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THE EFFECTS OF LAKE MICHIGAN DISCRETIONARY DIVERSION STRATEGIES ON ILLINOIS WATERWAY DISSOLVED OXYGEN RESOURCES

by

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CONTENTS

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ABSTRACT

The dissolved oxygen (DO) levels in the Illinois Waterway from Lockport to the Mississippi River during summer low flow conditions are greatly influenced by the quantity of water diverted from Lake Michigan into the waterway system. By U.S. Supreme Court decree, the total diversion from the lake, for all uses, is limited to 3200 cfs on an average annual basis. Of this, only 320 cfs is permitted for discretionary use in diluting wastewater discharges into the waterway system. Presently about 75 percent of this discretionary allocation is utilized during July, August, and September at a rate of 1280 cfs. Lake outlets are located at three widely separated points. A BOD-DO model study was performed to determine the optimum withdrawal rates at each point needed to provide the best overall DO balance in the channels above Lockport. The residual biochemical oxygen demand and ammonia load at Lockport were then used, in conjunction with the optimum DO, to model the DO profiles and residual ammonia and BOD_{5C} levels in the waterway below Lockport.

The optimum diversion scheme selected provided DO, BOD_{5C}, and NH3-N inputs at Lockport of 2.86, 1.77, and 1.73 mg/l, respectively. These values were not adequate to prevent DO standards from being violated. The critical reach occurred in the Peoria pool beginning 90 miles downstream of Lockport. A minimum DO of about 3.1 mg/l is predicted to occur here. Only a limited number of options are available to improve this situation, and none appears capable of bringing DO Revels up to standard during very low flow periods.

INTRODUCTION

The Illinois Waterway is special among the many streams and rivers within Illinois: it drains 43 percent of the state and small portions of Wisconsin and Indiana, as shown by figure 1. During dry weather, its headwaters consist principally of treated Chicago area wastewaters diluted with flow diverted from Lake Michigan. The waterway is no longer a free flowing stream; it consists of eight navigational pools extending over 327 miles between the Mississippi River and Lake Michigan, as shown by figure 2.

Chicago area treated wastewater flows are derived from approximately 5.4 million people and a large, mixed industrial base. The Metropolitan Sanitary District of Greater Chicago (MSD) operates treatment facilities which discharge an average of 1400 million gallons per day of secondary and

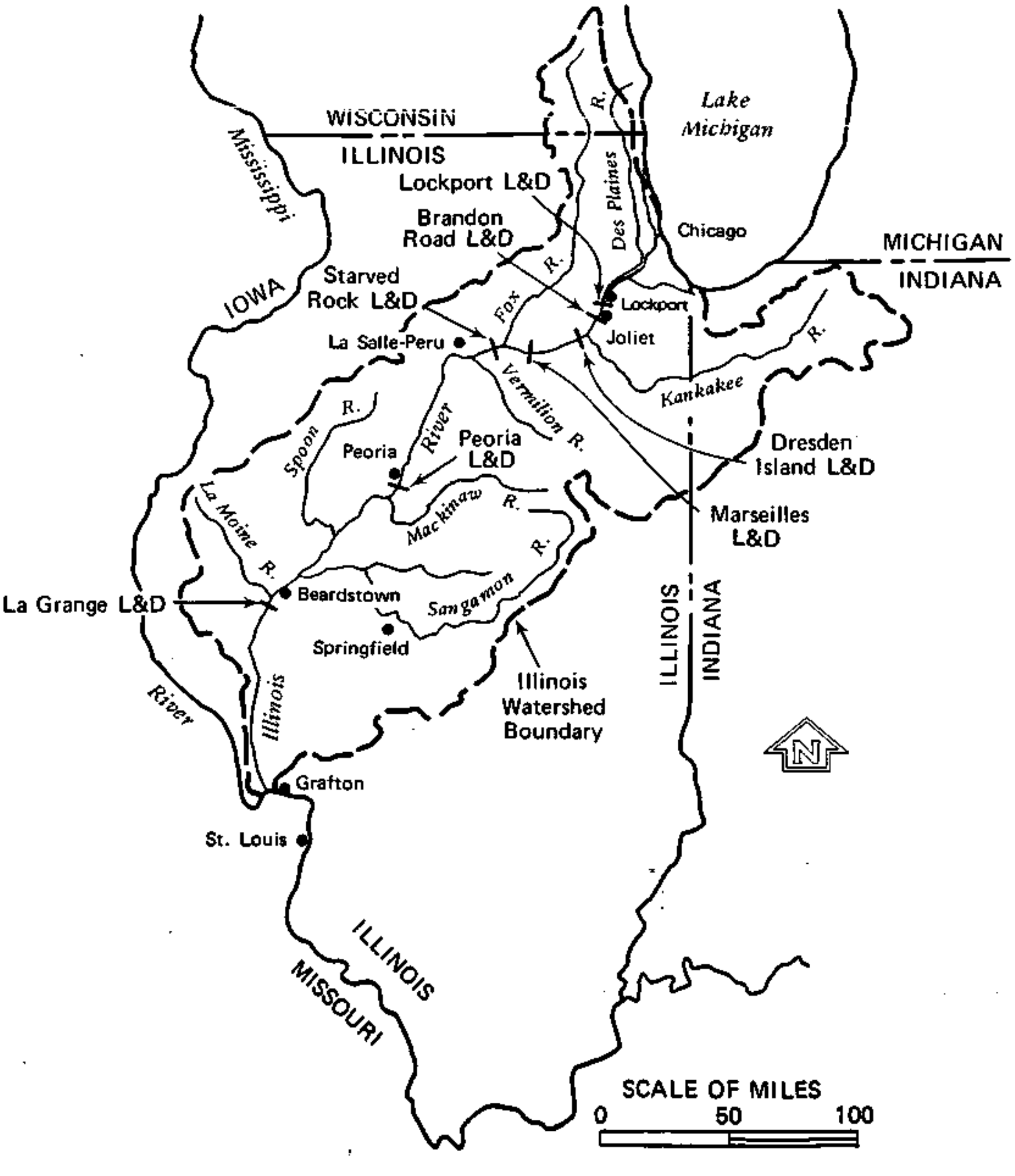

Figure 1. Illinois Waterway

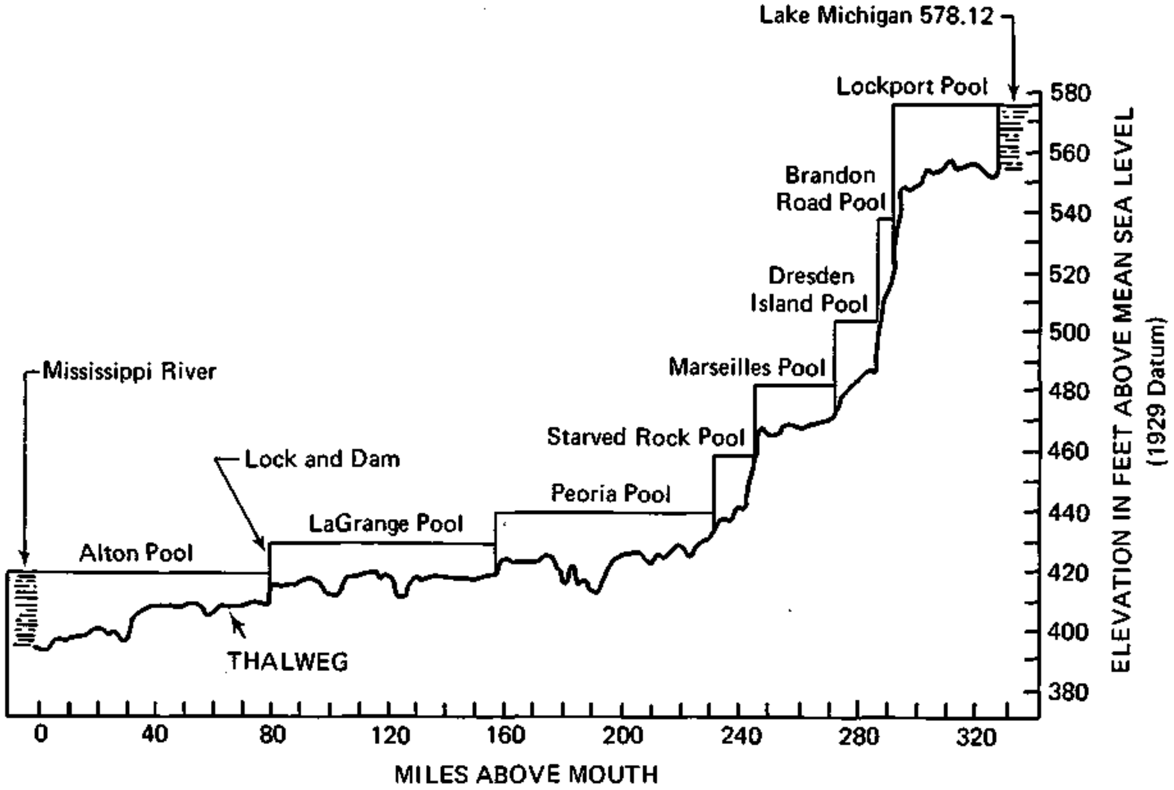

Figure 2. Illinois Waterway profile

tertiary treated sewage into 70.5 miles of constructed channels and "improved" natural water courses, as shown in figure 3 (Currie and Kendrick, 1981) .

Historical Perspective

Prior to 1900 most Chicago area wastes were discharged to Lake Michigan via either the Chicago River or the Calumet River systems, which are shown in figure 3. In 1871, a deep cut was made between the Chicago River and the Illinois and Michigan (I & M) Canal as a means of flushing a significant portion of the wastes down the canal and eventually to the Illinois River at LaSalle-Peru where the canal intersects the river. In most respects, this attempt to relieve the Chicago area of unsanitary water conditions was unsuccessful. Consequently, plans were soon formulated to dig what was to become known as the Chicago Sanitary and Ship Canal. This canal was to be bigger, deeper, and more hydraulically efficient than the old I S M canal. Although some downriver opposition to this plan was encountered, all physical and political obstacles were eventually overcome, and on January 17, 1900, popularly referred to then as "shovel day," the first Lake Michigan water was released into the high capacity canal.

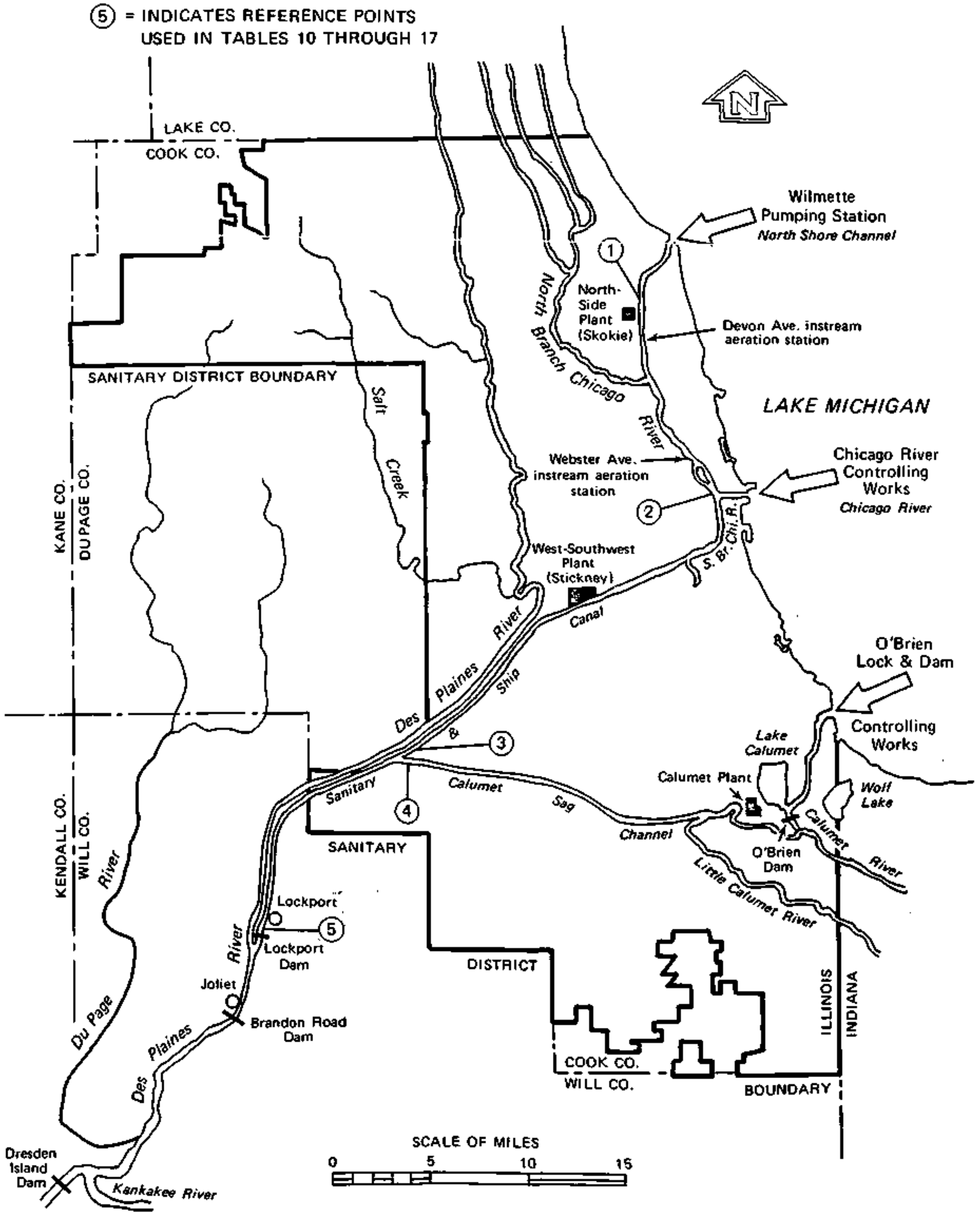

Figure 3. Chicago area drainage system

This act drew immediate opposition, and over the long term, many lawsuits materialized. The first of a long list of such lawsuits was the one filed in 1900 by the State of Missouri which claimed that typhoid bacteria from Chicago were polluting its Mississippi River water supply. The case went to the U.S. Supreme Court, where Missouri lost (Currie and Kendrick, 1981).

The Sanitary and Ship Canal is designed to handle a maximum flow of 10,000 cfs. However, in 1913 the United States filed the first of a long succession of suits designed to limit total diversion well below this. This suit requested a diversion limitation of 4167 cfs (Currie and Kendrick, 1981), and a U.S. Supreme Court decision was rendered in 1925 upholding this request. This constraint prompted the MSD to construct major treatment facilities to prevent downstream water quality deterioration.

Two other significant lawsuit decrees relative to diversion limitations (State of Illinois, 1980) are *Wisconsin v. Illinois (1930)* and *Wisconsin V. Illinois (1967)*'. As a result of the first case the Secretary of War issued a permit limiting the annual average diversion to 1500 cfs exclusive of municipal water supply needs. The second suit forms the basis for the present day diversion restrictions. It was prompted by a December 17, 1956, U.S. Supreme Court authorization to increase the diversion from 1500 cfs to a maximum of 8500 cfs through January 31, 1957, which then was extended through February 28, 1957. However, total diversion up to this maximum was allowed to occur subsequently at times until the U.S. Supreme Court ruled on June 12, 1967 that the State of Illinois cannot allocate or divert total flows greater than 3200 cfs on an average annual basis using a 5-year accounting period.

This 1967 decree was amended on December 1, 1980. Presently, the 1967 ruling and the 1980 amendments dictate present operating policy. The principal components of this policy are (Currie and Kendrick, 1981):

1) The regulation of discretionary diversion (direct wastewater dilution needs) and storm water runoff flow is the responsibility of the Illinois Department of Transportation, Division of Water Resources. Prior to 1967, the MSD was responsible for these actions.

2) A 40-year accounting period is to be used for computing the 3200 cfs average annual diversion, as opposed to the previously set 5-year period.

3) Discretionary diversion is set at a maximum of 320 cfs on an average annual basis.

4) The accounting year runs from October through September. Previously it ran from March through February. The new period coincides with the USGS standard "water year."

As an outgrowth of the 1980 amendments the Division of Water Resources issued a water allocation order (State of Illinois, 1980) directing various municipalities and subdivisions to fully utilize the flexibility of the

40-year averaging period. The order also limits the MSD to 255 cfs for navigation-related operations. Included are 130 cfs (40-year period) for lockages, 30 cfs (40-year period) for lock leakages, and 95 cfs (5-year period) for navigational makeup. The order, however, limits utilization of the 320 cfs direct diversion allocation to the time period ending October 1, 2000.

After the year 2000, the MSD Tunnel and Reservoir Project (TARP) phase I and instream aeration projects are projected to be completed, and the Division of Waterways has reduced the discretionary diversion commensurately to 101 cfs up to the year 2020.

Study Area

The water courses studied include the main diversion channels in the Chicago area (see figure 3) down to the Lockport dam, and the main stem of the Illinois Waterway from Lockport to Grafton on the Mississippi River (see figure 1). As shown in figure 3, lake diversion to the canal system is controlled at the Wilmette pumping station (WPS), the Chicago River controlling works (CRCW), and the O'Brien lock and dam and controlling works (O'Brien); releases from the system are controlled at the Lockport dam. The maximum diversion channel capacities for WPS, CRCW, and O'Brien are, respectively, 700, 500, and 3600 cfs (Macaitis and Cameron, 1977),

The WPS flow is discharged into the 7.63-mile-long North Shore Channel, which in turn discharges into a 7,85-mile-long channelized section of the North Branch of the Chicago River. The North Branch is tributary to the Chicago River at a point 1.31 miles from the lake (referenced to the CRCW). The combined WPS and CRCW diversions are routed down a channelized section of the South Branch of the Chicago River. At a point 4,83 miles downstream the Sanitary and Ship Canal branches from the South Branch and runs 30.06 miles to Lockport.

The Thomas J. O'Brien lock and controlling works is located 6,9 miles from the lake on the Calumet River. Diversion is passed through the controlling works, down a 6.7-mile reach of the Calumet River, and then into the Cal-Sag Channel which flows for approximately 16.5 miles before it empties into the Sanitary and Ship Canal. At this point all Chicago area waste and diversion flow are combined. The Sanitary and Ship Canal ends approximately one mile below the Lockport dam. Little aeration occurs at the dam because most of the flow is passed through penstocks for hydroelectric power generation (Butts and Evans, 1980).

The Sanitary and Ship Canal empties into the Des Plaines River and becomes the main stem of the Illinois Waterway for approximately 17 miles. At river mile point (MP) 272.86 it joins the Kankakee River, forming the Illinois River.

The Illinois Waterway really consists of eight navigation pools controlled by seven lock and dams on the waterway and the Alton dam on the

Mississippi (see figure 2). The gradient above the Starved Rock dam is relatively steep, and the five pools in this area are short and deep; the three pools below are long and somewhat shallower. Except for very short reaches below some of the dam flow release structures and approximately 2.5 miles of rapids below the Marseilles dam, the waterway has been completely restructured by man and no longer constitutes a free flowing stream. This has seriously reduced the organic waste assimilative capacity of the water course.

Pooling has reduced velocities and increased depths, which in turn has reduced natural reaeration, increased sediment deposition, and promoted algal production in some areas. Most of the dissolved oxygen (DO) required by saprophytic and autotrophic bacteria to stabilize oxygen-demanding wastes is now supplied almost instantly at the dam sites. The degree of reaeration achieved at each site is dependent upon the design of the flow release structure and the head loss.

The major metropolitan areas along the waterway below Chicago are the Joliet-Lockport, LaSalle-Peru, and Peoria-Pekin areas. Below Pekin (MP 150) the riverside population is small, and little industrial development exists. Above Peoria-Pekin numerous small to middle-size communities exist, and industrial development along the river is extensive. Commercial navigation along the entire waterway is extensive throughout the year.

Scope of Study

The output from this study is the result of a three-part endeavor. First a major effort was made to update the State Water Survey (SWS) computer files with the latest Corps of Engineers (COE) river sounding and cross sectional information. Along with this the SWS low flow waterway hydraulic and hydrologic computer model was revised and improved.

Next, various discretionary diversion routing schemes were examined to find the one which provided-the best overall average DO concentrations within the Chicago drainage system above the Lockport Dam. This was accomplished using the MSD water quality model and advice and information supplied by MSD personnel.

Selection of the best overall diversion scheme provided input information at Lockport for use in evaluating downstream water quality conditions. This third endeavor was accomplished using the SWS dissolved oxygen - biochemical oxygen demand (BOD) model for a limited number of critical low flow and waste load conditions. The net result of this overall effort was the development of ideas and concepts which could aid regulatory personnel in efficiently managing the water quality of the waterway during low flow conditions, consistent with the constraints imposed upon the MSD and the State in using the discretionary diversion allotment.

The report consists of four major sections. The first section presents details of the methods and procedures used and discusses the sources of input data. The second section outlines the results and presents them in generalized schematic or tabular form. The third section discusses the results and draws some conclusions, and the fourth section considers alternative management procedures and related concepts.

Acknowledgments

This study was conducted under the supervision of Ralph L. Evans, Head, Water Quality Section of the Illinois State Water Survey. Special acknowledgment is given to Robert Currie and Ken Kendrick of MSD, who provided technical advice and produced the desired computer outputs for the Chicago area drainage canals and channels. Thanks also are extended to Robert Sinclair, who gathered and organized the vast amount of cross sectional data and information for computer use; to Carl Lonnquist, who revised the hydraulic model; and to Dana Shackleford, who produced most of the SWS water quality model outputs.

Illustrations were prepared by John W. Brother, Jr., William Motherway, Jr., and Linda Riggin. Gail Taylor edited the report and Linda J. Johnson typed the original manuscript and the camera copy.

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METHODS AND PROCEDURES

All the information generated from this study was derived with existing data and tried and proven mathematical models and concepts. No field sampling was done. However, considerable effort was expended in gathering existing data from the files of IEPA, the U.S. Army Corps of Engineers, MSD, and the Illinois State Water Survey.

Hydraulic and Hydrologic Model and Data

Hydraulic and hydrologic parameters for the waterway between Lockport and Grafton were computed with the use of a flow and time-of-travel simulating program based on volume displacement, i.e., time equals the volume of water divided by the flow rate. This concept, although basically very simple, can be used to generate reliable information for steady state low flows, the condition under which most DO investigations are made. Critical to the accuracy and reliability of information generated are the quality and quantity of stream cross-sectional data available or used. This study provided the opportunity for the Water Survey to update its Illinois Waterway computer cross section file between the Peoria and Lockport dams. The computer file had already been updated with current information for the section of the waterway between Grafton and Peoria during the completion of another study (Butts et al., 1981).

The Corps of Engineers is required to maintain minimal channel depths in navigable streams such as the Illinois Waterway. As a part of the project of maintaining a navigation channel in the Illinois Waterway, the Corps has established permanent bench marks along the river which define cross sections. Soundings of the river bed are routinely made, and these data are plotted on maps at scales of 1" = 100' or 1" = 200". The most current maps (1977 through 1982) were obtained from the Corps. From these maps a data base of cross sections was generated by choosing cross sections along the river spaced at an average interval of approximately 930 feet.

Computer programs were written to utilize the Wang 720C Programmable Calculator and the Numonics Graphics Calculator in converting the graphic data to digital information. The programs were written so that the river mile location of the cross section was determined and sounding depths were measured as distances from the right bank of the river. The digital information generated was entered into permanent storage on tape.

The output from the hydraulic-hydrologic program includes cross section number, mile point, flow at the end of a reach, average flow within a reach, average cross sectional area and average depth within a reach, time of travel within a reach, accumulated time of travel, and reach lengths and volumes. Inputs required are staff gage elevations and main stem and tributary discharges.

Water Quality Modeling

The water quality modeling was done in two steps. First the Chicago area channels were analyzed through use of the MSD water quality model. The output from this model was then utilized as input to the SWS model which was used to simulate water quality conditions between Lockport and Grafton.

The MSD model is computerized, has been calibrated and verified numerous times, and was readily accessible for use at a nominal charge. Also the MSD has on file a large amount of basic input data such as stream geometry information and sediment oxygen demand measurements which are specific to this area. Similarly, a readily available data base was on file for the waterway below Lockport, which had been specifically designed for use as input to the SWS model.

The models have both been developed on the basis of first order oxygenation-deoxygenation principles. However, some inherent differences exist in the final form of the two. The MSD model is built around the basic Streeter Phelps DO sag equation, whereas the SWS model treats aeration and deaeration as separate entities according to the concepts of the Velz modification of the Black and Phelps methodology.

MSP Model Application

Model Development

The MSD model is a steady state form of the Streeter Phelps equation applicable to a continuous system. Modifications of the basic equation to account for nitrogenous BOD, sediment oxygen demand (SOD), and instream aeration have been made. Expressed in terms of the natural logarithm (base *e)* the equation takes the form:

$$D = \frac{K_c L_{ac}}{K_2 - K_c} \left(e^{-K_c t} - e^{-K_2 t}\right) + \frac{K_n L_{an}}{K_2 - K_n} \left(e^{-K_n (t - t_o)} - e^{-K_2 (t - t_o)}\right) + D_a{}^{-K_2 t} + G \qquad (1)$$

where D is the DO deficit at time t in days; K_C and K_n are respectively the carbonaceous and nitrogenous deoxygenation coefficients in days^{-1}; L_{ac} and L_{an} are, respectively, the ultimate carbonaceous and nitrogenous BOD in lbs/days; K_2 is the reaeration coefficient in days^{-1}; t_0 is the lag time to the onset of nitrification in days; D_a is the initial DO deficit; and G is the sediment oxygen demand in mg/l. Assumptions which have been made relative to usage of the model are: 1) one dimensional flow, 2) steady state conditions, 3) constant water depth, 4) instantaneous flow mixing, and 5) an algal productivity to respiration ratio of unity (The Metropolitan Sanitary District of Greater Chicago, 1976).

The reaeration calculations are made using a modification of the isotropic flow form of the O'Connor-Dobbins reaeration equation:

$$K_2 = \frac{24 (D_L V)^{0.8}}{H^{1.5}} \qquad (2)$$

where K_2 = the reaeration coefficient to the base *e* in days^{-1}

D_L = diffusivity coefficient = 8.1×10^{-5} ft /hr at 20°C

V = average velocity in ft/hr

H = average depth in ft

A value of 0.10 is the minimum value utilized; smaller values are reset to equal 0.10.

The nitrogenous BOD is assumed to follow first-order kinetics; however, a lag time of four days (to = 4) is imposed upon its inception. This essentially transfers all the ammonia load to Lockport unoxidized since travel times in the channel network are less than four days. If travel times exceeded four days, DO levels in the channel network would be very low. This would in itself suppress nitrification significantly, causing a transfer of the load, unchanged, to Lockport.

Sediment oxygen rate demand, G, in g/m^2/day is calculated using the Filos-Molof formula:

$$G = A\left[1-e^{-(1.22)(DO)}\right] \quad (3)$$

where A is a constant, the value of which depends upon the nature of the sediments; and DO is the DO concentration of the overlying water in mg/l. The expression indicates that when. DO levels fall below 2.0 mg/l, SOD rates decrease at an increasing rate; above 2.0 mg/l SOD rates are relatively independent of DO levels. SOD rates applied to this study are based upon *in situ,* measurements by MSD during 1972.

Deoxygenation temperature corrections are made using the equation:

$$K_T = K_{20}\ (1.047)^{(T-20)} \quad (4)$$

where K_T is the deoxygenation coefficient at T°C and K_{20} is the deoxygenation coefficient at 20°C.

DO saturation is computed using the ASCE formula:

$$DO_s = 14.652 - 0.41022T + 0.007991T^2 - 0.00007777T^3 \quad (5)$$

where DO_S = DO saturation at T°C.

The basic data input utilized in the model includes: 1) diversion and treatment plant flows, 2) diversion and treatment plant total BOD and ammonia loads, 3) SOD rates, 4) hydraulic geometry information including depths and cross sectional areas, 5) water temperature, and 6) instream aeration stations and efficiencies.

Model Application

The model was used to determine the optimum or best DO balance within the Chicago area drainage channel network by proportioning discretionary diversion for 100 trials at the three diversion points. The average annual allowable diversion is 320 cfs; however for this study it will be assumed that essentially all the allotted flow is used during July, August, and September, giving a three month-rate of 1280 cfs. The actual diversion figure was arrived at by allowing a 10 percent nondiversion time element due to rainfall.

Waste loads and water quality data inputs were estimated by examining the 1980 and 1981 MSD plant and lake sampling records. Values- which appeared to best represent conditions during the period of interest are given in table 1. In addition, out of the 100 runs, a number of trials were made by varying certain water quality parameters at specific locations. For instance an assumption was made that the Calumet plant was upgraded to achieve BOD_{5C} and ammonia outputs of 7 mg/ and 2 mg/l, respectively. Also, the system was examined for sensitivity to input DOs by varying the lake and plant DOs over a wide range of values. Similarly, the system was examined for sensitivity to variable lake BOD_{5c} inputs.

Table 1. Parametric Values Chosen for Input to MSD Water Quality Model for Dry Weather Conditions

Source	Flow (cfs)	DO (mg/l)	BOD_{5C} (mg/l)	NH3-N (mg/l)	Temperature (° C)
Northside plant	433.2	6.5	7.0	2.0	20.56
West-Southwest plant	1268.5	8.0	5.0	1.0	22.22
Calumet plant	340.3	6.5	14.0	13.0	21.11
Lake-Jardine plant	*	8.4	2.5	0.005	23.00
Lake-South filtration plant	*	8.4	2.5	0.005	23.00

* A total of 1280 cfs at three diversion points

Table 2. Uncontrollable Lake Diversion Flows

(Flows in cubic feet per second)

Diversion	Diversion location		
need	WPS	CRCW	O'Brien
Lockage	0	100	100
Leakage	3	11	11
Navigation makeup	£	80	80
Totals	3	191	191

Note: WPS=Wilmette pumping station; CRCW=Chicago River controlling works; O'Brien=O'Brien lock and controlling works

Besides the plant flows and discretionary diversion, certain uncontrollable flows are additive to the system (see table 2).

The two instream aeration stations, one at Devon Avenue (MP 334.8) on the North Shore Channel and the other at Webster Avenue (MP 328.8) on . the North Branch of the Chicago River (see figure 3) , were assumed operational at either 50 or 75 percent efficiency; the majority of the runs were made at 75 percent efficiency. The maximum capacities of the Devon and Webster stations are 13,300 and 8,000 lbs/day of DO, respectively. Four trials were run for placement of 1, 2, 3, and 4 aerators having DO transfer capacities of 13,300 lbs/day of DO at a point immediately below the Calumet plant.

Simulation water temperatures in the channel and river system ranged from a low of 20.56° C near the Northside plant outfall to a residual value of 26° C at Lockport. In some interior reaches temperatures as high as 28° C were reached.

SWS Model Application

Model Development

The basic model used by the SWS (State Water Survey) to evaluate BOD-DO relationships in a flowing stream is a simple one-dimensional model in which the basic components are computed separately and then algebraically combined to obtain a net DO concentration. The basic formulation is:

$$DO_n = DO_a - DO_u + DO_r + DO_x \qquad (6)$$

where DO_n is the net DO at the end of a reach; DO is the initial DO at the beginning of a reach; DOu is the DO used biologically; DO_r is the DO addition due to aeration; and DO_x is the DO addition due to dam aeration and/or tributary inputs.

Details of the methodologies that can be used to compute the various components of equation 6 have been outlined in detail in previous SWS publications and reports (Butts et al., 1970, 1974, 1975, 1981).

For this study, the DO_u term includes DO usage due to carbonaceous and nitrogenous BOD and to sediment oxygen demand. The ratio of algal productivity to respiration is assumed to be unity although the model can handle values greater or lesser than 1 when derived on a diurnal basis. Both forms of BOD are programmed to follow first order biochemical oxidation reactions as expressed by the general equation:

$$BOD_t = L_a\ (1-e^{-K_1(t-t_o)}) \qquad (7)$$

where BOD_t is the BOD exerted over a time period t in days; L_a is the ultimate BOD; K_1 is the rate coefficient; and t_o is the lag time in days to the onset of usage and in this case is equal to zero for carbonaceous demand.

The SOD portion of DO usage is computed using the expression:

$$G' = \frac{3.28Gt}{H} \qquad (8)$$

where G' is the oxygen usage per reach in mg/l; G is the SOD rate in g/m^2/day; t is the detention time per reach in days; and H is the average reach water depth in feet. Temperature corrections are applied through the use of equation 4. Unlike in the MSD model, no allowance is made for reducing the SOD rates when the overlying water DO falls below 2 mg/l. Based on several hundred *in situ* SOD measurements made by the Water Survey over the last few years the conclusion has been reached that when the SOD is due primarily to bacterial respiration the DO uptake rate remains relatively constant even at DO concentrations below 2 (Butts et al., 1974, 1981, 1982; Lee et al., 1975; Butts and Evans, 1978 and 1979; Roseboom et al., 1979; Mathis and Butts, 1981). The benthic biomass in the whole length of the waterway, except in a few short reaches, is sparse and most SOD is bacteria-related.

The aeration factor DO_r is computed using the theoretical concepts advocated by Velz (1947, 1970). Reference should be made to the Velz publications or to the 1973 report by Butts et al. for a detailed discussion of this somewhat complicated and lengthy computational procedure.

Dissolved oxygen, ammonia, and BOD inputs from tributaries are adjusted on a mass balance basis.

Aeration at the dam sites is accounted for through use of the British weir equation:

$$\frac{C_S - C_A}{C_S - C_B} = 1 + 0.38abh\,(1 - 0.11h)\,(1 + .046T) \qquad (9)$$

where C_S is the DO saturation concentration at a given temperature; C_A and C_B are, respectively, the DO concentrations above and below the dam flow release structure; a is the water quality factor; b is the weir aeration coefficient; h is the static head loss at the dam in meters; and T is the water temperature in °C. The Water Survey has studied the aeration characteristics of all the Illinois Waterway dams, and the appropriate water quality factors and weir aeration coefficients were selected from those reported by Butts and Evans (1980).

Inherent in the model design is the need to divide the water course into short well defined reaches. The oxygen credits and debits are balanced within each reach. When the net DO falls below 2.0 mg/l at the end of a reach, nitrification is not allowed to proceed until the DO level recovers and stabilizes above 2.0 mg/l.

Model Application

The SWS model was used to evaluate water quality conditions in the Illinois Waterway between Lockport and Grafton. Initial conditions were set at Lockport by the output achieved for optimum discretionary diversion using the MSD model. The residual carbonaceous BOD, ammonia, and DO loads at Lockport were routed downstream, and appropriate additional industrial, domestic, and tributary inputs were added for a number of hydraulic and hydrologic conditions. The strategy was to first evaluate the situation for downstream 7-day, 10-year low flow conditions. If standards could not be met under this restrictive low flow, additional flow regimes and/or waste reduction schemes were to be evaluated to determine what is needed to meet standards or to find out under what flow conditions the standards could be expected to be met.

The initial evaluation was based upon flow derived by adding to all waterway 7-day, 10-year low flows the excess flow generated at Lockport using the discretionary diversion allotment, the flows in tables 1 and 2, and Lockport area domestic and industrial waste inputs. The adjusted 7-day, 10-year low flow at Lockport is 2320 cfs. The flow routed through the Chicago channel and river system to Lockport is 4126.5 cfs; the input at Lockport is 12.5 cfs. This totals 4139 cfs, or 1819 cfs in excess of the 7-day, 10-year figure.

Adding 1819 cfs to the 7-day, 10-year low flows at downstream gaging stations results in the first trial "design" values given in table 3. The 9/27/71 and 9/3/71 design figures were used for evaluating conditions for incremental flow increases above the 7-day, 10-year base. These two dates

Table 3. Low Flow Characteristics of the Illinois Waterway for Three Design Flows

Gaging station	Corps MP	7-day, 10-year low flow (cfs)	Design flows (cfs)		
			1st trial	9/27/71	9/3/71
Lockport	291.04	2320	4139	4139	4139
Marseilles	246.60	3240	5059	6860	7810
Henry	196.12	3424	5243	6828	8146
Kingston Mines	145.41	3000	4819	6880	9000
Meredosia	70.81	3500	5319	7100	9850
Grafton	0	3600	5419	6515	10,201

were chosen because the flows at all the locations had been relatively stable for several weeks, and DO profiles from Lockport to Chillicothe are available for these dates (Butts et al., 1975) for comparative purposes.

Point source waste load information was obtained principally from IEPA files in Maywood, Peoria, and Springfield. A minor amount of dated supplemental information was available in Water Survey files and was used when necessary to fill in the gaps of the more current information supplied by IEPA. All tributary stream load estimates were made using recent SWS sampling results. The Mackinaw, Spoon, Sangamon, and LaMoine Rivers were sampled and analyzed for long term BOD values, ammonia, and DO levels during the summer of 1979; similarly the Des Plaines, DuPage, Kankakee, and Vermilion Rivers were sampled during 1982. Inputs from the lesser tributaries were estimated with the nearest measured tributary as a guide. Table 4 summarizes the tributary input data used for the runs made under the three flow conditions.

The file data carbonaceous BOD is in terms of 5 days at 20°C (BOD_{5C}). All this information had to be converted to ultimate demands compatible with river deoxygenation reaction rates. Both carbonaceous and nitrogenous reaction rates were varied throughout the waterway in accordance with long-term BOD information contained in studies by Butts et al. (1975, 1981).

Table 4. Tributary Input Data Used in Simulations

Tributary	Corps MP	BOD_{5C} conc. (mg/l)		Flows (cfs)		
		Carb.	Nit.	7-day, 10-yr.	9/27/71	9/3/71
Des Plaines R.	290.00	3.28	1.74	29	126	66
DuPage R.	276.82	3.29	2.09	46	62	44
Kankakee R.	272.86	1.67	0.86	635	1980	710
Mazon R.	263.54	2.35	1.00	0	15	4
Fox R.	239.77	3.64	1.56	208	342	427
Vermilion R.	226.34	2.32	1.07	8	19	10
I & M Canal	210.80	1.50	1.00	25	2	4
Bureau Cr.	209.03	1.50	1.00	18	2	4
Farm Cr.	163.00	2.00	0.20	0	4	3
Kickapoo Cr.	159.66	2.00	0.20	1	26	8
Mackinaw R.	147.73	3.79	0.94	47	55	18
Spoon R.	120.50	2.90	0.80	25	78	36
Sangamon R.	88.90	2.75	0.83	287	722	405
LaMoine R.	83.74	2.75	1.11	12	26	27
Macoupin Cr.	23.26	2.75	1.11	3	21	11

The river reaction rates selected for use within defined reaches of the waterway are presented in table 5.

Equation 7 was used to convert the carbonaceous BOD_{5C} values to ultimates. For example, with t = 5 days, $t_0 = 0$, BOD_{5C} = a specified value, and $K_{1c} = 0.0677$ day^{-1}, the ultimate BOD (L_{ac}) inputs down to mile 165.30 would equal $BOD_{5c}/0.287$. At mile 165.30, a BOD_{5c} would be calculated on the basis of the residual ultimate having a $K_{1C} = 0.0677$ day^{-1}. A new ultimate would then be computed on the basis of $K_{1C} = 0.123$ day^{-1}.

All ammonia-N point discharges, except for the tributaries, were converted to ultimates by multiplying the load by 4.57; 4.57 mg/l of oxygen is stoicheiometrically required to completely oxidize 1.0 mg/l of NH_3-N. The nitrogenous ultimate is theoretically independent of the rate, negating a need for downstream adjustments. The mile point locations of the values given in table 5 shift slightly upstream or downstream for low flows smaller or greater than the 7-day, 10-year value since the point of change is dependent on time and not on location. For nitrogenous BOD usage, t_0 in equation 7 was set at approximately 3.0 days on the basis of the findings of Butts et al. (1975).

The sediment oxygen demand rate inputs were derived from *in situ* measurements taken by the Water Survey along almost the whole length of the waterway from Lockport to Grafton during the last ten years. Values between Chillicothe and Lockport were estimated from those reported by Butts (1974), while those for the LaGrange pool are from Butts et al. (1981). Measurements have been made in the Peoria area of the Peoria pool and a limited number have been made in the lower Alton pool but have yet to be reported; these results are summarized in table 6. Table 7 lists the actual SOD rates applied to various subreaches in each pool for the simulations made during this study.

When a dam is encountered, the last DO calculated above the dam is set equal to C_A in equation 9, and the program proceeds to calculate the downstream DO (C_B) using specified values of a, b, h, and T. Table 8 lists the values of these parameters utilized for study simulations. The aeration coefficient was set equal to 0 for both the Lockport and Marseilles dams. All low flow is routed through the power plant penstocks at the Lockport site, while all flow below 8500 cfs is diverted through the Illinois Power Company hydroelectric plant at Marseilles (Butts et al., 1975). Very little reaeration is produced in flows routed through power plants.

Table 5. BOD Reaction Rates Applied to
Specified Reaches of Waterway for 7-day, 10-year Low Flow

	BOD reaction rates (day)	
Inclusive Corps MP	Carbonaceous (K_{1C})	Nitrogenous (K_{1C})
291.02 - 254.35	0.0677	0
254.35 - 165.30	0.0677	0.1195
165.30 - 80.19	0.1230	0.0920
80.19 - 0	0.1150	0.0550

Table 6. 1982 Peoria Pool and 1980 Alton Pool *In Situ* SOD Results

Pool	Corps MP	SOD (g/m^2/d at 20° C)
Peoria	165.84R	1.41
	165.25R	1.56
	164.40R	2.27
	163.62R	2.10
	162.90R	1.71
	162.77R	0.54
	162.77L	1.25
	162.68R	2.01
	162.21R	0.84
	161.51R	0.69
	161.51L	0.82
	160.97R	0.91
	160.97L	1.00
	160.12R	1.30
	160.12L	0.87
	158.57R	0.56
	158.57L	1.09
Alton	36.50R	0.55
	29.30R	0.58
	18.90R	0.29
	8.30R	1.46

Note: R and L = right and left banks, respectively, looking downstream

Table 7. SOD Rates Utilized for Subreaches throughout Waterway below Lockport

Pool	Corps MP	SOD g/m^2/d	Pool	Corps MP	SOD g/m^2/d
Brandon Road	291.02		Peoria	231.02	
	290.00	1.0		229.60	0.5
	286.17	3.5		226.34	2.0
Dresden Island	285.81	0.5		188.64	1.5
	285.40	2.0		183.00	2.5
	283.74	3.5		170.90	1.5
	280.38	3.0	LaGrange	157.70	1.0
	278.19	2.5		155.00	0.6
	277.71	3.0		153.00	0.5
	273.50	3.5		83.74	0.6
	272.86	2.0	Alton	80.19	0.5
Marseilles	271.46	3.0		55.00	0.5
	270.21	0.5		30.00	0.6
Starved Rock	246.98	1.5		23.26	0.5
	244.05	0.5		20.00	0.3
	234.50	1.5		15.00	0.5
	231.02	1.0		10.00	0.7
				0.00	1.0

Table 8. Data Input Used to Compute Dam Aeration for Simulated Conditions

Dam	Water temperature, T (C)	Water quality factor, a	Dam aeration coefficient, b	Head loss, h(ft) 7-d, 10-yr	9/27/71	9/3/71
Lockport*	26	1.28	0*	38.3	36.0	35.0
Brandon Road	26	1.29	25	34.0	33.5	33.5
Dresden Island	26	0.95	2	21.8	20.3	19.8
Marseilles	26	1.14	0*	14.3	9.7	9.7
Starved Rock	27	1.09	0.8	18.2	17.4	16.9
Peoria	28	1.19	1.0	10.0	9.3	6.4
LaGrange	28	1.32	0.6	9.8	7.5	6.4

* No low flow aeration

Note: b = 1.0 for flows in excess of 8500 cfs

The use of equation 9 is limited to uses where the head loss is 9.0 meters or less; consequently, for the Lockport and Brandon Road dams the h-factor is artificially set equal to 9 meters (29.52 ft.) and aeration is calculated on this basis. Note from table 8 that water temperatures are varied slightly, increasing in a downstream direction.

RESULTS

The results will be presented in three parts. First, pertinent general information will be given that has been derived from the updating of the Illinois Waterway cross-sectional data file and the subsequent revision of the Water Quality Section's low flow time-of-travel computer program. Next the output from the use of the MSD water quality model for various discretionary diversion schemes will be presented, and finally the effects of the optimum diversionary scheme on downstream water quality will be shown.

Hydraulic and Hydrologic Information

More than 1650 cross sections between Lockport and Grafton have been cataloged into the SWS data file. One of the results of the effort was to better define the longitudinal length of the waterway. The U.S. Army Corps-of Engineers mileage does not represent the true distance the main stream of water has to travel within selected reaches of the waterway. This is an important element to consider when evaluating time-dependent water quality parameters such as ammonia, BOD, SOD, and DO.

The river miles, as measured by the Water Survey, are presented and compared to the Corps designations in Appendix A. Differences occur for a number of reasons. Besides differences attributable to accuracy errors, which obviously can be a factor, the Corps distances deviate from those measured by the Water Survey for two major reasons: 1) the Corps retains original mileage designations even when channel shortening and straightening has occurred, and 2) the Corps measures mileage along direct navigation approaches to the locks whereas the actual water flow is usually over a more circuitous route via spillway and riffle areas. The effect of the former practice is to exaggerate the length, whereas the effect of the latter is to reduce it. The two, however, appear to balance each other in the end as can be noted from the upstream net results at Lockport (Corps MP 291.0) in Appendix A; only 0.04 of a mile separates the Corps designation from that actually measured by the Water Survey.

Nevertheless, differences do become obvious in specific pools or reaches. For example, because of channel shortening in the Starved Rock pool (Corps MP 230.0 to 247.0) the official designated distance is approximately 17 miles while the actual distance is 16.77 miles, almost a quarter of a mile shorter. Subsequent results will be referenced to Corps mileage for convenience, but all computations will have been done using Water Survey lengths.

A copy of a computer printout showing the input data and the subsequent output for the 7-day,10-year low flow simulation is presented in Appendix B. Included in the output is the Water Survey mile point, flow at the end of a reach (F), average flow within a reach (AVF), average reach cross-sectional area (AVA), average reach width (AVW), average reach depth (AVD), reach time of travel (DT), accumulated time of travel (SUMT), reach distance (DIS), and reach volume (VOL).

The basic hydraulic and hydrologic information for the simulation runs made under the three flow conditions are summarized by pools in table 9. Of particular note are the extremely long travel times involved during low flows. By definition 7-day, 10-year low flows can persist only during 7 continuous days and not the 20 to 30 days required to traverse the entire water course during low flow periods.

MSP Water Quality Model

The results of the hundred discretionary diversion trial runs are summarized in tables 10 through 17. The waste load inputs and water quality data selected as representative for July, August, and September low flow conditions are presented as sub-tables or lists at the beginning of each of these tables; Figure 3 should be referred to for the locations of the predicted DO values presented in the tables.

Table 10 presents the results for the most basic trial conditions. Existing waste and water quality conditions are used as inputs (as listed in the sub-table), and waterway conditions are examined at instream aeration efficiencies of 50 and 75 percent. From these results, the overall best diversionary scheme was selected. No clear-cut choice was evident, but run number 10 appears to give the best overall system DO balance.

Almost all runs produced DO levels at Lockport within small deviations of each other. For the 44 runs listed, the mean DO was 2.91 mg/l and the standard deviation was 0.09 mg/l. The mean Lockport DO at 50 percent aeration efficiency was 2.88 mg/l but the average was increased only slightly to 2.93 mg/l by increasing the efficiency to 75 percent.

Table 9. Hydraulic and Hydrologic Data Summaries by Pool

Pool	Inclusive MP Corps	SWS	SWS length (mi)	Average flow (cfs) 7d, 10y	9/27/71	9/3/71	Average depth (ft) 7d, 10y	9/27/71	9/3/71
	291.04	291.00							
Brandon Rd.	286.17	286.25	4.75	4,173	4,266	4,346	13.5	14.0	14.0
Dresden Is.	271.46	272.52	14.73	4,302	4,620	5,064	9.9	10.2	10.2
Marseilles	246.98	246.78	24.74	4,999	6,701	6,995	9.4	10.2	10.4
Starved Rock	231.02	231.02	15.76	5,155	6,777	8,015	8.6	9.0	9.0
Peoria	157.70	158.06	72.96	5,148	6,884	8,327	'9.4	9.6	9.7
LaGrange	80.19	80.01	78.05	4,742	6.774	9,190	9.4	9.4	10.2
Alton	0.00	0.00	80.01	5,362	6,841	10,001	9.3	9.0	9.4

Pool	Average velocity (fos) 7d, lOy	9/27/71	9/3/71	Accumulated travel time (days) 7d, lOy	9/27/71	9/3/71
				0	0	0
Brandon Rd.	0.71	0.69	0.71	0.411	0.419	0.409
Dresden Is.	0.59	0.58	0.64	1.946	2.024	1.885
Marseilles	0.82	0.95	0.97	3.783	3.557	3.375
Starved Rock	0.82	1.02	1.17	4.953	4.501	4.195
Peoria	0.41	0.51	0.60	15.955	13.276	11.606
LaGrange	0.81	1.10	1.19	21.860	17.606	15.603
Alton	0.62	0.71	0.73	29.733	24.523	22.272

Internally, however, significant differences were evident. For example, increasing the diversion down Cal-Sag Channel at the expense of the other two diversion points appeared to increase the Cal-Sag Channel DO without significantly affecting the DO in other critical locations, including Lockport. Comparing run 16 with run 66 illustrates this point. Increasing the Cal-Sag diversion by 236 cfs in run 66 over the amount in run 16 increases the minimum DO in the Cal-Sag by 0.5 mg/l, whereas at other points in the system, a decrease of only about half of this value is experienced. On the basis of an overall rational assessment of the results presented in table 10, run number 10 was selected to represent starting conditions for evaluating water conditions downstream of Lockport.

Tables 11 through 17 represent special or modified conditions. Table 11 contains information for many of the same diversion schemes as presented in table 10; however, the Calumet sewage treatment plant treatment efficiencies have been arbitrarily set equal to those of the Northside plant (see sub-table information). Tables 12 through 16 all have as a common denominator the diversions used for run 10, the optimum run under existing conditions. The variables in each case are: table 12 - Lake Michigan (Wilmette pumping station, Chicago River controlling works, O'Brien lock and controlling works) BOD_{5c}; table 13 - Lake Michigan DOs; table 14 - Calumet plant DOs; table 15 - West-Southwest plant DOs; and table 16 - Northside plant DOs. Table 17 lists conditions resulting from the hypothetical installation of instream aeration in the Cal-Sag Channel below the Calumet treatment plant.

Selection of run 10 established the following baseline information at Lockport:

Flow: 4126.49 cfs BOD_{5C} = 1.766 mg/l

Temperature: 26.0°C NH -N = 1.727 mg/l

DO = 2.863 mg/l

Table 10. Minimum DO Concentrations within Selected Channel Reaches for Various Discretionary Diversion Flow Combinations and Specific Waste Inputs of:

	NS	WSW	Cal.	L.M.
BOD_{5C} (mg/l)	7	5	14	2.5
NH_3-N (mg/l)	2	1	13	.005
DO (mg/l)"	6.5	8.0	6.5	8.4
Discharge (cfs)	433.2	1268.5	340.3	*

Instream Aeration Efficiency = 50%

Run	Discretionary diversion (cfs)			Minimum predicted DO (mg/l) at points referenced in fig. 3				
no.	WPS	CRCW	O'Brien	1	2	3	4	5
1	128	640	512	2.15	2.48	4.29	0.79	2.89
2	128	704	448	2.15	2.48	4.35	0.68	2.95
3	128	768	384	2.15	2.48	4.41	0.58	3.00
4	192	576	512	3.83	2.89	4.27	0.79	2.88
5	192	640	448	3.83	2.89	4.33	0.68	2.93
6	192	704	384	3.83	2.89	4.38	0.58	2.98
7	256	512	512	4.81	3.28	4.25	0.79	2.87
8	256	576	448	4.81	3.28	4.31	0.68	2.92
9	256	640	384	4.81	3.28	4.36	0.58	2.97
50	200	448	632	3.98	2.94	4.15	1.03	2.81
51	180	448	652	3.59	2.82	4.14	1.07	2.80
52	160	448	672	3.11	2.69	4.12	1.12	2.80
53	240	300	740	4.61	3.19	4.04	1.26	2.76
54	240	350	690	4.61	3.19	4.09	1.15	2.78.
55	240	400	640	4.61	3.19	4.13	1.05	2.80

Instream Aeration Efficiency = 75%

Run no.	WPS	CRCW	O'Brien	1	2	3	4	5
10	200	448	632	3.98	3.91	4.26	1.03	2.86
11	200	512	568	3.98	3.91	4.32	0.90	2.90
12	200	576	504	3.98	3.91	4.38	0.78	2.94
13	200	640	440	3.98	3.91	4.44	0.67	2.99
14	200	704	376	3.98	3.91	4.50	0.57	3.05
15	160	448	672	3.11	3.69	4.23	1.12	2.85
16	160	576	544	3.11	3.69	4.35	0.85	2.92
17	160	704	416	3.11	3.69	4.47	0.63	3.02
18	180	448	652	3.58	3.80	4.24	1.07	2.85
19	180	576	524	3.58	3.80	4.37	0.82	2.93
20	180	704	396	3.58	3.80	4.48	0.60	3.03
32	215	660	405	4.24	4.00	4.47	0.61	3.02
33	215	690	375	4.24	4.00	4.49	0.57	3.05
34	215	630	435	4.24	4.00	4.44	0.66	3.00
35	205	660	415	4.07	3.94	4.46	0.63	3.01
36	205	690	385	4.07	3.94	4.49	0.58	3.04
37	205	630	445	4.07	3.94	4.43	0.67	2.99
38	225	660	395	4.40	4.05	4.47	0.60	3.03
39	225	690	365	4.40	4.05	4.50	0.56	3.06
40	225	630	425	4.40	4.05	4.45	0.64	3.00
59	200	300	780	3.98	3.91	4.11	1.35	2.80
60	200	350	730	3.98	3.91	4.16	1.24	2.82
61	200	400	680	3.98	3.91	4.21	1.13	2.84
62	240	300	740	4.61	4.13	4.14	1.26	2.81
63	240	350	690	4.61	4.13	4.20	1.15	2.83
64	240	400	640	4.61	4.13	4.25	1.05	2.85
65	150	300	830	2.84	3.63	4.05	1.46	2.78
66	150	350	780	2.84	3.63	4.11	1.35	2.80
67	150	400	730	2.84	3.63	4.16	1.24	2.82

Note: In this and subsequent tables, NS = Northside plant; WSW = West-Southwest plant; Cal. = Calumet plant; L.M. = Lake Michigan; WPS = Wilmette pumping station; CRCW = Chicago River controlling works; O'Brien = O'Brien lock and controlling works

Table 11. Minimum DO Concentrations within Selected Channel Reaches for Various Discretionary Diversion Flow Combinations and Specific Waste Inputs of:

	NS	WSW	Cal.	L.M.
BOD_{5C} (mg/l)	7	5	7	2.5
NH_3-N (mg/l)	2	1	2	.005
DO (mg/l)	6.5	8.0	6.5	8.4
Discharge (cfs)	433.2	1268.5	340.3	*

Instream Aeration Efficiency = 50%

Run	*Discretionary diversion (cfs)			Minimum predicted DO (mg/l) at points referenced in fig. 3				
no.	WPS	CRCW	O'Brien	1	2	3	4	5
56	205	295	780	4.07	2.97	4.00	2.10	3.09
57	215	285	780	4.24	3.04	4.00	2.10	3.09
58	225	275	780	4.40	3.10	4.00	2.10	3.09
Instream Aeration Efficiency = 75%								
21	200	448	632	3.98	3.91	3.19	1.84	3.19
22	200	512	568	3.98	3.91	3.22	1.74	3.22
23	200	576	504	3.98	3.91	3.25	1.63	3.25
24	200	640	440	3.98	3.91	3.29	1.52	3.29
25	200	704	376	3.98	3.91	3.33	1.42	3.33
26	160	448	672	3.11	3.69	3.18	1.91	3.18
27	160	576	544	3.11	3.69	3.24	1.69	3.24
28	160	704	416	3.11	3.69	3.31	1.48	3.31
29	180	448	652	3.58	3.80	3.19	1.88	3.19
30	180	576	524	3.58	3.80	3.25	1.66	3.25
31	180	704	396	3.58	3.80	3.32	1.45	3.32
41	215	325	740	4.24	4.00	4.15	2.03	3.15
42	215	365	700	4.24	4.00	4.19	1.96	3.17
43	215	285	780	4.24	4.00	4.11	2.10	3.14
44	205	335	740	4.07	3.94	4.15	2.03	3.15
45	205	375	700	4.07	3.94	4.19	1.96	3.17
46	205	295	780	4.07	3.94	4.11	2.10	3.14
47	225	315	740	4.40	4.05	4.15	2.03	3.15
48	225	355	700	4.40	4.05	4.19	1.96	3.16
49	225	275	780	4.40	4.05	4.10	2.10	3.14
68	150	300	830	2.84	2.19	4.05	2.19	3.12
69	150	350	780	2.84	2.10	4.11	2.10	3.14
70	150	400	730	2.74	2.01	4.16	2.01	3.16

Table 12. Minimum DO Concentrations within Selected Channel Reaches for Variable Lake Michigan BOD_{5C} Concentrations for Conditions of:

	NS	WSW	Cal.	WPS	CRCW	O'Brien
BOD_{5C} (mg/l)	7	5	14	*	*	*
NH_3-N (mg/l)	2	1	13	.005	.005	.005
DO (mg/l)	6.5	8.0	6.5	8.4	8.4	8.4
Discharge (cfs)	433.2	1268.5	340.3	200	448	632

Instream Aeration Efficiency = 75%

Run	*L.M.	Minimum predicted DO (mg/l) at points referenced in fig. 3				
no.	BOD_{5C}	1	2	3	4	5
71	1	4.55	4.18	4.55	1.38	3.16
72 .	2	4.17	4.00	4.36	1.14	2.96
73	3	3.79	3.83	4.17	0.92	2.77
74	4	3.41	3.65	3.97	0.73	2.58
75	5	3.03	3.48	3.78	0.56	2.41
76	6	2.65	3.31	3.59	0.42	2.25

Table 13. Minimum DO Concentrations within Selected Channel Reaches for Variable Lake Michigan DO Concentrations for Conditions of:

	NS	WSW	Cal.	WPS	CRCW	O'Brien
BOD_{5C}(mg/l)	7	5	14	2.5	2.5	2.5
NH_3-N (mg/l)	2	1	13	.005	.005	.005
DO (mg/l)	6.5	8.0	6.5	*	*	*
Discharge (cfs)	433.2	1268.5	340.3	200	448	632

Instream Aeration Efficiency = 75%

Run no.	*L.M. DO	Minimum predicted DO (mg/l) at points referenced in fig. 3 1	2	3	4	5
77	5	1.62	3.51	3.90	0.77	2.61
78	6	2.27	3.62	4.00	0.84	2.68
79	7	2.97	3.74	4.11	0.92	2.76
80	8	3.69	3.86	4.22	1.00	2.83
81	9	4.42	3.99	4.32	1.08	2.91
82	10	5.16	4.11	4.43	1.18	2.99

Table 14. Minimum DO Concentrations within Selected Channel Reaches for Variable Calumet Plant Effluent DO Concentrations for Conditions of:

	NS	WSW	Cal.	WPS	CRCW	O'Brien
BOD_{5C}(mg/l)	7	5	14	2.5	2.5	2.5
NH_3-N (mg7l)	2	1	13	.005	.005	.005
DO (mg/l)	6.5	8.0	*	8.4	8.4	8.4
Discharge (cfs)	433.2	1268.5	340.3	200	448	632

Instream Aeration Efficiency = 75%

Run no.	*Cal. DC)	Minimum predicted DO (mg/l) at points referenced in fig. 3 1	2	3	4	5
83	3	3.98	3.91	4.26	0.75	2.78
84	4	3.98	3.91	4.26	0.82	2.80
85	5	3.98	3.91	4.26	0.90	2.82
86	6	3.98	3.91	4.26	0.99	2.85
87	7	3.98	3.91	4.26	1.08	2.88

Table 15. Minimum DO Concentrations within Selected Channel Reaches for Variable West-Southwest Plant Effluent DO Concentrations for Conditions of:

	NS	WSW	Cal.	WPS	CRCW	O'Brien
BOD_{5C} (mg/l)	7	5	14	2.5	2.5	2.5
NH_3-N (mg/l)	2	1	13	.005	.005	.005
DO (mg/l)	6.5	*	6.5	8.4	8.4	8.4
Discharge (cfs)	433.2	1268.5	340.3	200	448	632

Instream Aeration Efficiency = 75%

Run no.	*WSW DO	Minimum predicted DO (mg/l) at points referenced in fig. 3 1	2	3	4	5
88	4	3.98	3.91	2.85	1.03	2.16
89	5	3.98	3.91	3.20	1.03	2.33
90	6	3.98	3.91	3.55	1.03	2.51
91	7	3.98	3.91	3.91	1.03	2.69

Table 16. Minimum DO Concentrations within Selected Channel Reaches for Variable Northside Plant Effluent DO Concentrations for Conditions of:

	NS	WSW	Cal.	WPS	CRCW	O'Brien
BOD_{5C} (mg/l)	7	5	14	2.5	2.5	2.5
NH_3-N (mg/l)	2	1	13	.005	.005	.005
DO (mg/l)	*	8.0	6.5	8.4	8.4	8.4
Discharge (cfs)	433.2	1268.5	340.3	200	448	632

Instream Aeration Efficiency = 75%

Run no.	*NS DO	Minimum predicted DO (mg/l) at points referenced in fig. 3 _1	_2	_3	_4	_5
92	3	3.98	2.66	4.12	1.03	2.79
93	4	3.98	3.01	4.16	1.03	2.81
94	5	3.98	3.36	4.20	1.03	2.83
95	6	3.98	3.72	4.24	1.03	2.85
96	7	3.98	4.10	4.28	1.03	2.87

Table 17. Minimum DO Concentrations within Selected Channel Reaches for Variable Instream Aeration Capacity below Calumet Plant Discharge (MSD River Mile 51) for Conditions of:

	NS	WSW	Cal.	WPS	CRCW	O'Brien
BOD_{5C} (mg/l)	7	5	7	2.5	2.5	2.5
NH_3-N (mg/l)	2		12	.005	.005	.005
DO (mg/l)	6.5	8.0	6.5	8.4	8.4	8.4
Discharge (cfs)	433.2	1268.5	340.3	215	235	830

Instream Aeration Efficiency = 75%

Run no.	Aerator capacity at MSD Mile 51 (lbs/dav O_2)	Minimum predicted DO (mg/l) at points referenced in fig. 3 _1	_2	_3	_4	_5
97	13,300	4.24	4.00	4.05	2.83	3.34
98	26,600	4.24	4.00	4.05	3.49	3.57
99	39,900	4.24	4.00	4.05	4.15	3.80
100	53,200	4.24	4.00	4.05	4.83	4.03

SWS Water Quality Model

The baseline waste load data established at Lockport were used in conjunction with point load discharges along the waterway to develop low flow DO profiles. The waste source inventory is summarized in table 18 for three periods: the 12 months of 1971, the 12 months of 1980, and 3 months (July, August, and September) of 1980. Listed for historical and comparative purposes are some industrial sources which were in existence in 1971 but which

Table 18. Waste Discharge Loads Discharged Directly to the Illinois Waterway

		Average flow (mgd)			Average waste loads (lbs/day)					
					BOD$_{5c}$ at 20°C			NH$_3$-N		
	Corps	12 month		3 mo.	12 month		3 mo.	12 month		3 mo.
Load Source	MP	1971	1980	1980	1971	1980	1980	1971	1980	1980
Sanitary Shin Canal	291.04	2670.87	2670.87	2670.87	72,817	61,095	38,711	101,461	51,436	38,488
Lockoort	290.76	2.00	2.68	3.17	134	205	264	117	87	103
Locknort Heights	290.76		0.15	0.10		44	15		19	13
Texaco	290.76	5.89	4.53	4.56	196	183	177	295	159	156
GAF Corp.	290.00	2.20	0.34	0.34	846	28	26	129	20	20
U.S. Steel	288.90	23.00	0.40	0.43	1,743	0	0	316	0	0
Joliet West	286.17		3.49	3.27		170	200		17	16
Joliet East	286.17	21.20	17.63	18.00	4,952	2,717	2,898	2,158	2,039	2,134
Com. Ed. Joliet	284.37		0.04	0.02		8	3		10	5.
Olin Blockson	284.37	3.00	0.05	0.05	856	.3	3	107	0	0
Caterpillar	283.74	0.77	0.87	0.90	157	46	46	8	0	0
Amoco Chemical	280.38	0.82	0.77	0.80	121	39	31	123	7	7
SteDan Chemical	280.05	0.84	0.73	0.80	10	91	56	18	0	0
Mobil Refinery	278.19	2.40	2.92	3.23	846	377	565	1,895	410	475
Joliet Ammo Plant	277.71		0.91	0.42		30	12		0	0
Mobil Chemical	277.71	0.13	0.15	0.14	7	13	8	120	0	0
Glidden-Durkee	276.41	0.22	0.27	0.34	1057	6	13	9	5	6
Com. Ed. Dresden	272.14		7.58	6.07		865	380		0	6
N. Illinois Gas	270.57		0.38	0.31		24	26		0	0
Reichhold Chemical	270.21	0.10	0.10	0.15	121	3	3	6	0	0
N. Petrochemical	269.86	1.01	1.92	1.63	205	74	77	39	6	0
Com. Ed. Collins	690.00		0.03	0.01		2	<1		0	0
Federal Paper Co.	264.30	2.70	0	0	1,031	0	0	3	0	0
Morris	262.79	0.76	1.33	1.40	106	134	175	17	59	52
DuPont Corp.	254.35	1.63	1.02	0.78	61	97	87	152	103	67
Seneca	252.44		0.30	0.30		138	130		38	38
National Phosphate	249.80	1.67	0	0	138	0	0	63	0	0
Illinois Nitrogen	248.71	16.30	13.30	9.70	2,174	0	0	3,478	611	415
Nabisco	246.66	0.36	0	0	880	0	0	0	0	0
Marseilles	246.10	1.10	0.98	1.00	626	58	50	136	9	9
Borg Warner	244.05	0.56	0.71	0.67	69	56	56	277	150	29
Ottawa	239.17	2.98	2.45	2.53	439	116	99	15	21	21
LOF Corp.	237.50	3.73	2.03	1.70	134	93	71	0	0	0
Utica	229.57	0.15			29			6		
Com. Ed. LaSalle			0.05	0.05		7	6		0	0
Illinois Cement	223.00		<0.01	<0.01		<1	<1		<1	0
LaSalle	223.00	1.20	1.33	1.23	463	138	31	103	11	10
Carus Chemical	223.00		1.13	1.27		0	0		18	. 11
Peru	222.00	1.84	3.06	2.73	106	128	76	16	26	23
Spring Valley	218.00	0.88	0.90	0.83	121	62	42	22	34	31
DePue	210.80	0.20	0.42	0.37	19	77	41	7	7	6
J & L Steel	208.20	3.60	2.56		412		0			
B. F. Goodrich	198.02	1.00	0.76	0.67	151	76	57	192	127	112
Sparland	190.00		0.03	0.03		1	<1		1	<1
Lacon	188.64	0.28	0.22	0.20	90	36	25	14	8	7
Chillicothe	179.10	0.46	0.51	0.50	92	66	57	21	77	75
Cat Mossville	174.40		1.03	0.91		171	111		9	8
E. Peoria #3	165.30		0.95	0.90		93	105		34	32
E. Peoria #1	160.72	2.96	1.85	1.80	622	147	135	44	25	24
Cat. E. Peoria	160.68	6.98	7.50	8.00	1,976	839	533	41	63	67
Peoria S.D.	160.05	36.89	24.05	24.13	7,925	1,387	1,071	1,321	665	537
Creve Coeur	158.16	0.48	0.79	0.73	1,456	399	336	73	110	102
Marquette Hts.	157.53	0.22	0.36	0.40	169	225	197	45	63	70
Pekin #2	156.00		.0.80	0.80		120	120		72	72
CILCO Edwards	154.48		<0.01	<0.01		<1	<1		<1	<1
Pekin #1	152.20	2.53	2.10	2.60	285	194	296	24	189	234
Pekin Energy Co.*	151.60	0.76	25.50	25.50	713	2,124	2,124	32	22	21
Midwest Solventst	151.30	0.36	2.26	1.45	108	153	131	6	0	2
Quaker Oats	151.20		0.43	0.43		169	168		1	1
Cat Mapleton	147.29		3.96	1.00		410	211		33	33
Havana	119.17	0.44	0.38	0.47	37	34	38	63	7	8
Illinois Power Co.	118.50		0.01	0.13		<1	<1		<1	<1
Beardstown	87.90	1.18	0.82	0.90	849	216	255	196	69	75
Beard. Ind. Lagoons	87.95	1.22	0	0	659	0	0	365	0	0
CIPS	70.81		<0.01	<0.01		<1	<1		<1	<1
National Starch	70.00		0.33	0.27		10	10	.	0	0

*Formerly CPC International

tFormerly American Distillery Co.

no longer discharge. All known point sources are included; some are very small and have no discernible effects on the waterway DO resources but have been included for "bookkeeping" purposes.

Table 19 summarizes the results for the three periods, and compares the absolute and relative 1971 and 1980 yearly average contributions. Noteworthy is the fact that the 1980 3-month B0D$_{5C}$ load contributed by Chicago is significantly different from the 1980 yearly contribution. This is primarily because the 1980 yearly averages at the Northside and WSW plants exceed the 3-month averages by 2.8 mg/l and 3.0 mg/l, respectively. The Chicago area percentage contribution has increased, although in absolute terms the load has actually been reduced 16.1 percent. Relative to this, however, is the fact that the downstream load has been reduced a monumental 61.1 percent, an extremely commendable accomplishment. Just as commendable is the fact that both area NH3-N loads have been reduced by around 50 percent.

The yearly 1971 and 1980 and 3-month 1980 loads presented in table 18, when applied to 7-day, 10-year low flows, produced the DO profiles outlined in figures 4 through 8. Also presented in these figures are the curves produced as a result of applying the 3-month loads to the 9/27/71 and 9/3/71 flow conditions. Residual BOD$_{5C}$ and ammonia concentrations produced as a result of these simulations are presented for numerous points along the waterway in tables 20 and 21.

DISCUSSION AND CONCLUSIONS

A generalized discussion of the results will be presented, and some comparisons will be made with field DO sampling results obtained during 1982. Specific ideas and concepts relative to management strategies will be presented in the next section.

Finite proportionment of the discretionary diversion flow does not appear to be warranted relative to water quality conditions below Lockport. A minor exception to this may be the Brandon Road pool. Basically, proportional diversion is pertinent only to DO levels in the Chicago area drainage system. As noted earlier only minor fluctuations occur in the DO levels at Lockport irrespective of the diversion scheme employed. Since no nitrifi-

Table 19. Comparison of Chicago Area Loads
to Total Downstream Contributions

	B0D$_{5C}$(lbs/day)			NH3-N (lbs/day)			1971 to 1980	
	12 month		3 mo.	12 month		3 mo.	% reduction	
Source	1971	1980	1980	1971	1980	1980	B0D$_{5C}$	NH3-N
Chicago residual at Lockport	72,817	61,095	38,711	101,461	51,436	38,488	16.1	49.3
Direct discharges below Lockport	33,191	12,906	11,653	12,072	5,445	5,137	61.1	54.9
Total	106,008	74,001	50,364	113,533	56,881	43,625	30.2	49.9
% Chicago residual	68.7	82.6	76.9	89.4	90.4	88.2		
% Contributed below Lockport	31.3	17.4	23.1	10.6	9.6	11.8		

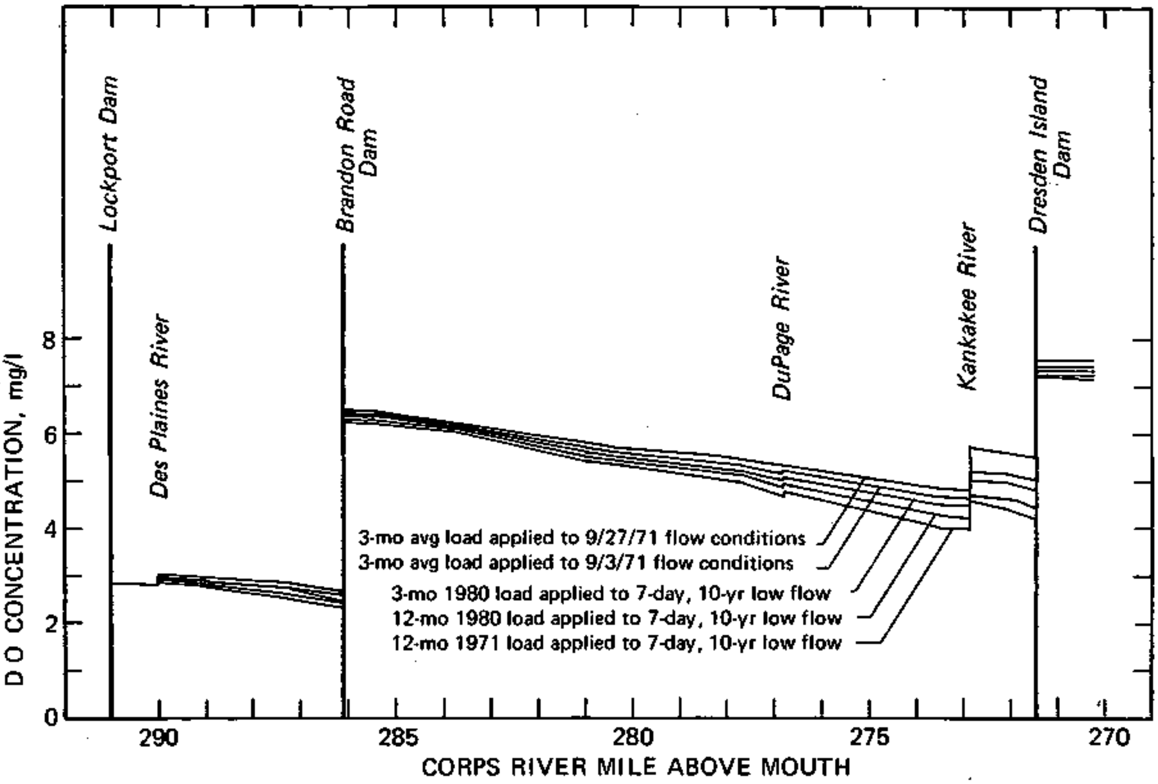

Figure 4. Brandon Road and Dresden Island pool DO curves for various conditions

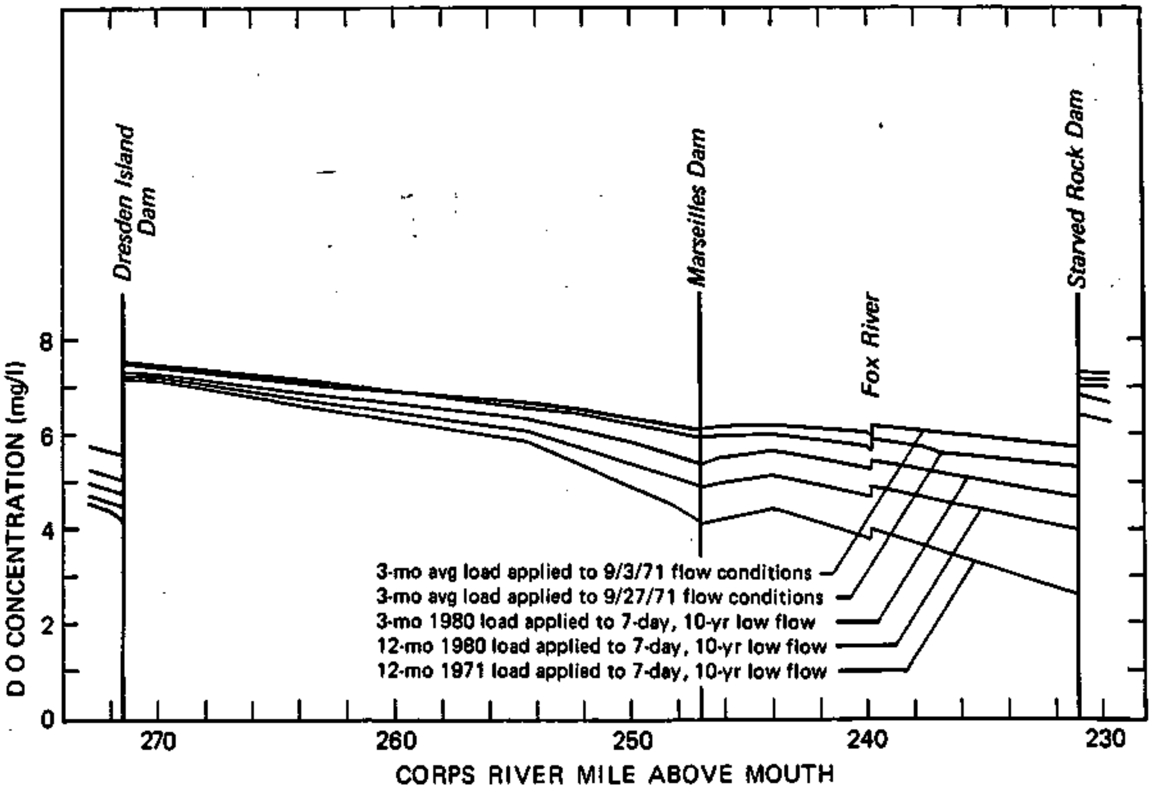

Figure 5. Marseilles and Starved Rock pool DO curves for various conditions

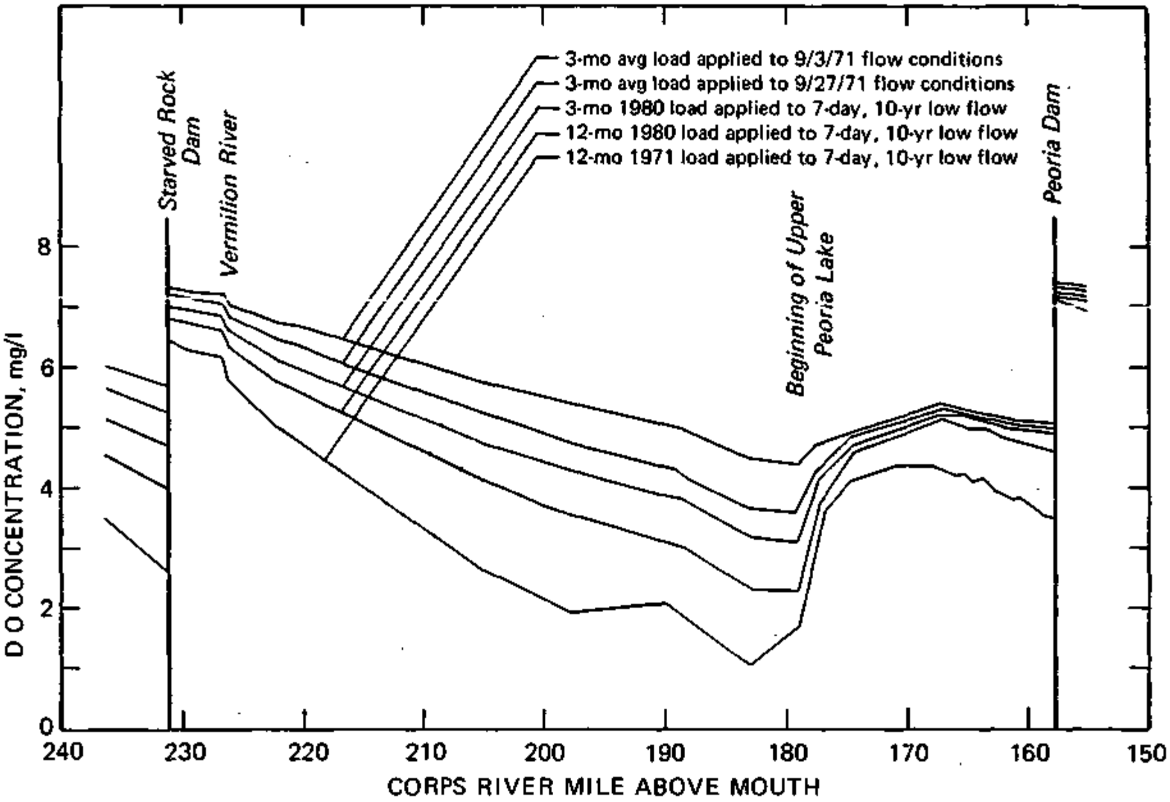

Figure 6. Peoria pool DO curves for various conditions

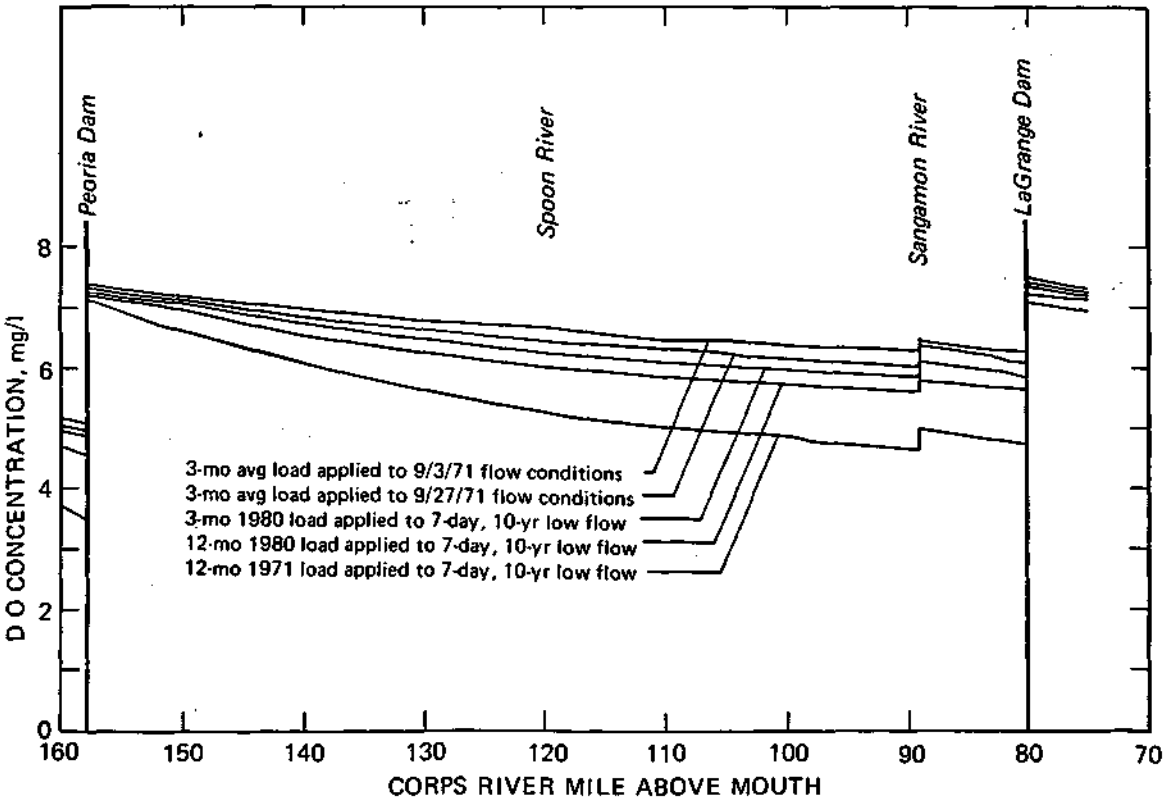

Figure 7. LaGrange pool DO curves for various conditions

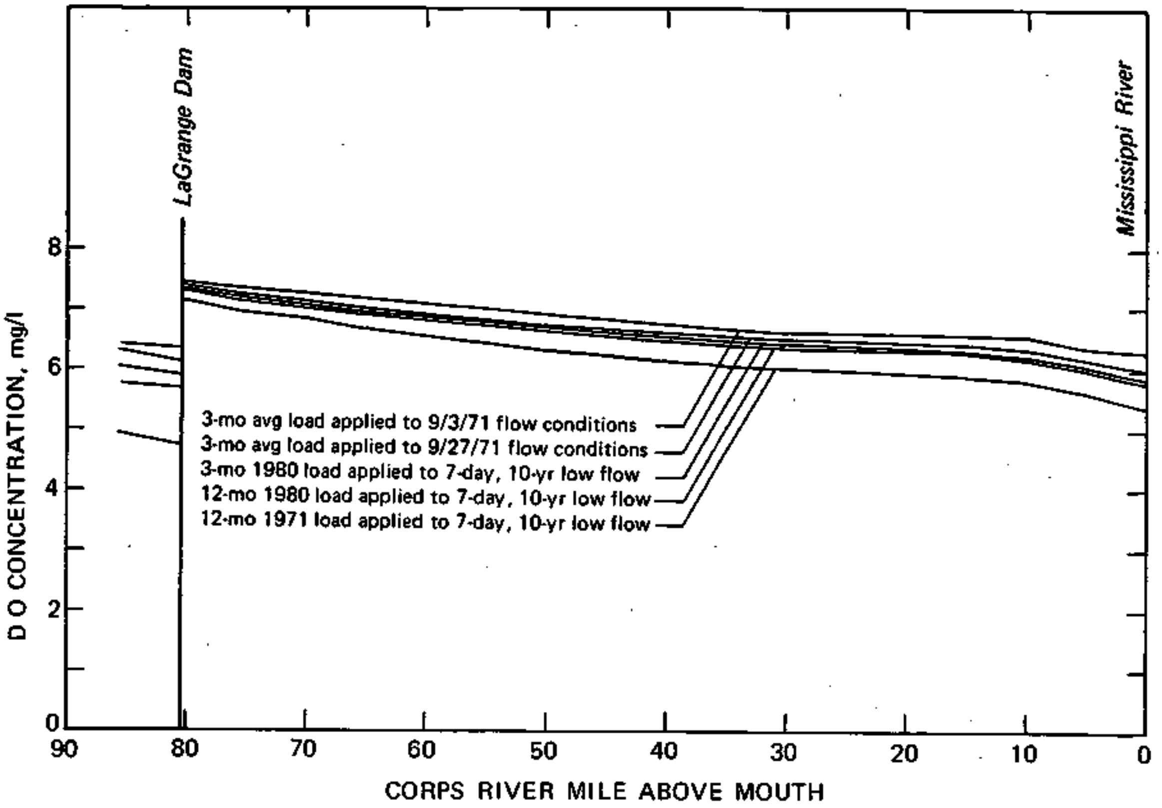

Figure 8. Alton pool DO curves for various conditions

cation occurs above Lockport, the ammonia load is totally unaffected by the amount or nature of the diversion.

Although carbonaceous BOD is used within the system in quantities proportional to detention times within specific channels, the net BOD$_{5C}$ concentrations show almost no variance at Lockport, as shown in table 22. BOD$_{5C}$ and NH$_3$-N loads can be significantly reduced at Lockport only by reducing the plant loads, particularly those from the Calumet plant, as indicated by the values in table 22 for the diversion schemes in tables 11 and 17. Also the sensitivity of the BOD at Lockport to large changes in lake diversion water BOD concentrations is minimal as shown by the data in table 22 for the diversion scheme in table 12; a six-fold increase in lake BOD$_{5C}$ from 1.0 to 6.0 mg/l resulted in only a 0.3 mg/l BOD$_{5C}$ increase at Lockport.

Dissolved oxygen conditions in the Brandon Road pool are almost totally dependent upon the net DO concentration above the Lockport dam since very little aeration occurs at the structure and the assimilation capacity of the pool is poor. During low flow conditions in the Brandon Road pool, minimum DOs will drop to values slightly lower than the value above the Lockport dam as demonstrated by the lower curve given in figure 9. However, the effect of Lockport DOs on values downstream of Brandon Road are minimized be-

Table 20. Simulated BOD$_{5c}$ and NH$_3$-N Concentrations at Selected Mile Points CMP) for 7-day, 10-year Low Flows

		BOD$_{5C}$ (mg/l)			HH$_3$-N (mq/1)		
Corns	Flow	12 month		3 mo.	12 month		3 mo.
MP	(cfs)	1971	1980	1980	1971	1980	1980
291.02	4139	3.28	2.76	1.75	4.56	2.32	1.73
290.00	4173	3.29	2.74	1.75	4.54	2.30	1.73
286.17	4190	3.18	2.65	1.69	4.52	2.29	1.72
286.13	4190	3.40	2.78	1.82	4.62	2.39	1.81
284.37	4199	3.40	2.75	1.81	4.61	2.38	1.81
283.74	4202	3.39	2.73	1.80	4.61	2.40	1.81
280.38	4218	3.27	2.64	1.74	4.60	2.37	1.80
278.19	4228	3.25	2.61	1.73	4.67	2.38	1.82
277.71	4230	3.23	2.60	1.73	4.67	2.38	1.82
276.82	4280	3.25	2.58	1.73	4.63	2.37	1.81
272.86	4934	2.92	2.57	1.65	4.07	2.11	1.62
272.14	4937	2.89	2.58	1.65	4.07	2.10	1.62
271.46	4941	2.86	2.34	1.64	4.06	2.10	1.62
270.21	4947	2.85	2.33	1.62	4.06	2.10	1.62
262.79	4982	2.76	2.23	1.55	4.03	2.09	1.61
254.35	5021	2.60	2.10	1.47	4.01	2.07	1.60
252.44	5031	2.55	2.07	1.45	3.94	2.04	1.57
248.71	5048	2.55	2.00	1.40	3.94	2.00	1.54
246.98	5057	2.56	1.96	1.37	3.87	1.96	1.51
244.05	5055	2.55	1.96	1.37	3.87	1.96	1.51
239.77	5256	2.52	1.97	1.42	3.67	1.87	1.44
239.17	5255	2.53	1.97	1.42	3.65	1.86	1.44
237.50	5253	2.50	1.94	1.40	3.62	1.85	1.42
231.02	5244	2.37	1.84	1.33	3.46	1.77	1.36
226.34	5245	2.31	1.79	1.29	3.39	1.73	1.34
223.00	5240	2.26	1.75	1.26	3.32	1.69	1.31
222.00	5238	2.25	1.74	1.25	3.30	1.69	1.30
218.00	5232	2.19	1.70	1.22	3.23	1.65	1.28
210.80	5247	2.07	1.61	1.16	3.08	1.58	1.22
209.03	5262	2.05	1.58	1.14	3.04	1.55	1.20
199.02	5246	1.87	1.44	1.04	2.82	1.44	1.11
190.00	5186	1.74	1.34	0.97	2.84	1.36	1.06
188.64	5172	1.71	1.32	0.95	2.80	1.35	1.04
179.10	5084	1.55	1.20	0.86	2.85	1.25	0.97
174.40	5040	1.39	1.07	0.78	2.71	1.15	0.89
165.30	4955	1.07	0.83	0.60	2.79	0.98	0.75
160.70	4913	0.95	0.70	0.50	2.17	0.92	0.72
160.05	4907	1.23	0.74	0.53	2.21	0.94	0.73
158.16	4890	1.23	0.72	0.52	2.13	0.94	0.73
157.70	4886	1.22	0.72	0.52	2.19	0.94	0.73
156.00	4870	1.20	0.71	0.52	2.18	0.94	0.73
152.00	4833	1.17	0.70	0.51	2.17	0.94	0.74
151.20	4826	1.19	0.78	0.60	2.17	0.94	0.74
147.73	4884	1.17	0.78	0.60	2.13	0.92	0.72
147.29	4863	1.17	0.80	0.61	2.14	0.93	0.73
120.50	4903	0.85	0.59	0.45	1.93	0.84	0.66
119.17	4906	0.84	0.58	0.45	1.92	0.84	0.66
88.90	5265	0.71	0.52	0.44	1.65	0.73	0.58
83.74	5289	0.64	0.47	0.35	1.59	0.70	0.56
80.19	5298	0.59	0.43	0.22	1.55	0.69	0.54
70.81	5319	0.53	0.39	0.20	1.52	0.67	0.53
0.00	5419	0.16	0.11	0.06	1.20	0.53	0.42

Table 21. Simulated BOD_{5C} and NH_3-N Concentrations at Selected Mile Points (MP) for 9/27/71 and 9/3/71 Flow Conditions

	9/27/71 flow			9/3/71 flow		
Corps MP	Flow (cfs)	BOD_{5C} (mg/l)	NH_3-N (mg/l)	Flow (cfs)	BOD_{5C} (mg/l)	NH_3-N (mg/l)
291.02	4139	1.74	1.74	4139	1.74	1.74
290.00	4152	1.82	1.76	4207	1.75	1.72
286.17	4322	1.69	1.69	4508	1.58	1.60
286.13	4323	1.83	1.78	4511	1.71	1.69
284.37	4345	1.80	1.77	4627	1.66	1.65
283.74	4353	1.79	1.77	4670	1.63	1.64
280.38	4392	1.72	1.75	4877	1.52	1.57
278.19	4418	1.71	1.76	5016	1.48	1.54
277.71	4424	1.70	1.76	5046	1.46	1.53
276.82	4434	1.72	1.77	5101	1.46	1.53
272.86	4545	2.34	1.91	5404	1.55	1.49
272.14	6534	1.62	1.33	6159	1.36	1.31
271.46	6542	1.61	1.33	6202	1.34	1.30
270.21	6557	1.60	1.32	6285	1.32	1.28
263.54	6638	1.53	1.31	6713	1.19	1.20
262.79	6663	1.53	1.30	6766	1.18	1.20
254.35	6764	1.44	1.29	7302	1.05	1.11
252.44	6878	1.42	1.27	9425	1.02	1.08
248.98	6833	1.38	1.24	7666	0.97	1.03
246.98	6855	1.35	1.22	7785	0.94	1.00
244.05	6839	1.35	1.22	7804	0.94	1.00
239.77	6802	1.51	1.24	7794	1.12	1.03
239.17	7140	1.43	1.18	8220	1.25	0.97
237.50	7127	1.42	1.17	8216	1.05	0.96
231.02	7079	1.37	1.14	8203	1.01	0.94
226.34	7043	1.35	1.12	8193	1.00	0.92
223.00	7037	1.32	1.10	8197	0.98	0.91
222.00	7028	1.32	1.10	8194	0.97	0.90
218.00	6996	1.29	1.08	8185	0.95	0.89
210.80	6940	1.24	1.05	8170	0.92	0.86
209.03	6927	1.23	1.04	8170	0.91	0.86
198.02	6843	1.15	0.99	8150	0.85	0.81
190.00	6824	1.08	0.94	8245	0.79	0.77
188.64	6823	1.06	0.93	8270	0.78	0.76
179.10	6817	0.97	0.87	8424	0.71	0.70
174.40	6814	0.88	0.80	8500	0.65	0.65
165.30	6808	0.71	0.70	8649	0.53	0.57
163.00	6806	0.62	0.67	8685	0.48	0.55
160.70	6809	0.61	0.67	8726	0.47	0.54
160.05	6809	0.64	0.68	8736	0.49	0.55
158.16	6833	0.62	0.67	8776	0.47	0.55
157.70	6833	0.62	0.67	8783	0.48	0.55
156.00	6832	0.62	0.67	8810	0.47	0.54
152.00	6829	0.60	0.67	8875	0.46	0.54
151.20	6829	0.66	0.67	8888	0.50	0.54
147.73	6881	0.67	0.66	8968	0.49	0.53
147.29	6881	0.67	0.67	8970	0.49	0.53
120.50	6678	0.58	0.65	9127	0.39	0.49
119.17	6745	0.57	0.64	9170	0.38	0.48
88.90	6498	0.75	0.67	9326	0.42	0.47
83.74	7178	0.64	0.59	9158	0.41	0.47
80.19	7174	0.59	0.58	9803	0.37	0.43
70.81	7100	0.55	0.58	9850	0.33	0.42
23.26	6752	0.37	0.56	10078	0.20	0.38
0.00	6515	0.21	0.52	10201	0.12	0.52

Table 22. Residual BOD_{5C} and NH_3-N Concentrations at Lockport

Table number of diversion scheme	No.of values	NH_3-N (mg/l)	BOD_{5c}(mg/l) Low	Avg.	High	Comments
10	44	1.73	1.72	1.734	1.74	Ambient July, Aug., Sept. conditions
13	6	1.73	1.73	1.737	1.74	Lake DOs varied
14	5	1.73	1.73	1.736	1.74	Calumet plant (CSTP) DOs varied
15	4	1.73	1.74	1.740	1.74	West-Southwest Plant DOs varied
16	5	1.73	1.74	1.740	1.74	Northside Plant DOs varied
11	26	0.82	1.53	1.539	1.57	CSTP BOD_{5c}=7;NH,-N=2
17	4	0.82	1.53	1.530	1.53	CSTP BOD_{5c}=7;NH,-N=2 with instream aeration varied"below CSTP
12	6	1.73	1.65	1.800	1.95	Lake BOD_{5c}varied 1 to 6 mg/l

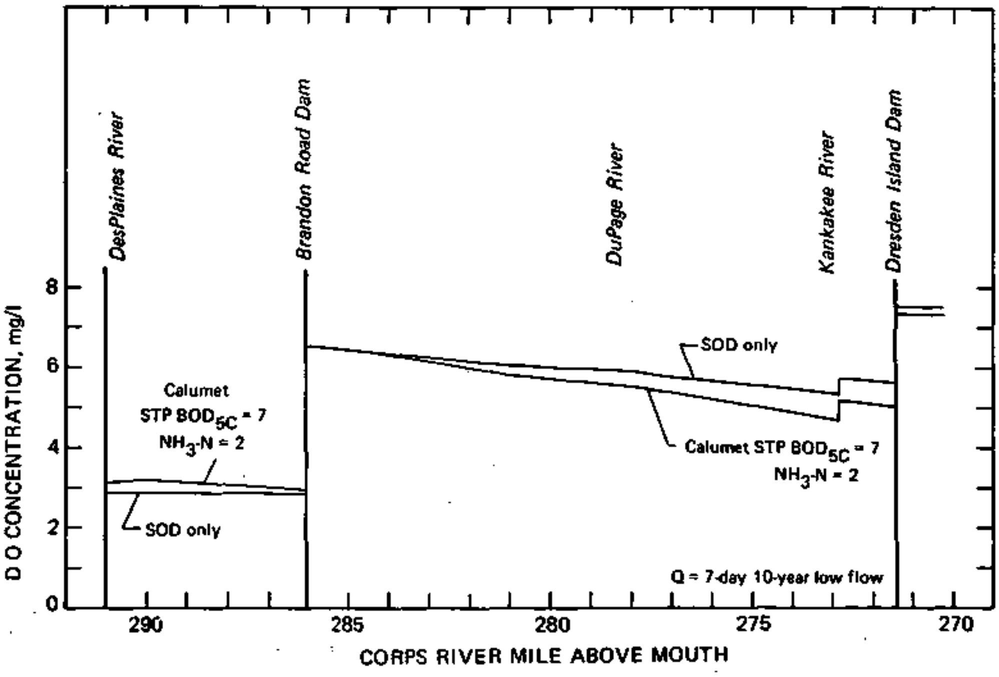

Figure 9. Brandon Road and Dresden Island pool DO curves for a Calumet Sewage Treatment Plant BOD_{5C} *of 7 mg/l and an* NH_3*-N of 2 mg/l and for all other plant* BOD_{5C} *and* NH_3*-N inputs equal to the 1980 S-month average*

cause of the very high reaeration capacity of the Brandon Road dam. This is illustrated by the upper curve in figure 9. Even if the Lockport DO is zero, a DO reserve of about 5.7 mg/l can be expected to occur at the beginning of the Dresden Island pool. Figure 4 shows that minimum DO standards (2.0 mg/l and 5.0 mg/l above and below Corps MP 278.0, respectively) are nearly met in the Dresden Island pool by using all the discretionary diversion allotment during the 3-month period. The Kankakee River comes to the aid of the DO resources in the lower reaches of the pool.

Excellent aeration is achieved at the Dresden Island dam, providing a good initial DO reserve for water entering the Marseilles pool. This, coupled with the facts that the pool assimilative capacity is relatively good (see velocity and depths, table 9) and low SODs exist throughout the pool length (see table 7), prevents the minimum DO standard of 5.0 mg/l from being violated. This pool historically has demonstrated its ability to sustain relatively high DO levels. The lowest DO level recorded for 25 sampling runs made by Butts et al. (1975) during 1971-1972 was 3.70 mg/l and that occurred right above the dam. Sixteen of the runs had minimum DOs of 4.50 mg/l or better, with the highest being 6.20 mg/l.

These minimum values show good agreement with the minimum pool DO of 4.14 mg/l computed using the 3-month "design" flow in conjunction with the 1971 12-month average loads (see figure 5). The minimum DO computed using the 3-month load imposed upon the "design," 9/27/71, and 9/3/71 flows were 5.44, 5.92, and 6.15 mg/l, respectively. These values, in turn, are comparable to those observed during a number of sampling runs made during July, August, and September 1982. For a wide range of flows the 1982 observations ranged from 5.5 mg/l to 7.5 mg/l.

Nitrification begins in the Marseilles pool. During the "design flow," it is initiated around MP 254. For the higher simulated flows it commences a few miles farther downstream.

Unfortunately the "design," 9/27/71 and 9/3/71 flow DO sag curves which start to develop in the Marseilles pool continue to do so unabated in the Starved Rock pool since all the flow is diverted for power generation, resulting in little aeration at the Marseilles dam. As a result the 5.0 mg/l DO standard is violated to a small degree in the last four or five miles of the Starved Rock pool. In actuality though, this violation presently is seldom observed during daylight hours because primary productivity enhances daytime DO concentrations in the wide, shallow lower reach of the pool. The minimum daytime DO observed during 1982 sampling was 6.2 mg/l; however, a nighttime low of 5.5 mg/l occurred during a diurnal sampling period in September 1982.

Good aeration is achieved at the Starved Rock dam, but it is not sufficient to prevent standard violations within the Peoria pool. The middle section of the pool is the critical section of the waterway during low to intermediate flow conditions. The pool is long and somewhat sluggish, and nitrification becomes a dominant factor. A minimum DO of about 3.0 mg/l can be expected to occur near Chillicothe (MP 179) for "design" flow conditions of around 5084 cfs. The 9/3/71 flow of 8424 cfs for this reach was not quite sufficient to bring the DO up to standard. Extrapolation indicates that between 9000 and 9500 cfs is needed.

Below MP 179 the river enters Upper Peoria Lake; it becomes shallower, and since most of the flow remains in the channel, this reach tends to assimilate wastes better, as shown by figure 6. Also, primary productivity at times appears to enhance DO levels in this area. September 1982 diurnal sampling showed a wide swing in DO levels in the lake, ranging from a high of 13.4 mg/l during the day to a low of 6.7 mg/l during the night. The 1982 summer flows, however, were much greater than the "design" flow, and the minimum points on the DO sag curve were pushed farther downstream; a minimum value of 4.8 was observed at MP 170.9.

Neither the LaGrange nor the Alton pool DO resources appear to become stressed under "design" flow conditions based on the model output. However, historically the standards are violated for significantly greater flows where the ammonia load is "pushed" down into the LaGrange pool. For instance, on July 30, 1979, with flows in the pool ranging between 9200 cfs on the upper end to 15,000 cfs on the lower end a minimum DO of 4.0 mg/l was observed (Butts et al., 1981).

MANAGEMENT STRATEGIES

The model runs show that 320 cfs average annual discretionary diversion dispensed over a 3-month summer period (at 1280 cfs) will not be sufficient to maintain DO standards below Lockport. This is despite the fact that significant reductions have been made in waste load discharges all along the waterway in the last ten years. The last major plant or discharge that appears to be a candidate for improvements which will result in discernible changes in water quality is the Calumet plant. Effort and money should be expended to bring the effluent quality in line with that routinely produced at the Northside plant.

Figures 9 through 13 show the improvements in DO which could be expected if the Calumet BOD_{5C} and NH_3-N discharges were reduced to 7 mg/l and 2 mg/l, respectively, during summer low flow conditions. The middle reach of the Peoria pool remains critical but the minimum DO is raised somewhat from 3.1 to 3.7 mg/l. The BOD_{5C} and NH_3-N concentrations for these conditions at selected points along the waterway are given in table 23. Comparison of these results with the 3-month results in table 20 shows that downstream ammonia concentrations are reduced considerably. For example, at Peoria (MP 160.05) projected ammonia concentrations for ambient and improved conditions are, respectively, 0.74 and 0.42 mg/l. The effect on BOD_{5C} is much less.

Purely from a dissolved' oxygen standpoint, expenditure of funds for local reductions at other point discharge sites does not seem warranted. The fact is that bottom sediments alone will cause significant oxygen depletion in all the pools above the Peoria dam as illustrated by the top curves shown in figures 9 through 11. Even if all point loads were eliminated, the maintenance of a minimum DO of 5.0 mg/l appears somewhat questionable in some short reaches of the Dresden Island and Peoria pools.

The results of extensive sampling by Water Survey personnel of the waterway sediments from Lockport to Grafton over the last ten years indicate that waterway SOD rates appear to be little influenced by treatment plant discharges. The SOD rates below the Dresden Island dam will continue to exert the same ambient demands irrespective of what is done in the Chicago area to eliminate storm overflows or to improve treatment plant efficiencies. By creating relatively deep pools and long residence times, the dams will perpetuate the negative influence of sedimentation and attendant SODs on the dissolved oxygen resources of the upper reaches of the waterway. Rela-

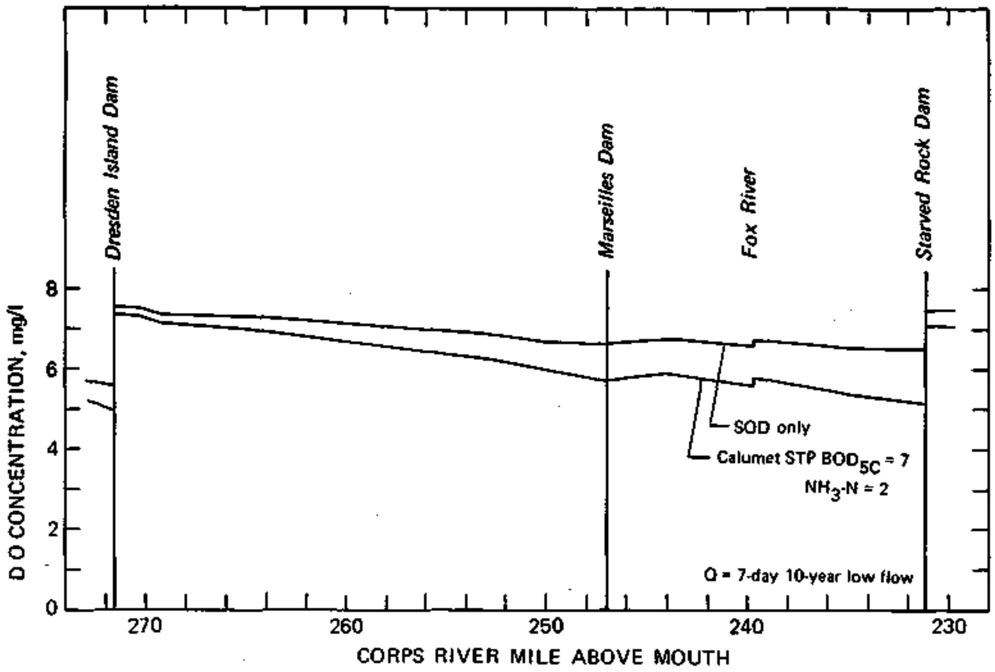

Figure 10. Marseilles and Starved Rock pool DO curves
for a Calumet Sewage Treatment Plant BOD_{5C} of 7 mg/l and an NH_3-N of 2 mg/l
and for all other plant BOD_{5C} and NH_3-N inputs equal to the 1980 3-month average

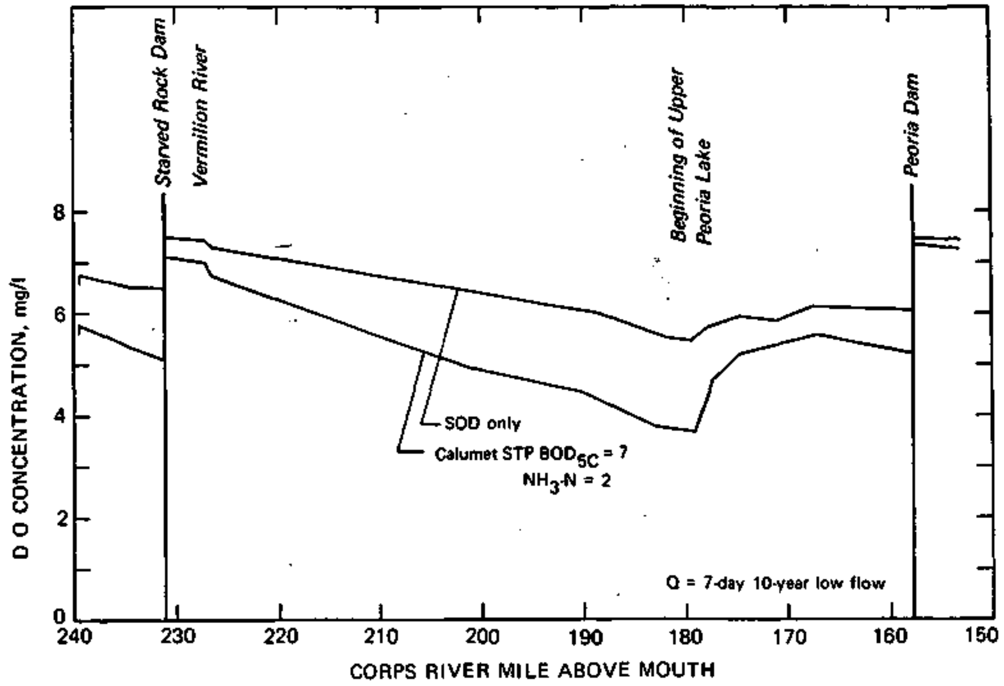

Figure 11. Peoria pool DO curves
for a Calumet Sewage Treatment Plant BOD_{5C} of 7 mg/l and an NH_3-N of 2 mg/l
and for all other plant BOD,- and NH_3-N inputs equal to the 1980 3-month average

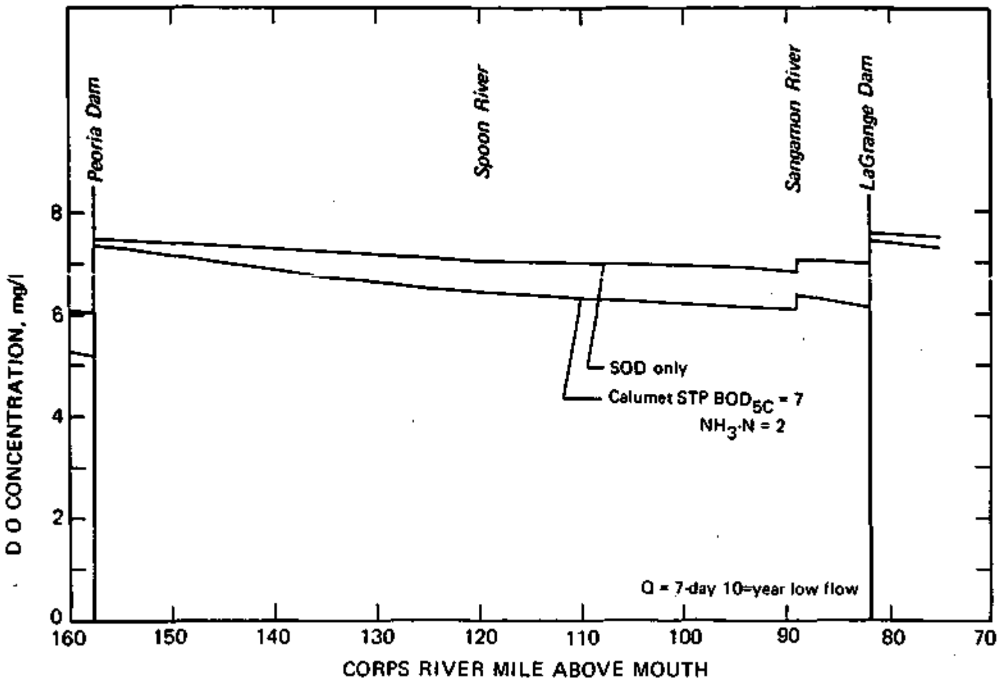

Figure 12. LaGrange pool DO curves for a Calumet Sewage Treatment Plant BOD_{5c} of 7 mg/l and an NH_3-N of 2 mg/l and for all other plant BOD_{5c} and NH_3-N inputs equal to the 1980 Z-month average

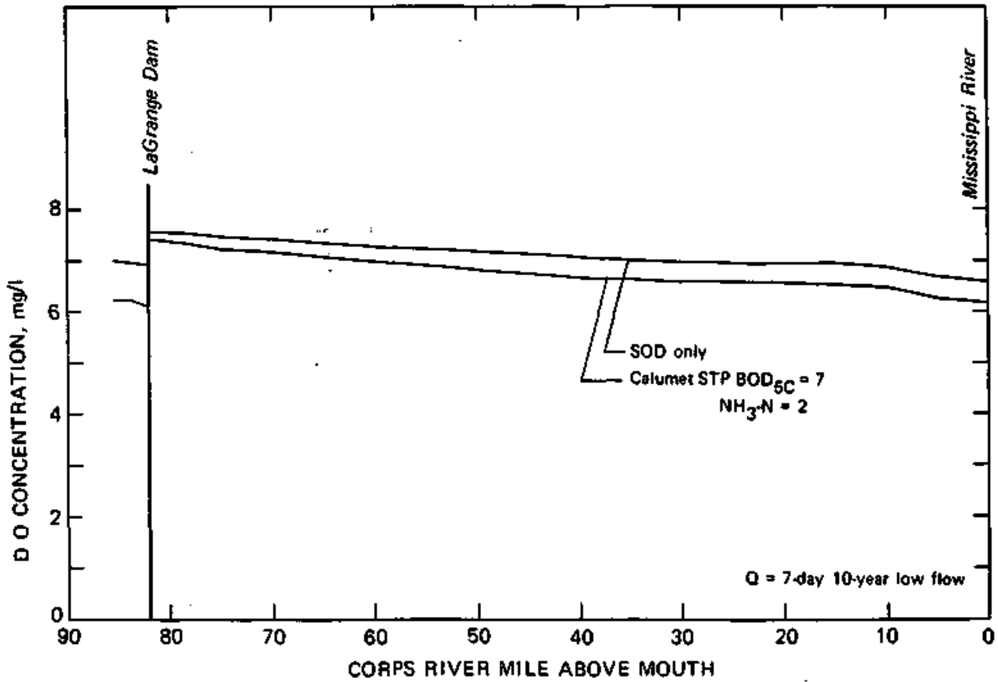

Figure 13. Alton pool DO curves for a Calumet Sewage Treatment Plant BOD_{5c} of 7 mg/l and an NH_3-N of 2 mg/l and for all other plant BOD_{5c} and NH_3-N inputs equal to the 1980 3-month average

Table 23. Simulated BOD_{5C} and NH_3-N Concentrations at Selected Mile Points (MP) for 7-day, 10-year Low Flow with Calumet Plant BOD_{5C} = 7 mg/l and NH_3-N = 2 mg/l

Corps MP	Flow (cfs)	BOD_{5c} (mg/l)	NH3-N (mg/l)	Corns MP	Flow (cfs)	BOD_{5c} (mg/l)	NH_3-N (ma/l)
291.02	4139	1.54	0.82	165.30	4955	0.55	0.42
290.00	4144	1.56	0.82	160.70	4913	0.46	0.40
286.17	4190	1.49	0.81	160.05	4907	0.50	0.42
286.13	4190	1.63	0.91	158.16	4890	0.48	0.42
284.37	4199	1.62	0.91	157.70	4886	0.49	0.42
283.74	4202	1.61	0.91	156.00	4870	0.48	0.42
280.38	4218	1.56	0.90	152.00	4833	0.48	0.43
278.19	4228	1.55	0.92	151.20	4826	0.56	0.43
277.71	4230	1.55	0.92	147.73	4837	0.58	0.43
276.82	4234	1.57	0.93	147.29	4863	0.58	0.43
272.86	4299	1.73	0.98	120.50	4878	0.43	0.39
272.14	4937	1.51	0.85	119.17	4906	0.43	0.39
271.46	4941	1.49	0.85	88.90	4978	0.45	0.37
270.21	4947	1.48	0.85	83.74	5277	0.38	0.34
2.62.79	4982	1.42	0.85	80.19	5298	0.36	0.33
254.35	5021	1.34	0.84	70.81	5319	0.32	0.33
252.44	5031	1.32	0.83	0.00	5419	0.09	0.26
248.71	5048	1.28	0.82				
246.98	5057	1.25	0.80				
244.05	5055	1.25	0.80				
239.77	5048	1.36	0.82				
239.17	5255	1.31	0.78				
237.50	5253	1.29	0.77				
231.02	5244	1.22	0.74				
226.34	5237	1.20	0.73				
223.00	5240	1.16	0.71				
222.00	5238	1.16	0.71				
218.00	5232	1.13	0.69				
210.80	5222	1.07	0.67				
209.03	5244	1.06	0.66				
198.02	5246	0.96	0.61				
190.00	5186	0.89	0.58				
188.64	5172	0.88	0.57				
179.10	5084	0.80	0.53				
174.40	5040	0.72	0.49				

tive to this, thoughts of increasing pool depth's either by dredging or raising dam heights should be discouraged.

Sediments associated with storm water overflows and sewage treatment plant discharges from the Chicago area appear to have the greatest effect on the water quality of the lower wide portion of the Brandon Road pool and most of the Dresden Island pool. Sedimentation immediately above the Brandon Road dam in the last 20 years has been just short of phenomenal. Prior to the update of the Water Survey cross-sectional data for use in this study, the average water depth used for the first mile above the dam for low flow conditions was 22.3 feet. The present updated depth is now only 11.9 feet.

During periods of minimal diversion, the sediments reduce the DO in the overlying water to very low levels. During 1982 SWS sampling, dissolved oxygen concentrations as low as 0.4 mg/l were observed in the area of the dam. Values below 2.0 mg/l were common; an examination of figure 4 reveals that values around 2.5 mg/l can be expected to occur with 1280 cfs diversion during July, August, and September. However, with little or no diversion during late spring or early summer dry periods, very low DO levels will occur. For example, on May 25, 1982 the minimum observed DO in the Brandon Road pool was 0.4 mg/l and the value immediately above the dam was 0.7 mg/l.

The maintenance of a minimum DO of 2.0 mg/l during warm weather appears to be achievable throughout the Brandon Road pool only during periods of discretionary diversion. Without diversion during all critical periods, consideration should be given to either supplementing the DO in the pool or eliminating the sediments. The latter alternative appears less attractive. Dredging and disposing of the highly polluted sediments would be expensive and would provide only a temporary symptomatic cure without addressing the root cause. Only by eliminating polluted sediment discharges from storm and combined sewer overflows can a continuous buildup of polluted bottom sediments be avoided. In addition, dredging would be partially self-defeating since the detention time has been reduced by almost 50 percent because of the filling of the pool, thereby reducing the total oxygen used by a like amount. Even with dredging, a residue would probably persist which would exert a significant SOD for many years under the influence of much longer detention times.

Four Alternative Strategies

Consideration should be given to supplementing the DO resources of the Brandon Road pool either at the Lockport dam or immediately above or below it. Possible alternatives are: 1) instream aeration above the dam, 2) instream aeration below the dam, 3) air inducement into the penstocks, and 4) elimination of hydropower production. Historically (Butts et al., 1975) and currently (1982 Water Survey sampling), DO levels above the Lockport dam persistently fall below 1.0 mg/l. On 12 of the 19 days sampled during 1982, the DOs fell below 1.0 mg/l and on nine of these days they were essentially zero. The model runs showed that approximately 3.0 mg/l DO can be maintained at Lockport for 1280 cfs diversion. At diversion flows less than this, sharp drops in DO can be expected, and for little or no diversion DO levels approaching zero will occur and will be carried over into the Brandon Road pool during periods of power generation.

All four alternatives listed above pose some problems relative to actual implementation. The purpose of this study was to explore and present solutions; it did not include preparing and presenting engineering designs and cost analyses even on a preliminary basis. However, a discussion of some obvious limitations which could hinder the practical application of each appears to be warranted. The only difference between alternatives 1 and 2 is the location of the aerators at the dam. The physical placement of the aerators seems better suited above than below the dam. An enclosed bay, protected by a fender wall, exists above the dam at the penstock intakes, whereas below the dam the tailrace is swift and at times turbulent.

However, an upstream location could possibly create a cavitation problem in the turbines since entrapped air bubbles could coalesce in the penstocks. If this is a possibility downstream placement would alleviate this problem. In either case, though, instream aeration probably cannot supply all the oxygen needed to insure compliance with minimum DO standards in the Brandon Road pool. This is demonstrated by the following load matrix:

	0	1	2
1	27,500		
2	50,000	27,500	
3	73,000	27,500	27,500

When the water above the dam is void of DO (Column 0), approximately 73,000 lbs/day of dissolved oxygen would have to be generated to maintain 3.0 mg/l (line 3) at the Brandon Road dam. The maximum production capacity of any of the proposed MSD instream aeration installations is 40,000 lbs/day at the Stevenson Expressway in the Sanitary and Ship Canal. With this amount used as an indication of the upper practical limit, only about 2 mg/l could be maintained when the canal DO is void of oxygen. For an ambient 1.0 mg/l level, a generation of 50,000 lbs/day would bring the Brandon Road pool DO almost up to standard. Only a 27,500 lbs/day generation would be needed to raise an ambient level of 2.0 mg/l to 3.0 mg/l.

The induction of air into the water stream in hydroelectric generating facilities (alternative 3 above) is known as turbine aspiration or turbine venting. Some studies have been conducted to explore the feasibility of utilizing this method to supplement DO in the releases from high head hydroelectric plants, but it has not been applied in continuous full scale operations. Reference should be made to the works of Raney (1977) and TVA (1981) for a detailed discussion of the basic concepts involved and the state of the art of this process. The U.S. Army Corps of Engineers (1982) proposed to use this technique to supplement DO at the navigation dams along the waterway in the event hydroelectric generating plants are established at the Brandon Road, Dresden Island, and Starved Rock dams.

TVA studies of prototype installations showed that turbine venting coupled with hub baffling can increase DO levels by as much as 4.5 mg/l, but at the expense of a 3 percent loss in power generation. Use of hub baffles alone produced a 2.5 mg/l increase with a power loss of about 2 percent. These figures are for an installation 265 feet high, whereas the Lockport dam is only 35 feet high. The percentage loss in generating capacity for the much lower Lockport dam would likely be somewhat greater. This would result in a significant revenue loss to the MSD, possibly in the range of $60,000 to $100,000 per year assuming power production is worth at least $2,000,000 per year to the MSD.

Alternative 4 superficially looks attractive but in actuality is not. It is totally unacceptable to the MSD (personal communication), and for some very good reasons. First it would eliminate several million dollars' worth of electricity generated annually that offsets a significant portion of MSD's operating expenses. The elimination of the facilities would run counter to the present national trend toward energy conservation. Elimination of the facility would also be contradictory to the Corps of Engineers plans of adding hydroelectric generating plants at the Brandon Road, Dresden Island, and Starved Rock dams. Finally, the mere elimination of the generating plant would not insure reaeration at the dam. The penstocks would have to be eliminated and a spillway built in place of them, which would be very costly and possibly impractical.

Preferred Strategies

Overall turbine venting and/or hub baffling appears to be the most practical solution. With the current Corps of Engineers studies being conducted relative to using this method at proposed hydropower sites along the waterway, the practicality of employing this method should become known in the near future. Instream aeration with aerator placement above the dam should receive second consideration, and aerator placement below the dam should receive third consideration. Elimination of the power plant and subsequent installation of a spillway should at this time be placed a distant fourth.

Improved Calumet treatment plant efficiencies coupled with instream aeration in the Cal-Sag Channel below the plant appears to offer an attractive overall management alternative. Reference to run 97 in table 17 shows that, for the specified diversion scheme in conjunction with Calumet plant discharges of BOD_{5C} = 7 mg/l and NH_3-N = 2 mg/l and instream aeration capable of delivering 13,300 lbs/day of dissolved oxygen, over 2.8 mg/l of DO can be maintained throughout the system. About 3.3 mg/l of DO can be expected to be carried over into the Brandon Road pool, and the effects further downstream would be essentially equal to those described by figures 9 through 13.

Instream aeration capable of producing 26,600 lbs/day of DO in the Cal-Sag Channel would probably produce DOs in excess of 3.5 mg/l throughout the drainage system. This coupled with a high degree of nitrification within the Calumet plant would probably promote the onset of nitrification above Lockport, which in turn would alleviate considerable stress on the downstream DO resources. It would reduce the nitrogenous BOD load and effectively move the major impact area farther upstream. Care would have to be taken, though, to insure that during non-diversion periods additional instream aeration is available when needed to maintain a viable nitrifying environment.

Both upgrading the Calumet plant to a BOD_{5C} of 7 mg/l and an ammonia of 2 mg/l and installing instream aeration below the plant are technically and economically feasible. These desirable effluent limits can be achieved and realistically maintained from a process and operation standpoint, although according to MSD officials (private communication) it would be more difficult to do so than is presently the case at the Skokie and Stickney plants. This is because the Calumet plant influent consists of a high percentage of industrial wastes which vary considerably in quality and quantity, whereas the Skokie and Stickney plants receive primarily domestic loads.

Instream aeration has never been considered by MSD officials as a replacement for on-bank treatment; they consider it as a supplemental source of DO only. They feel that even with an upgrading of the Calumet plant coupled with instream aeration, nitrification still will not commence within the Calumet-Sag Channel. Whether instream aeration will actually increase the DO levels in the channel can, at present, be evaluated only from a design and specification viewpoint supplemented by an evaluation of the results being produced by the two aeration stations now on line in the Northshore Channel - Chicago River drainage area. The real success of any implementation and management program reduces to the basic problem of funding; the basic "seeds" for detailed engineering analyses and design have been presented in this study.

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Appendix A

U.S. Army Corps of Engineers
Illinois Waterway Mile Point Designations
Compared to Illinois State Water Survey Designations

SWS to Corps Illinois Waterway Mile Point Conversions

Corps	SWS	Corps	SWS	Corps	SWS	Corps	SWS	Corps	SWS	Corps	SWS	Corps	SWS	Corps	SWS
291	290.96	253	252.97	215	215.27	177	177.35	139	139.33	101	101.24	63	63.13	25	25.11
290	289.94	252	252.00	214	214.26	176	176.33	138	138.33	100	100.22	62	62.14	24	24.16
289	288.93	251	251.00	213	213.30	175	175.32	137	137.31	99	99.22	61	61.11	23	23.26
288	287.93	250	249.99	212	212.30	174	174.36	136	136.33	98	98.21	60	60.09	22	22.27
287	286.97	249	248.94	211	211.34	173	173.31	135	135.34	97	97.21	59	59.20	21	21.27
286	286.07	248	247.94	210	210.32	172	172.35	134	134.34	96	96.20	58	58.18	20	20.25
285	285.01	247	246.80	209	209.35	171	171.35	133	133.34	95	95.18	57	57.16	19	19.24
284	284.00	246	245.90	208	208.34	170	170.32	132	132.34	94	94.17	56	56.21	18	18.23
283	283.04	245	244.74	207	207.36	169	169.32	131	131.32	93	93.20	55	55.18	17	17.23
282	282.04	244	243.67	206	206.40	168	168.29	130	130.32	92	92.15	54	54.18	16	16.22
281	281.09	243	242.78	205	205.35	167	167.47	129	129.32	91	91.15	53	53.19	15	15.17
280	280.09	242	241.77	204	204.39	166	166.45	128	128.32	90	90.14	52	52.19	14	14.18
279	279.12	241	240.83	203	203.41	165	165.37	127	127.32	89	89.10	51	51.20	13	13.10
278	278.12	240	239.45	202	202.43	164	164.36	126	126.32	88	88.09	50	50.21	12	12.11
277	277.14	239	238.46	201	201.45	163	163.41	125	125.31	87	87.08	49	49.21	11	11.12
276	276.02	238	237.45	200	200.48	162	162.40	124	124.31	86	86.04	48	48.21	10	10.11
275	275.02	237	236.43	199	199.51	161	161.39	123	123.29	85	85.02	47	47.22	9	9.10
274	274.04	236	235.56	198	198.51	160	160.37	122	122.30	84	83.95	46	46.23	8	8.08
273	273.04	235	234.80	197	197.52	159	159.32	121	121.27	83	82.92	45	45.24	7	7.05
272	272.05	234	233.80	196	196.53	158	158.31	120	120.26	82	81.89	44	44.22	6	5.98
271	271.03	233	232.81	195	195.44	157	157.36	119	119.26	81	81.90	43	43.24	5	4.87
270	270.02	232	231.80	194	194.41	156	156.36	118	118.27	80	79.82	42	42.20	4	4.02
269	269.01	231	231.00	193	193.43	155	155.36	117	117.26	79	78.98	41	41.22	3	3.08
268	268.00	230	230.03	192	192.47	154	154.35	116	116.26	78	77.97	40	40.22	2	2.05
267	267.01	229	229.03	191	191.48	153	153.35	115	115.25	77	76.96	39	39.20	1	1.0
266	266.00	228	228.06	190	190.51	152	152.36	114	114.25	76	76.20	38	38.23	0	0
265	265.00	227	227.03	189	189.40	151	151.36	113	113.24	75	75.14	37	37.26		
264	263.99	226	226.15	188	188.42	150	150.35	112	112.24	74	74.10	36	36.22		
263	262.98	225	225.17	187	187.39	149	149.33	111	111.24	73	73.07	35	35.22		
262	261.99	224	224.16	186	186.40	148	148.36	110	110.23	72	72.06	35	34.23		
261	260.97	223	223.23	185	185.40	147	147.36	109	109.23	71	71.08	33	33.27		
260	259.98	222	222.21	184	184.39	146	146.33	108	108.23	70	70.19	32	32.20		
259	258.99	221	221.25	183	183.39	145	145.35	107	107.26	69	69.19	31	31.20		
258	257.97	220	220.24	182	182.37	144	144.35	106	106.24	68	68.19	30	30.13		
257	256.98	219	219.25	181	181.38	143	143.35	105	105.24	67	67.20	29	29.14		
256	255.98	218	218.24	180	180.40	142	142.35	104	104.24	66	66.13	28	28.09		
255	254.99	217	217.26	179	179.40	141	141.35	103	103.24	65	65.15	27	27.09		
254	254.00	216	216.26	178	178.37	140	140.34	102	102.23	64	64.15	26	26.09		

Appendix B

Computer Printout of 7-Day, 10-Year Low Flow Hydraulic and Hydrologic Data

ABBREVIATIONS USED IN APPENDIX B

F = flow at the end of a reach
AVF = average flow within a reach
AVA = average reach cross-sectional area
AVW = average reach width
AVD = average reach depth
DT = reach time of travel
SUMT = accumulated time of travel
DIS = reach distance
VOL = reach volume

```
  TYPE,0/CC
 7D10Y+1819 DATA      PROCESSED 82/12/21. AT 13.59.15.

 STAFF GAGE ELEVATIONS       USGS GAGING STATIONS
    0.00   418.04              0.00    5419.
   21.74   418.13             70.89    5319.
   31.66   418.25            145.76    4819.
   43.39   418.60            196.66    5243.
   56.14   419.05            246.39    5059.
   61.47   419.20            291.00    4139.
   70.89   419.65
   80.00   420.22            TRIBUTARY CONFLUENCE
   80.01   429.00            289.94      29.
   88.91   429.04            276.96      46.
   97.40   429.09            272.90     635.
  111.44   429.20            239.17     208.
  119.90   429.28            226.50       8.
  128.86   429.40            211.19      25.
  137.21   429.56            209.36      18.
  145.76   429.77            160.03       1.
  153.31   429.95            148.09      47.
  158.05   430.00            120.78      25.
  158.06   440.00             88.94     287.
  164.61   440.01             83.72      12.
  180.68   440.05             23.44       3.
  196.66   440.09
  207.85   440.14
  218.69   440.17
  223.05   440.21
  231.01   440.30
  231.02   458.51
  246.77   458.51
  246.78   482.76
  271.51   482.76
  271.52   504.54
  286.24   504.54
  286.25   538.55
  291.00   538.55
```

MILE	F(CFS)	AVF(CFS)	AVA(FT^2)	AVW(FT)	AVD(FT)	DT(D)	SUMT(D)	DIS(FT)	VOL(FT^3)
290.990	4139.047	4139.047	2140.500	148.000	14.46284	.00032	.00032	53.	56509
290.680	4140.506	4139.926	3406.283	238.667	14.27214	.01449	.01480	1637.	5242970
289.940	4143.990	4142.421	4209.092	289.333	14.54755	.04566	.06046	3907.	16349925
288.660	4179.015	4176.232	4555.556	412.125	11.05382	.08496	.14542	6758.	30771886
287.230	4185.747	4182.529	5104.636	316.364	16.13534	.10559	.25101	7550.	38219178
286.250	4190.360	4188.748	11985.575	1007.339	11.89825	.15986	.41086	5174.	59383008
286.210	4190.549	4190.549	1348.500	707.000	1.90736	.00137	.41223	211.	1080805
285.820	4192.385	4191.961	1351.925	524.000	2.58001	.00619	.41842	2059.	2495402
285.330	4194.691	4194.244	4094.775	697.000	5.87486	.01996	.43838	2587.	7794044
284.390	4199.116	4197.017	5339.990	510.600	10.45826	.07281	.51118	4963.	26424171
284.010	4200.905	4200.089	5777.017	648.333	8.91057	.03122	.54241	2006.	11370491
283.720	4202.270	4201.941	5621.000	603.000	9.32172	.02250	.56490	1531.	8491402
281.090	4214.651	4208.170	7579.487	857.867	8.83527	.29787	.86277	13886.	110474588
280.470	4217.570	4216.299	7243.200	689.750	10.50120	.06430	.92708	3274.	23574056
278.300	4227.785	4223.124	5536.346	506.214	10.93676	.17498	1.10205	11458.	64168371
278.120	4228.632	4228.632	8227.800	658.000	12.50426	.01992	1.12197	950.	7311190
277.820	4230.044	4229.621	7517.900	693.000	10.84834	.03286	1.15483	1584.	12040222
276.960	4234.093	4232.671	7951.500	1056.200	7.52840	.09641	1.25124	4541.	35385464
276.220	4283.576	4282.199	8169.312	1138.750	7.17393	.08813	1.33937	3907.	32648513
273.560	4296.098	4290.284	8030.166	727.875	11.03234	.30307	1.64244	14045.	113496033
272.900	4299.205	4297.670	7415.920	663.400	11.17866	.06948	1.71193	3485.	27008265
272.410	4936.512	4935.394	11126.537	855.250	13.00969	.06698	1.77891	2587.	28603678
272.190	4937.547	4937.547	12891.550	853.000	15.11319	.03132	1.81023	1162.	13517104
271.670	4939.995	4938.654	16181.837	1106.000	14.63096	.10192	1.91215	2746.	43696359
271.520	4940.701	4940.395	18224.525	1309.000	13.92248	.03354	1.94569	792.	14324715
270.640	4944.844	4942.720	3233.500	637.125	5.07514	.03483	1.98053	4646.	16712644
270.230	4946.774	4946.774	4350.550	449.000	9.68942	.01979	2.00032	2165.	8544357
267.090	4961.555	4953.893	4628.678	557.389	8.30422	.18084	2.18115	16579.	77523443
265.000	4971.394	4966.983	5523.360	603.000	9.15980	.14034	2.32150	11035.	60455087
263.670	4977.655	4974.454	5800.700	627.714	9.24099	.09408	2.41558	7022.	40479321
263.520	4978.361	4978.361	5140.650	518.000	9.92403	.01006	2.42564	792.	4343724
262.750	4981.986	4980.329	5875.660	584.400	10.05418	.05608	2.48172	4066.	24183731
261.580	4987.494	4984.837	5627.329	602.143	9.34550	.08110	2.56282	6178.	35122746
257.970	5004.488	4995.608	5260.526	565.421	9.30373	.23234	2.79516	19061.	101215823
256.000	5013.761	5008.836	6091.145	650.364	9.36575	.14755	2.94271	10402.	64068907
254.350	5021.529	5017.543	6083.067	679.667	8.95007	.12090	3.06360	8712.	52510000
252.970	5028.025	5024.724	7386.775	713.500	10.35287	.12417	3.18777	7286.	54013762
252.420	5030.614	5029.414	6269.375	651.000	9.63038	.04202	3.22979	2904.	18558103

MILE	F(CFS)	AVF (CFS)	AVA (FT^2)	AVW (FT)	AVD (FT)	DT (D)	SUMT(D)	DIS(FT)	VOL(FT^3)
250.010	5041.959	5036.553	7516.679	719.000	10.45435	.21879	3.44858	12725.	95643719
248.650	5048.361	5045.530	7841.450	800.571	9.79482	.12951	3.57810	7181.	56841676
247.080	5055.752	5052.208	8863.157	791.000	11.20500	.16454	3.74264	8290.	72353758
246.780	5057.164	5057.164	10988.750	930.000	11.81586	.04021	3.78284	1584.	17566243
246.750	5057.305	5057.305	255.700	600.000	.42617	.00018	3.78302	158.	890560
245.900	5061.307	5059.471	514.375	644.000	.79872	.00498	3.78801	4488.	2210683
243.730	5054.988	5056.708	1325.918	541.545	2.44840	.03293	3.82093	11458.	15322664
243.420	5054.521	5054.739	4964.650	598.500	8.29515	.01809	3.83902	1637.	7969719
242.680	5053.405	5054.068	5902.250	679.667	8.68404	.05356	3.89258	3907.	23398505
239.450	5048.533	5051.058	5835.233	616.933	9.45845	.22822	4.12080	17054.	100467802
239.170	5048.111	5048.111	8329.500	724.000	11.50483	.02765	4.14845	1478.	12065001
238.630	5255.297	5255.639	8946.833	754.333	11.86058	.05597	4.20441	2851.	25476958
236.970	5252.793	5253.965	7087.833	693.111	10.22611	.13564	4.34005	8765.	62237344
236.290	5251.768	5252.167	11492.287	958.750	11.98674	.08506	4.42511	3590.	38943498
234.300	5248.767	5250.204	8319.670	837.907	9.92911	.19563	4.62074	10507.	91732172
231.060	5243.880	5246.087	10269.676	949.723	10.81334	.32293	4.94367	17107.	151498145
231.020	5243.820	5243.820	20132.071	1323.316	15.21335	.00971	4.95338	211.	4405559
229.630	5241.724	5242.832	4273.004	833.203	5.12841	.07243	5.02581	7339.	34585982
228.850	5240.547	5241.060	5852.757	579.156	10.10566	.05316	5.07897	4118.	24104485
226.500	5237.003	5238.781	5813.617	607.158	9.57512	.15816	5.23713	12408.	71857225
224.890	5242.575	5243.751	7293.603	663.199	10.99761	.13658	5.37370	8501.	63101482
223.350	5240.252	5241.314	9202.393	566.248	16.25154	.16100	5.53471	8131.	74272021
222.660	5239.212	5239.604	6210.329	456.845	13.59396	.05348	5.58819	3643.	24602805
222.210	5238.533	5238.820	5487.929	417.847	13.13382	.02681	5.61500	2376.	12369356
220.100	5235.351	5236.830	6109.460	627.018	9.74368	.15016	5.76516	11141.	68608287
218.240	5232.546	5233.848	7085.386	722.822	9.80240	.15313	5.91829	9821.	69526708
217.340	5231.188	5231.728	7000.998	807.691	8.66791	.07423	5.99252	4752.	33587179
213.660	5225.638	5228.377	7186.636	712.130	10.09174	.30784	6.30037	19430.	140131361
211.190	5221.913	5223.731	8372.033	830.719	10.07806	.24060	6.54096	13042.	108671104
209.720	5244.696	5245.775	7899.172	655.835	12.04444	.13306	6.67402	7762.	60482306
209.360	5244.153	5244.289	7655.090	886.752	8.63273	.03248	6.70651	1901.	14798439
208.510	5260.872	5261.394	9197.346	732.131	12.56244	.08934	6.79584	4488.	40624262
205.350	5256.106	5258.455	8771.354	791.752	11.07841	.32178	7.11762	16685.	147531129
200.840	5249.304	5252.642	8056.721	698.241	11.53860	.42093	7.53856	23813.	191451639
198.530	5245.820	5247.576	9956.059	1052.707	9.45758	.24517	7.78372	12197.	113228773
197.450	5244.191	5245.041	10097.282	1053.459	9.58488	.12586	7.90958	5702.	57112561
196.660	5243.000	5243.445	10426.652	1220.142	8.54544	.09991	8.00950	4171.	45610022
190.510	5185.971	5213.195	9777.656	1105.021	8.84839	.65453	8.66402	32472.	326386968
189.040	5172.339	5178.923	12514.847	1110.483	11.26973	.21729	8.88131	7762.	98308826
188.420	5166.590	5169.032	12269.858	951.688	12.89274	.09135	8.97266	3274.	40836026

MILE	F(CFS)	AVF (CFS)	AVA (FT^2)	AVW (FT)	AVD (FT)	DT (D)	SUMT (D)	DIS (FT)	VOL (FT^3)
183.390	5119.946	5143.550	12525.583	1094.299	11.44621	.74383	9.71649	26558.	333676936
179.510	5083.967	5101.864	8978.351	913.382	9.82979	.41339	10.12988	20486.	183852091
179.400	5082.947	5082.947	15590.159	6400.787	2.43566	.01392	10.14380	581.	6834619
177.490	5065.235	5073.813	20401.694	6269.296	3.25422	.46130	10.60510	10085.	204220585
175.220	5044.185	5054.166	25187.481	7114.650	3.54023	.66152	11.26662	11986.	295526525
174.790	5040.198	5041.990	29388.549	8532.067	3.44448	.15444	11.42106	2270.	67657763
171.260	5007.464	5021.824	21280.442	5915.076	3.59766	.91631	12.33737	18638.	413434366
167.470	4972.319	4989.116	32476.400	6713.831	4.83724	1.49821	13.83557	20011.	652921375
166.550	4963.787	4966.963	10508.892	876.761	11.98605	.12561	13.96119	4858.	56605549
165.690	4955.813	4960.449	21814.689	3561.327	6.12544	.22955	14.19074	4541.	102733672
165.650	4955.442	4955.442	26561.448	4923.382	5.39496	.01371	14.20444	211.	5880965
165.060	4949.971	4951.887	32753.687	5370.751	6.09853	.23230	14.43674	3115.	100062159
164.720	4946.818	4946.818	31729.079	5101.476	6.21959	.13226	14.56900	1795.	56547854
164.240	4942.367	4944.067	28501.219	5283.276	5.39461	.17351	14.74251	2534.	79618421
163.410	4934.670	4937.869	43471.395	7017.408	6.19479	.39147	15.13398	4382.	176296022
163.160	4932.352	4932.352	23233.847	2214.846	10.49005	.09920	15.23317	1320.	49351737
162.850	4929.477	4929.477	18406.771	1666.904	11.04249	.07892	15.31209	1637.	34078681
161.950	4921.131	4925.420	10178.155	784.185	12.97928	.10373	15.41582	4752.	46435160
161.080	4913.064	4916.819	8718.914	805.903	10.81881	.09365	15.50947	4594.	39824685
160.930	4911.673	4911.673	13364.380	1035.904	12.90117	.02070	15.53017	792.	9047911
160.420	4906.943	4908.520	12484.249	998.413	12.50410	.07988	15.61005	2693.	33911767
160.030	4903.327	4905.058	9609.424	824.698	11.65205	.04783	15.65788	2059.	20406892
159.680	4901.081	4901.081	14507.485	1045.107	13.88134	.05272	15.71060	1848.	22972505
158.890	4893.756	4896.692	12325.289	648.708	18.99975	.12071	15.83131	4171.	51635851
158.480	4889.954	4891.461	13347.302	707.759	18.85854	.06838	15.89970	2165.	28936534
158.310	4888.377	4888.377	10904.606	803.013	13.57961	.02492	15.92461	898.	10585384
158.060	4886.059	4887.079	10062.472	722.544	13.92646	.03078	15.95539	1320.	13239427
156.360	4870.295	4878.656	5425.586	566.723	9.57361	.10334	16.05873	8976.	45164725
155.360	4861.022	4865.963	4607.028	562.158	8.19526	.05773	16.11647	5280.	24397204
153.350	4842.383	4852.000	5272.022	508.874	10.36018	.13330	16.24977	10613.	56189590
152.360	4833.202	4837.508	5564.209	589.440	9.43982	.06882	16.31859	5227.	28922123
151.550	4825.691	4828.798	5459.686	624.020	8.74922	.05757	16.37615	4277.	24161185
151.360	4823.929	4823.929	4533.539	538.096	8.42516	.00980	16.38596	1003.	4128933
150.350	4814.563	4819.316	4729.275	589.907	8.01698	.05898	16.44494	5333.	25050566
148.480	4797.223	4806.161	4621.514	524.066	8.81857	.10751	16.55244	9874.	44888399
147.730	4837.268	4812.555	5111.098	528.952	9.66269	.04843	16.60088	3960.	20237132
147.620	4836.248	4836.248	5298.663	544.049	9.73931	.00745	16.60832	581.	3113213
145.770	4819.093	4827.467	5358.616	608.168	8.81108	.12472	16.73305	9768.	52110650
143.590	4824.101	4821.652	5387.355	657.222	8.19717	.14881	16.88186	11510.	62020805
139.360	4834.045	4829.120	5243.043	583.022	8.99287	.27994	17.16180	22334.	117061573

```
  MILE      F(CFS)     AVF (CFS)   AVA (FT^2)   AVW (FT)   AVD (FT)     DT (D)   SUMT (D)       DIS (FT)     VOL (FT^3)
 136.060   4841.802   4837.760   4950.310    589.665    8.39512     .20592   17.36772        17424.      86369548
 132.260   4850.735   4846.284   4800.583    616.596    7.78563     .22980   17.59751        20064.      96313606
 129.590   4857.011   4853.909   4971.134    629.902    7.89192     .16694   17.76446        14098.      70100261
 126.180   4865.028   4860.971   5586.366    530.946   10.52154     .23972   18.00418        18005.     100810879
 121.340   4876.405   4870.660   6063.481    666.558    9.09670     .36022   18.36440        25555.     153465089.
 120.780   4877.722   4877.181   9460.899    960.243    9.85261     .06775   18.43215         2957.      28661178.
 119.890   4904.814   4903.844   6298.151    631.718    9.96988     .07148   18.50363         4699.      30388134.
 119.430   4905.895   4905.437   5518.952    594.520    9.28303     .03155   18.53517         2429.      13414507.
 116.570   4912.618   4909.166   5996.645    672.855    8.91224     .21344   18.74862        15101.      90704200.
 113.540   4919.741   4916.220   5902.324    714.507    8.26069     .22218   18.97080        15998.      94432016
 110.410   4927.099   4923.417   4807.945    516.458    9.30945     .18673   19.15753        16526.      79678982
 107.090   4934.903   4930.990   4676.028    499.803    9.35573     .19294   19.35047        17530.      82363086.
 103.550   4943.225   4939.274   5946.931    678.653    8.76285     .25758   19.60805        18691.     110177019
  99.700   4952.275   4947.799   6489.514    546.066   11.88413     .30900   19.91705        20328.     132277392
  98.210   4955.778   4954.156   6180.196    534.528   11.56197     .11245   20.02950         7867.      48251615
  97.400   4957.682   4956.746   6192.003    637.410    9.71432     .06273   20.09223         4277.      26968934
  93.740   4966.286   4962.277   5983.362    614.431    9.73806     .26956   20.36179        19325.     115800025.
  89.340   4976.629   4971.558   7022.318    760.787    9.23034     .37778   20.73958        23232.     162824790
  88.940   4977.569   4977.169   7622.098    687.489   11.08686     .03719   20.77677         2112.      16113441.
  85.500   5272.656   5268.539  10284.761   1099.660    9.35268     .40804   21.18481        18163.     186376650
  83.720   5276.840   5274.753  10834.328    997.947   10.85662     .22371   21.40852         9398.     102089515.
  82.160   5292.507   5290.483   9597.035    748.054   12.82933     .17634   21.58486         8237.      81012863
  82.110   5292.625   5292.625  13133.775   1023.983   12.82616     .00760   21.59245          264.       3473105
  80.010   5297.561   5295.133  11082.028    847.810   13.07136     .26803   21.86049        11088.     123011239.
  79.860   5297.914   5297.914   7037.651    734.106    9.58670     .01604   21.87653          792.       8162531.
  75.140   5309.009   5303.370   6008.375    776.287    7.73989     .32746   22.20398        24922.     150783740.
  70.890   5319.000   5313.999   6056.012    750.591    8.06832     .28956   22.49354        22440.     136174339.
  65.150   5326.854   5323.031   6107.306    806.373    7.57380     .40110   22.89463        30307.     185272565.
  60.090   5333.778   5330.294   6400.279    808.050    7.92065     .37430   23.26893        26717.     173409550.
  55.180   5340.496   5337.182   6668.141    773.047    8.62579     .37487   23.64381        25925.     173464046.
  50.210   5347.297   5343.933   7019.972    883.366    7.94684     .39758   24.04139        26242.     184148610
  45.240   5354.097   5350.616   6863.527    837.441    8.19584     .38563   24.42702        26242.     179355062.
  40.220   5360.966   5357.507   7702.307    959.197    8.02995     .44146   24.86848        26506.     204748109.
  35.220   5367.808   5364.434   7756.534   1076.425    7.20583     .43843   25.30691        26400.     204137490.
  30.130   5374.773   5371.344   9133.899   1087.282    8.40067     .52626   25.83318        26875.     244831578.
  23.440   5383.927   5379.448   6924.963    739.436    9.36519     .52745   26.36063        35323.     245871997.
  20.550   5390.881   5388.998  10190.743   1003.901   10.15115     .32874   26.68936        15259.     153989899.
  15.170   5398.243   5394.638  10476.353   1066.840    9.81999     .63692   27.32629        28406.     297836908.
  10.110   5405.166   5401.814  11662.416    901.254   12.94022     .66256   27.98885        26717.     315006680.
   4.870   5412.336   5408.747  13115.945   1153.333   11.37221     .77585   28.76470        27667.     362776550.
    .000   5419.000   5415.567  17468.641   1097.722   15.91354     .96821   29.73291        25713.     454301259.
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