by MPCA, completed in 1986, determined that reductions in $CBOD_5$ and ammonia-nitrogen loads to the Minnesota River were needed at both plants to maintain minimum acceptable DO levels within the river. Reductions in effluent ammonia-nitrogen and chlorine concentrations were also necessary to protect aquatic life from chronic toxicity problems. The reduction in ammonia loading to the Minnesota River is also a critical factor in the maintenance of water quality standards within the Mississippi River. The assignment of ammonia effluent limitations for the Metro WWTP on the Mississippi River by MPCA in 1981 included the assumption that the Blue Lake and Seneca WWTPs would discharge a future nitrified effluent.

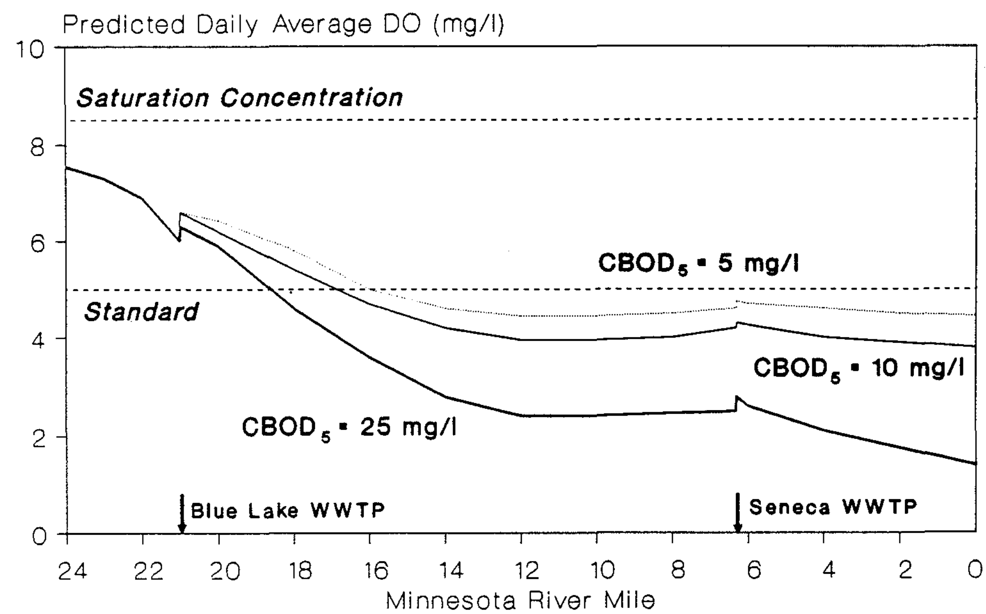
In 1985, MPCA modeled the future effects of these upgraded plants while operating at their new design capacities at 7Q10 instream low flow levels in the Minnesota River. Since the Seneca WWTP at RM 6.5 is located within the zone of the Minnesota River impacted by the upstream Blue Lake WWTP at RM 20.5, treatment requirements at the Seneca facility depend in part upon the level of treatment provided at the Blue Lake facility. A common level of treatment was assumed by MPCA to be provided for by each upgraded facility when the river's assimilative capacity was modeled. Mass loads of $CBOD_u$ that result from the two major sources of CBOD in the lower Minnesota River, the headwaters and WWTP sources, are compared under 7Q10 design conditions in Table 10. Figure 31 plots the predicted daily average DO concentrations in the Minnesota River under anticipated future WWTP design loads, 7Q10 flows, and summer conditions with WWTP effluents first equalling a secondary treatment level of 25 mg/l $CBOD_5$; next a nitrified effluent of 10 mg/l $CBOD_5$; and lastly a nitrified, tertiary filtered effluent of 5 mg/l $CBOD_5$. As the figure indicates, the water quality standard of 5 mg/l for DO applicable to the lower Minnesota River would still be consistently violated during critical low-flow river conditions, even under the most stringent level of wastewater treatment that can be required, limiting $CBOD_5$ to 5 mg/l. Modelling indicated that even if WWTP discharges from both Blue Lake and Seneca were eliminated and diverted elsewhere, instream levels of DO would still drop to an unacceptable minimum of 4.6 mg/l as a daily average under 7Q10 flow conditions and future background loadings (MPCA, 1985).

Table 10
YEAR 2000 $CBOD_U$ MASS LOADINGS

WWTF Effluent $CBOD_5$ Level	Headwater Load, lbs/day	WWTF Load, lbs/day	Total Load, lbs/day
25 mg/l	19,949 (32.3%)	41,861 (67.7%)	61,810
10 mg/l	19,949 (50.9%)	19,253 (49.1%)	39,202
5 mg/l	19,949 (66.0%)	10,295 (34.0%)	30,244

Source: MPCA, 1985

Figure 31
PREDICTED DO SENSITIVITY TO EFFLUENT $CBOD_5$ UNDER FUTURE SUMMER CONDITIONS



Source: MPCA, 1985

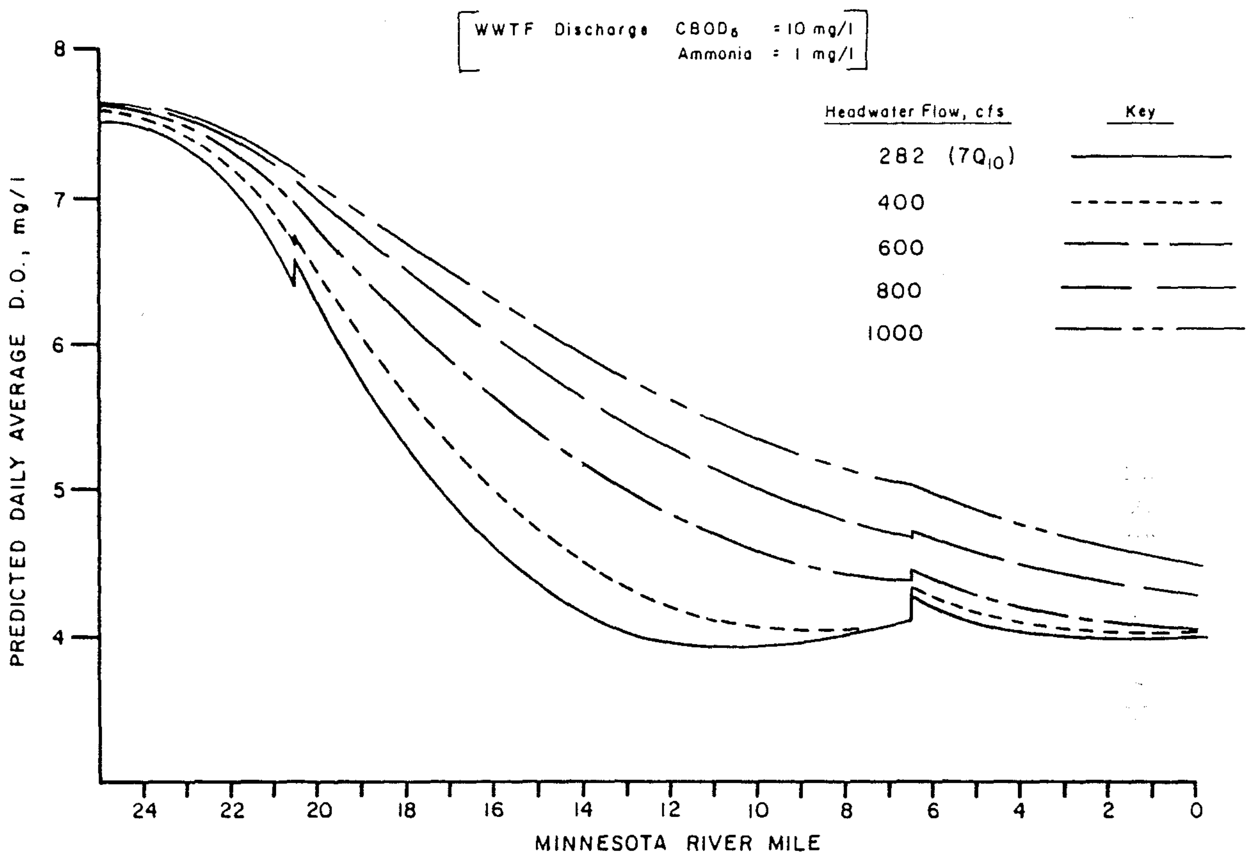
Figure 32 plots the 1985 WLA study-predicted DO concentrations within the Minnesota River under future WWTP design loading, summer conditions. The study indicated both facilities would need to reduce the maximum discharged effluent concentrations of $CBOD_5$ to 10 mg/l and ammonia nitrogen to 1.0 mg/l. The figure indicates the predicted response of the river to those pollutant loads, under flowrates varying from the 7Q10 flow up to 1000 cfs. At 7Q10 flowrates, DO was predicted to fall below 5 mg/l as a daily average in the lower 17 miles of the river. Even at flows of 1000 cfs, the lower 6 miles would be below the water quality standard. The MPCA ultimately determined that a 40% reduction in nonpoint source loadings of organics from upstream of the WWTPs would be necessary to maintain minimum DO levels of 5 mg/l in the Minnesota River during future summer low flow periods. This position objectively recognized that both point and nonpoint sources of organic pollutants required more stringent control to guarantee future instream water quality during critical periods of low flow. The MPCA accepted the MWCC proposal to substitute effluent oxygenation for tertiary filtration, resulting in modified $CBOD_5$ limits for each WWTP, given the ultimate oxygen demand upon the river would be equivalent (MPCA, 1985).

The current NPDES permits for these two facilities expire on September 30, 1992. During their next five-year permit period that begins on October 1, 1992, both upgraded plants will begin full-scale operation of their upgraded facilities in an effort to meet the more stringent limits established by the 1986 WLA study. The MPCA target date of July 1, 1996 for achieving 40% reduction in observed levels of nonpoint source pollution in the Minnesota River will also pass during that five-year period of time. If either or both of these efforts to achieve water quality standards in the Minnesota River provide an inadequate degree of success in maintaining minimum instream DO levels, according to future WLA studies, one or both of these WWTPs may be required to provide additional treatment of wastewater flows prior to discharge. Seneca will already be supersaturating its effluent with DO, leaving the previously mentioned tertiary filtration option as the most probable plant addition to achieve a higher degree of CBOD removal, probably to within the 5 mg/l range, which would result in a decreased instream DO demand. Blue Lake may have to provide supersaturation of its effluent in lieu of saturation with DO, as is currently being added, and/or the provision of tertiary filtration (as with Seneca) may be necessary to achieve the desired level of instream water quality. Provision of oxygenation of the Minnesota River itself has also been given long-range consideration as a potential option by the MWCC to maintain future water quality standards for DO to maintain aquatic life during extreme low flow periods.

Anoka WWTP Phaseout

The Anoka WWTP currently provides secondary treatment of wastewater at very near its rated flow capacity of 2.46 mgd. Expansion of this plant was not determined to be a cost-effective alternative to rerouting of its flows, due to the increased level of treatment that might have been required by the MPCA to maintain water quality standards within this reach of the Mississippi River. The facility will be phased out by December of 1992. Future flows will be directed through a new lift station and an addition to the existing interceptor system to the Metro WWTP for treatment. The current Anoka effluent limitations are less stringent than those for the Metro facility. The Metro plant must remove more CBOD on a year-round basis, and ammonia nitrogen on a seasonal basis than the Anoka plant. Metro must also provide effluent oxygenation on a low flow or as-needed basis. By shutting down the Anoka WWTP at RM 871 on the Mississippi River, any possible negative effects that its current oxygen demand and nutrient contributions

Figure 32
PREDICTED DISSOLVED OXYGEN SENSITIVITY TO HEADWATER FLOW UNDER FUTURE SUMMER CONDITIONS



Source: MPCA, 1985

might have upon river water quality within the 35-mile reach between Anoka and the Metro WWTP will be effectively eliminated.

The phaseout of the Anoka facility will reduce the instream flow volume in the Mississippi River by the current average daily discharge volume from the facility of 2.46 mgd (3.81 cfs). This amount of flow constitutes less than 1% of the current annual 7Q10 flow of 1180 cfs for the river at Anoka. The instream flow gage at Anoka recorded its lowest 1988 drought-related flow of 842 cfs, on July 30, 1988.

When the Anoka WWTP is eliminated as a point source of organic pollutants to the Mississippi River, only the Crow and Rum Rivers will remain as sources to the Mississippi within the TCMA that will continue to assimilate WWTP effluent discharges above the water supply intakes for the St. Paul and Minneapolis utilities.

Centralization/Decentralization

The continued provision of wastewater treatment at the Anoka facility in lieu of transmission of its flow to the Metro facility for treatment would more efficiently utilize the assimilative capacity of the Mississippi River for pollutants within the TCMA. Since its inception in 1969, the MWCC, with Council concurrence, has been consolidating treatment of wastewater to fewer and fewer plants. The original 33 plants in the system have been pared down to 11. With phaseout of the Anoka and Bayport plants in 1992 and 1993, respectively, the MWCC will have further reduced the number of treatment plants under their operation to nine. Many of the plants that have been phased out were small, outdated, inefficient, and in locations not suited for expansion or modernization. The Council and MWCC are now facing the very real possibility of reaching pollutant load ceilings within the effluent receiving streams of some of the major existing plants within the next 20 years.

The 7Q10 value is used as the design low flow rate upon which each stream's waste assimilative capacity and allowable future pollutant loads for each contributor are determined. A reduction in the magnitude of low flows and/or increases in their duration in TCMA stream reaches in future years may result in future reductions in allowable waste loads from current levels. The occurrence of two significant drought periods during the last 15 years, one in 1975-76, and the other from 1986 through 1989, would have resulted in a reduction in the magnitude of low flow rates, and in particular, the 7Q10 rates within TCMA streams, had the extremely wet period from 1982 through 1986 not also occurred during the same 15-year span of time.

The major MWCC WWTPs that discharge to TCMA streams are already required to provide advanced secondary levels of treatment to maintain water quality standards within the streams. If 7Q10 flow values decrease for a stream reach receiving discharge from one of those plants, the level of wastewater treatment provided at that plant may have to increase, even if the waste load entering the plant has not increased since its effluent limitations were last established through a WLA study. The Mississippi River is most apt to be faced with this future prospect. The summer season 7Q10 value for the reach below the Robert Street bridge flow gage on the Mississippi River at RM 839.3 is used to allocate future waste loads for the Metro WWTP. The 7Q10 flow applicable to the Metro plant diminished from a value of 1690 cfs in 1978, to 1633 cfs in 1981, but has subsequently increased to a currently estimated summer season level of 1910 cfs. The effects of recent wet year flows have outweighed those of dry year flows upon the calculated

7Q10 flow figures. (Hydroscience, 1979, MPCA, 1985 and MWCC, 1991). However, the possibility of increased pollutant removal requirements in future NPDES permits must be considered, in the event future summer low flows (and 7Q10 values) in TCMA streams resume the downward trend.

Several sources of water for augmentation of Mississippi River flow during low flow periods have been considered in the past as a means of supplying supplemental flow to meet needs for water supply, water quality/wastewater assimilation, power generation, and navigation. If the supplemental flow could be proven to the MPCA to be dependable and controlled under applicable laws or regulations, the MPCA could set future discharge permit limitations using a modified 7Q10 value that would take into account minimum guaranteed augmentations to the "natural" river flows. It does not seem prudent, keeping in mind that future droughts could be more severe than any to date, to rely upon other TCMA streamflows, headwaters reservoirs, or TCMA ground water wells to provide this dependable source. Whatever source(s) might be put into place, close coordination would need to exist between in-stream water users to ensure "7Q10 augmentation flow" would not be withdrawn by another user prior to reaching the point(s) in the stream where its capacity to provide proper assimilation of pollutants is required (State, 1991).

The need for evaluation of reversal of the present trend toward more centralized treatment of wastewater within the TCMA was presented by the Council to the MWCC as a policy directive in the Metropolitan Council Water Resources Management Development Guide/Policy Plan in 1988. The MWCC has already begun to explore the long-term alternatives to providing additional wastewater treatment service at the Blue Lake and Seneca WWTPs discharging to the Minnesota River, the Empire WWTP on the Vermillion River, the Stillwater WWTP on the St. Croix River, and the Metro WWTP on the Mississippi River. These five facilities currently must provide or are undergoing modifications to provide advanced secondary levels of treatment. Each additional degree of treatment becomes increasingly more costly to provide. This study will deal with the concept of continuing to centralize treatment at larger facilities versus decentralization into new, smaller facilities, and consider the economic, environmental, and political feasibility of both approaches. The Council will also work with the MWCC in evaluating how to most efficiently deliver sewer services to expanding and newly developing areas within the metropolitan urban service area (Council, 1988).

Analysis of 1988 Low Flow Survey Data

The MWCC will be evaluating TCMA stream water quality data obtained during the 1988 Low Flow Survey, in mid-1991. An effort will be made to compare observed instream conditions with those modeled during previous WLA studies. Models used in previous studies, as well as updated versions, will be utilized to determine which one most accurately simulates the in-stream events observed during the 1988 survey. The 1988 survey occurred during a very opportune time, in that flows dropped below the prevailing 7Q10 level for a period of 48 consecutive days. In fact, the flow reached a daily low of approximately 750 cfs in the area of the Robert Street bridge during the first week of July in 1988. In spite of these extreme conditions, instream water quality standards were maintained in the Mississippi River through consistent operation of the Metro WWTP that provided levels of treatment in excess of minimum required levels, and supplemental aeration of the plant's effluent flow that is estimated to have elevated the daily minimum DO by as much as 2 mg/l in the river below the Metro discharge point (Corps, 1990).

The MPCA will begin a revised WLA study of the Mississippi River during 1992, preliminary to establishing effluent limits for the Metro facility to maintain instream water quality standards for the next NPDES permitting period that will begin June 1, 1995.

CSO Program

The vast majority of the TCMA is served by separated storm sewers that convey most surface runoff directly or ultimately to the Mississippi River. However, like most large, older urban areas in the United States, Minneapolis, St. Paul, and South St. Paul initially constructed certain portions of their sewer systems to convey both sanitary sewage and stormwater. During dry weather, such sewers were typically able to convey all of the flow, consisting predominantly of wastewater, to treatment facilities prior to stream discharge. During rainfall events or spring snowmelt however, flow in these lines either has exceeded WWTP capacity or pipe capacities, resulting in its direct discharge to the Mississippi River through a system of 19 CSO structures.

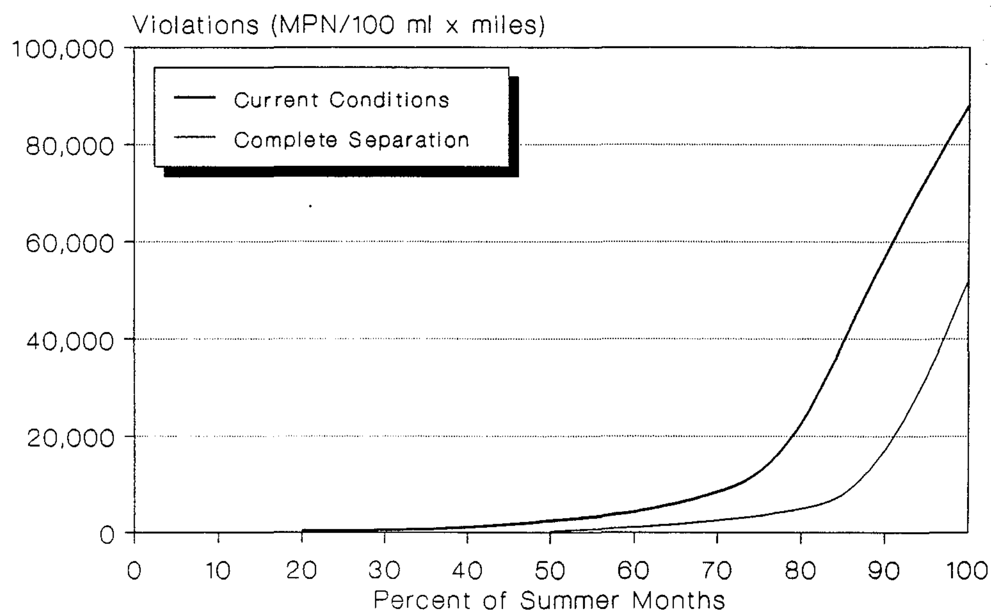
In 1984, MPCA and EPA, working through a broad-based CSO Task Force, developed and adopted new state-federal discharge permits for the CSO outfalls in the TCMA. The permits set progressively tighter discharge standards and deadlines for the hundreds of construction and modification projects needed to eliminate the CSO problem within an allotted ten-year period. Complete separation of the TCMA's remaining storm and sanitary sewers, located in Minneapolis, St. Paul, and South St. Paul, was determined to be necessary in order to achieve compliance with applicable water quality standards and requirements in Minnesota Rules Chapter 7050. After five years of construction, the program is on schedule, and over 11,000 acres of formerly combined sewer area has been separated. At the total estimated cost of this program in 1984 dollars of $250 million, the three cities and the MWCC will ultimately provide separation of an estimated annual overflow of nearly 5 billion gallons of combined untreated sewage and stormwater to the Mississippi River. Completion of the program will benefit all MWCC system users by reducing storm-related peak flows and the additional measures of facility operation and maintenance necessary to accommodate those flows, and making more treatment capacity available within the existing Metro WWTP to accommodate future growth within its service area (Council, 1990).

Completion of the CSO program in 1996 will eliminate any untreated wastewater from bypassing MWCC wastewater treatment plants and flowing into the Mississippi River. This program, started in 1986, accelerated the separate on-going removal programs of Minneapolis, St. Paul, and South St. Paul. As the cities continue to build separate sewer systems, the MWCC is constructing new interceptor sewers to match the redesigned city systems. When all of the presently combined sewers have been separated, a sizeable decrease in rainfall-induced peak flows to the Metro plant is anticipated to be observed. In the interim, however, an increase in average daily flows is being observed at the Metro plant during the spring and summer seasons. The flow increase is presumed to be a result of the more thorough capture and transmission of sanitary as well as infiltration and inflow (I/I) flows that had previously managed to pass through diversion structures to the Mississippi River in lieu of treatment.

Upon complete separation of combined sewers in the TCMA, the frequency, severity, and geographical extent of fecal coliform violations will be dramatically reduced but not eliminated. In Figure 33, the area under each curve represents the relative magnitude of the fecal coliform problem in the TCMA reach of the Mississippi River under pre- and projected post-separation program conditions. The difference in area under each curve reflects the impact of CSOs on the river, as well as the potential benefit to be obtained by separating the remaining combined sewers. The CSO program is expected to reduce the total fecal coliform load to the river by approximately 80% from levels measured in 1984. Prior to inception of this program, water in approximately 67% of the 48 mile reach of the Mississippi River between RM 863 and RM 815 exceeded the water quality standard for coliform bacteria approximately 67% of the time. At RM 839, the frequency of violation has historically been approximately 80% of the time. Complete separation is expected to reduce the violation frequency at RM 839 to about 50% during the summer months. Over the entire 48 mile reach, average noncompliance with the water quality standards is expected to drop to 27%. What all of this basically means is that the severity and the inferred public health threat posed by future water quality fecal coliform violations will be greatly reduced (MPCA, October 1984).

MPCA contends that under complete sewer separation, the Mississippi River in the TCMA will attain substantial compliance with the objective of obtaining a "swimmable" water from the bacteriological point of view. While the use of fecal coliforms as an indicator of human enteric pathogens is reasonably valid for assessing sanitary wastewater, the sole use of fecal coliform content to assess the public health threat of urban or rural stormwater is essentially invalid. The remaining detectable fecal coliform contamination in stormwater after full separation may essentially all be associated with decaying animal fecal matter, which will not necessarily pose the public health threat of human pathogenic bacterial contamination which would preclude the full recreational use of the Mississippi River for activities such as swimming (MPCA, Oct 1984).

Figure 33
PROJECTED MAGNITUDE OF FECAL COLIFORM VIOLATIONS FOR THE MISSISSIPPI RIVER



Source: MPCA, 1984

Phosphorus Study

An extensive Mississippi River study is currently underway by the MWCC, in cooperation with MPCA, to evaluate the impacts of phosphorus loads from the Metro Plant and other sources, upon the water quality of Lake Pepin and Spring Lake. The study, due for completion by December 31, 1992, will evaluate the impacts upon these lakes under high, average, and low river flow conditions, as well as during different seasons of the year. Future Metro plant effluent limits for phosphorus will be recommended by the study to meet applicable water quality standards. The capital costs, operation and maintenance costs, and proposed construction schedules shall also be included in the evaluation of all alternatives.

The basis of need for phosphorus removal at the Metro WWTP is the implication that the plant's discharge of phosphorus adversely affects water quality in Lake Pepin and, therefore, is subject to a Minnesota Rule Chapter 7050 effluent concentration limitation of 1 mg/l total phosphorus. A WWTP study, due in final form by May 1, 1993, is also underway to evaluate alternative methods of its removal during continuous, seasonal, and low river flow periods to WWTP effluent concentrations of 1.0 mg/l and 0.4 mg/l. Phase I of this study is an engineering evaluation of treatment plant options for phosphorus removal. Preliminary recommendations of the best removal alternatives were presented to the MWCC by their consulting engineer during May of 1991. The extent of plant construction or modification that will be necessary to carry out plant scale pilot studies is currently under review by the MWCC. Phase II of the study involves implementation of plant-scale pilot phosphorus removal trials.

Analysis of trial results and recommendation of the best alternative is to be made by May 1, 1993 to the MPCA. The feasibility of interim removal during the span of time required for construction of the full scale modification must also be evaluated by the MWCC.

During the period of time between January 1, 1993 and May 31, 1993, MPCA will indicate the phosphorus limitations they intend to place upon the Metro WWTP. An effluent limitation of 1 mg/l as a monthly average on a continuous basis will automatically apply, unless the river water quality study indicates less stringent limitations (if any) will maintain in-stream water quality standards, or if more stringent limitations will be necessary. Preliminary WWTP study results indicate that reduction of allowable effluent phosphorus concentrations to 1 mg/l or less would likely involve a capital cost of between $200 and $400 million, and more than $20 million per year in increased costs for operation and maintenance. The current Metro NPDES permit establishes a time limit of May 31, 1995 by which construction contracts shall be awarded to comply with any phosphorus limitation costing over $10 million.

The uncertainty of phosphorus removal and the various impacts of its alternatives upon existing and future facilities has made evaluation of whether or not to proceed with several on-going rehabilitation and replacement projects very difficult for the MWCC. It may be well into 1993 before MPCA determines the course of action to be required for phosphorus removal at the Metro WWTP.

FINDINGS

The most frequently used determinant of the overall water quality within a stream is the quantity of dissolved oxygen required to stabilize the pollution it contains by natural biological processes of decay.

Five dams on the Mississippi River within the TCMA have effectively converted both the lower Minnesota and Mississippi Rivers from free-flowing streams into a series of controlled backwater pools with constant water surface elevations during average to low flow conditions. These changes have decreased the natural self-cleansing and reaeration abilities of the rivers, resulting in diminished flow velocities and accumulations of nutrient-rich sediments and organic matter within the backwater pools.

Channelization and instream pools are in basic conflict with the natural equilibrium of a stream. While they do provide enhanced flood protection and increased navigation capabilities, these benefits are at the expense of natural instream pollutant purification processes that previously diverted floodwaters through adjoining oxbow lakes and created overland sheet flow across adjacent marshlands and wetlands, maintaining wildlife habitats and depositing nutrient-laden and organic sediments outside the normal stream channels. Those sediments are now coerced to remain in suspension within an aggrading, fabricated channel, and deposited within the in-stream pools or in the channel itself during low flow periods where they continue to contribute internal loading and oxygen demand upon the streams.

During the 1988 drought period, releases from the six Mississippi River Headwaters reservoirs comprised approximately 25% of the instream flow measured at Anoka, with consideration of losses enroute.

The St. Paul District of the U. S. Army Corps of Engineers currently considers that emergency low flow conditions exist in the Mississippi River when streamflows diminish to a level of 554 cfs. Upon reaching this flow level, the release of emergency supplemental flow from headwaters reservoirs will be considered, but will not occur automatically. Conservation measures must be underway in the TCMA for this release to ever be considered.

Drought conditions, typified during the summer season by high temperatures and extremely low streamflows, exert the greatest strain on a stream's self-purification abilities. For this reason, they exemplify the conditions in which to best determine a stream's assimilative capacity for pollutants.

Drought conditions more severe than those experienced most recently during 1986 through 1989 will occur in the TCMA in the future.

Water quality standards may conceivably be violated within any stream reach that assimilates wastewater treatment facility effluent when streamflows drop below established 7Q10 levels, even though that facility is operating acceptably and its effluent is in compliance with its NPDES permit limitations.

The Minnesota Pollution Control Agency's most recent waste load allocation study of the Mississippi River, completed in 1981, assumed a minimum 7Q10 streamflow of 1633 cfs was necessary to provide adequate dilution of MWCC Metro wastewater treatment plant effluent while operating at its design capacity flow and loading to maintain water quality within the Mississippi, during all but the lowest weekly flow with a probability of recurring only once each ten years.

The calculated summer season 7Q10 streamflow applicable to wastewater assimilation calculations for the MWCC Metro wastewater treatment plant on the Mississippi River has risen from the 1981 level of 1633 cfs to the current level of 1910 cfs, having been affected more by the extreme high summer flows during 1982 through 1986 than the subsequent extreme low flows during 1986 through 1989.

Neither the Minneapolis Water Works nor the St. Paul Water Utility experienced increased water treatment difficulties as a direct result of diminished instream Mississippi River water quality during the extreme low flow period in 1988.

Since water withdrawn from the Mississippi River by the St. Paul Water Utility is pumped into, and passes through the Vadnais chain of lakes prior to treatment and distribution, instream water quality fluctuations due to low flow do not create immediate water treatment problems for the utility.

The Minneapolis Water Works withdraws water from the Mississippi River as its sole source of potable water to service all or part of eight TCMA cities. The design of its intake structures within the Mississippi River channel will permit the continuous physical withdrawal of streamflow down to streamflow rates approaching 310 cfs.

Commercial navigation within the Mississippi River channel requires a flow of at least 350 cfs to satisfy the current minimum traffic demands.

NSP's Monticello power generating facility, located approximately 20 miles upstream of the TCMA, would typically be the first power facility located in or near the TCMA to undergo restrictions in generation capacity as a result of declining low flows in the Mississippi River and/or unusually high, summer-season, in-stream water temperatures. River flows below 860 cfs will initially require in-plant recirculation of cooling water, and ultimately, a derating of output capacity. Low streamflows during the summer of 1988 required derating of this facility to 70% of its supply capacity during a corresponding period of increased power demand.

The valleys of the Mississippi, Minnesota, and St. Croix Rivers act as principal regional drains for the bedrock aquifers as well as the surficial drift deposits within the TCMA. During periods of extreme low flow, ground water inflow from above and within the TCMA is the source of the majority of instream flow. The TCMA depends on this inflow for navigation, wastewater assimilation, public water supplies, power production, and recreation.

Current or future consumptive uses of water from TCMA streams during low flow periods that cause flows to fall below the established 7Q10 flow for a particular stream reach will result in the probable reduction of future calculated 7Q10 flow values for that reach. The lowered 7Q10 values could then lead to more stringent effluent limitations on wastewater discharges to maintain in-stream water quality standards.

Future increases in the withdrawal of ground water from new or existing wells located near streams within the TCMA may intercept and eliminate ground water inflow to streams that currently is anticipated for continued minimum low-flow and water quality standard maintenance in those streams.

Any surface or ground water uses that directly result in the reduction of in-stream flows to below 7Q10 levels can exceed the capability of instream assimilation of pollutants to maintain instream water quality standards.

CONCLUSIONS

Even though minimum acceptable in-stream water quality levels were maintained in the Mississippi River for a period of 48 consecutive days during the summer of 1988 when instream flows were significantly below 7Q10 levels, the ability to similarly maintain in-stream water quality standards during future low flow occurrences can not be expected.

In the future, as major TCMA WWTPs approach the design limits of best available treatment technology, their respective design capacities, and assimilation limits within their effluent receiving streams, their discharge of effluent during sub-7Q10 streamflow conditions can be anticipated to violate minimum instream water quality standards.

Historic streamflow data are analyzed to calculate 7Q10 flows that are utilized by the MPCA as the minimum design flows determined to be needed in receiving streams to ensure sufficient dilution water is available for proper assimilation of WWTP effluents to maintain minimum levels of in-stream water quality. Future events that result in flows below current 7Q10 values within the TCMA will have the negative effect of lowering future 7Q10 values. This, in turn, may result in more stringent WWTP effluent limitations as determined by future WLA studies. The increased cost of providing increased levels of treatment will impact all system users.

Primary consumptive uses of in-stream flow during periods when critical summer low flows are equal to or below 7Q10 flows should be evaluated for discontinuance in lieu of secondary sources of water which do not impact instream flows, or restriction, if alternative sources are unattainable, as a method of minimizing the potentially negative water quality effects that could occur with further reductions of instream flows.

The development of dependable supplemental sources of water to maintain in-stream flows at or above critical-season 7Q10 levels in all or selected TCMA streams would ensure that the effects of future extreme low flow periods in each respective stream would not further lower 7Q10 values and jeopardize in-stream water quality standards, thereby affecting wastewater assimilation, recreational uses, and maintenance of aquatic life. These sources could also ensure sufficient instream flow would be present to prevent derating of NSP power generation facilities as a result of extreme low flows in area streams. The potential for brown-outs as a result of power outages carries with it many health and safety concerns for the entire TCMA.

Emergency low flow releases from the Mississippi River headwaters reservoirs cannot be relied upon during periods of extreme low flow in the Mississippi River within the TCMA to maintain instream water quality standards. Supplemental releases from these reservoirs will not even be considered until instream flows at Anoka have dropped to 554 cfs. This flow level is roughly one-third the minimum river flow modeled to be necessary through the TCMA to adequately assimilate present wastewater treatment facility effluent flows without anticipated violations of in-stream water quality standards.

Future waste load allocation studies of the Mississippi River will determine whether the Metro treatment facility will be able to guarantee maintenance of water quality standards without significant treatment upgrades. These studies will calibrate water quality models with 1988 low flow data; utilize a revised, higher 7Q10 streamflow value; and take into account anticipated improvements in the water quality of flow in the lower Minnesota River as a result of on-going efforts to reduce nonpoint source pollution and Blue Lake and Seneca WWTP upgrades.

The MWCC evaluation study (scheduled for 1992-3) of whether to further centralize or begin decentralization of wastewater treatment in the future should model the criteria (future 7Q10 flows and ultimate WWTP capacities) that would require the upgrade of major MWCC WWTPs to be able to produce effluent that would meet instream water quality standards without the benefit of dilution. The MWCC study should also evaluate all potential options involving the beneficial reuse of WWTP effluent within the TCMA.

Based upon the considerable preliminary estimates of cost for provision of various methods and levels of phosphorus removal at the Metro WWTP, the MPCA should support their ultimate choice of plant effluent limitations through an analysis of the economic impacts of the decision upon TCMA residents. The evaluation should verify that the state's resources will be efficiently allocated in the endeavor.

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