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A PROCEDURE TO DETERMINE
DIRECT DIVERSIONS FROM
LAKE MICHIGAN

by

James W. Male* and Karim Soliman**
Department of Environmental Engineering
Illinois Institute of Technology
Chicago, IL 60616

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2535 Hydrosystems Laboratory
Urbana, Illinois 61801

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*Now at Department of Civil Engineering, University of Massachusetts, Amherst, MA 01003.

**Now with Flour Pioneer, Incorporated, Chicago, IL 60606.

ABSTRACT

A PROCEDURE TO DETERMINE DIRECT DIVERSIONS FROM LAKE MICHIGAN

Illinois diverts water from Lake Michigan to the Chicago River and Canal System in three primary ways: (1) diversions for municipal water supply, (2) storm water diverted away from the lake, and (3) direct diversions primarily for water quality purposes. The U.S. Supreme Court has ruled that the total average diversion must not exceed 3200 cfs. Since the stormwater diversion is uncontrollable, by reducing the amount necessary for direct diversion, the diversion available for municipal use can be increased.

An optimization procedure, utilizing an efficient network algorithm, is developed to determine the average monthly flowrates at the three diversion points on Lake Michigan. The algorithm minimizes the total amount diverted that is necessary to maintain the dissolved oxygen standard in the waterway system. The procedure is applied to evaluate direct diversion needs under existing conditions and after installation of ten instream aeration stations. Results show the need for large diversions during the summer months and primarily at one diversion point. The installation of instream aerators reduces the need for direct diversions by approximately 25 percent.

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INTRODUCTION

Multipurpose intentions for the nation's water resources have often created problems due to their different and often conflicting characteristics. Various water resource projects can be used for several purposes, including municipal water supply, recreation, navigation, wastewater disposal, flood control, hydroelectric power and irrigation. However, problems arise when one water body is used for conflicting goals, such as recreation and wastewater disposal.

BRIEF BACKGROUND

The Chicago River and Canal System is an example of a natural water resource modified by man to serve several purposes. The waterway system is operated with the intention of managing floods, providing navigable waterways, providing a receptacle for treated waste disposal, and maintaining a certain water quality in consideration of health and aesthetic concerns.

The waterway system, prior to its modification, consisted of the Chicago and Calumet River basins, emptying into Lake Michigan. Modification of the system involved the construction of three canals enabling controlled interbasin transfer of water, at three different locations, from the Lake Michigan Watershed to the Mississppi Watershed.

These diverted waters help satisfy conflicting requirements for municipal water supply, navigation, and the maintenance of water quality in the waterway system. However, the U. S. Supreme Court severely restricted the total amount of water that can be diverted by the state of Illinois from Lake Michigan. Because of expanding requirements for municipal water supply and the limit on total diversion, the amount of water remaining to maintain surface water quality standards has been severely reduced.

The characteristics of the Chicago River and Canal System allow significant human control over the allocation of streamflows in the various tributary channels. Through judicious management of the waterway system, the adverse impact of restricted use of lake water on the water quality of the river and canal system can be minimized.

NEED FOR A DIRECT DIVERSION POLICY

The constraint on lake water diverted by Illinois includes all water diverted from the Lake Michigan Watershed. This includes municipal water supply and diverted runoff, in addition to the direct diversions. Projected demands for treated lake water are high because of the continued demand for municipal water by Chicago and many surrounding communities. The suburban demand has resulted from a steadily decreasing availability of groundwater, upon which many of the suburban municipalities rely.

Current dissolved oxygen (DO) levels are often substandard, and during summer months, some sections of the waterway system are anaerobic. Proper allocations of lake water diversions in conjunction with remedial measures will allow maintenance of the DO standard. Use of lake water for dilution purposes however, eliminates its use for domestic purposes.

There is a great need to determine how much water should be diverted directly into the river and canal system to upgrade its water quality. These diversions should be the minimum necessary, in order to allow the maximum amount to be used for domestic purposes. A mathematical optimization procedure which minimizes the direct diversion necessary to maintain proper water quality, would aid in the formulation of an overall diversion policy for the state of Illinois.

This report describes an optimization procedure which determines the minimum direct diversion necessary to maintain dissolved oxygen standards in the stream. While determining the minimum total direct diversion, the procedure allocates the diversions both temporally and geographically, allowing a decision maker to specify the monthly average diversion at each of the three diversion points.

The use of an optimization procedure will also allow rapid determination of the diversion under varying conditions. Changes in the physical characteristics of the streams can easily be incorporated. In addition, various plans to upgrade aspects of the system can be incorporated in the procedure.

RELATED RESEARCH

Numerous studies have used mathematical modelling to aid in the management of water resource systems. The earliest was the development by Streeter and Phelps (1925) of the dissolved oxygen sag curve. Although dissolved oxygen is only one measure of surface water quality, it has been used as parameter because: (1) DO is accepted as a principal indicator of stream quality, (2) it is easily determined in the field, and (3) the modified Streeter-Phelps equation has been shown to be reasonable for describing the DO concentration in streams.

Several studies have used optimization procedures in conjunction with the dissolved oxygen sag curve to aid in water quality management decisions, including Thomann (1965), Deininger (1966), Liebman and Lynn (1966), Meier and Beightler (1967), ReVelle, Loucks, and Lynn (1967, 1968), Anderson and Day (1968), Dysart (1970), and Shih (1970). In most cases the flowrate was known and assumed constant, and the management decisions involved waste discharge allocations. In addition, optimization procedures have been applied to low flow augmentation and its effects on dissolved oxygen concentrations, as reported by Worley, Burgess and Towne (1965) and Rogers and Gemmel (1966).

The Chicago River and Canal System has been the subject of several studies concerned with both specific water quality aspects and the effect the system has on overall water use in northeastern Illinois.

The specific aspects of water quality determination and prediction have been the subject of several reports by the Illinois State Water Survey. Butts, Kothandaraman, and Evans (1973) discussed practical considerations for computing the waste assimilative capacity of Illinois streams and stated that the net effects of benthal deposits, photosynthesis, and BOD removal by sedimentation could be included in a mathematical formulation by calibration.

Butts (1974) presented a study on waste allocation for selected streams in the state of Illinois. The study was prepared for the Illinois Environmental Protection Agency and included the Calumet River Basin, the Chicago River, and the DuPage River Basin. A simplified computer simulation was presented that included values for sludge (benthal) oxygen demand (SOD) and oxygen production by photosynthesis. An additional study (Butts, Evans, and Lin 1975) on the water quality features of the upper Illinois River concluded that the DO concentration can be greatly influenced by the presence of sludge benthic deposits, algal growth, presence of locks and dams, and water circulation by power plants.

Mathematical simulation models have been used as a basis for planning on the river and canal system. Considerable research has been conducted by the Metropolitan Sanitary District of Greater Chicago (MSDGC) on an in-house basis. Macaitis, Povilaitis, and Cameron (1974, 1977) present results from a computer program designed to calculate the necessary discretionary diversions for dry weather days. Their model is based on the Streeter-Phelps equation, allowing both conservative and nonconservative pollutants. The model was used to analyze three capital improvements scheduled by MSDGC: instream aeration, upgrading of sewage treatment plants, and Phase I of the Tunnel and Reservoir Plan. (The capital improvements are described in Chapter II). The average yearly discretionary diversions necessary to maintain the water quality standards after the anticipated improvements were reported as:

Conditions	Discretionary Diversion in cfs
Existing (1975)	2550
Instream Aeration	370
Tertitary Treatment	320
Phase I TARP	0

Macaitis (1974) utilized the same model to further study the capabilities of instream aeration. The report points out the limitations of instream aeration during wet periods when combined sewers overflow into the waterway system.

A study similar to the MSDGC project was performed by Harza Engineering Company (1976) for the Division of Water Resources of the Illinois Department of Transportation. The objective again was to determine the discretionary diversion necessary to maintain water quality standards. QUAL-II (Norton et al. 1974) was used as the basis for development of a mathematical model for the river and canal system both above and below Lockport. The study emphasized the importance of carbonaceous BOD and benthic deposits. Results of the analysis for the section above Lockport are summarized below for the sequence of improvements proposed by MSDGC:

Conditions	Direct Diversion in cfs
Existing	2060
Instream aeration	660
TARP-Phase I	420
Nitrification	420
TARP-Phase II	310

It should be pointed out that these numbers represent direct diversions and therefore include lockage and leakage.

The Department of Transportation also contracted with Keifer and Associates, Incorporated, to provide an overall evaluation of water use in northeastern Illinois (Keifer and Associates, Inc. 1976). Part of the project included the study of the potential reduction in the use of dilution water. The Haza and MSDGC findings were reported and compared, but no additional discretionary diversion studies were performed. Potential reductions in lockage and leakage were estimated and included a variety of measures to minimize leakage and lower the number of watercraft using the locks. The existing and estimated lockage and leakage are shown in Table 1. The study concluded that the direct diversions necessary to maintain water quality standards would gradually diminish because of the proposed improvements. As a result, the lockage and leakage will become a major part of the direct diversions.

Table 1

Existing and Estimated Minimum Lockage and Leakage
(Kiefer and Associates, Incorporated 1976)

Existing Lockage and Leakage for	Winter	Spring	Summer	Fall
Wilmette	46	46	46	46
Chicago River	64	135	157	92
O'Brien Locks	51	112	154	76

Estimated Minimum Lockage and Leakage for	Winter	Spring	Summer	Fall
Wilmette	5	5	5	5
Chicago River	39	62	57	51
O'Brien Locks	51	58	58	53

THE STUDY AREA

THE CHICAGO RIVER AND CANAL SYSTEM

The Chicago River and Canal System is a unique waterways network which was developed over the years to meet specific needs of the Greater Chicago Metropolitan area (see Fig. 1). The Chicago River (North and South Branch) originally flowed into Lake Michigan, but in the early part of the century the flow of the river was reversed by means of a channel leading to the Des Plaines River, which eventually empties into the Mississippi River. This channel, called the Chicago Sanitary and Ship Canal, leads from the South Branch of the Chicago River and allows the city to dispose of wastes without contaminating Lake Michigan, which acts as the city's water supply. Two other channels were subsequently added which also connect the river system with Lake Michigan. The Calumet Sag Channel was constructed from the Calumet River on the south end of Lake Michigan to the Sanitary and Ship Canal. The Calumet Sag Channel also allowed the flow to be reversed in the Calumet River and therefore drained water from Lake Michigan. The North Shore Channel draws water from Lake Michigan in Wilmette, north of Chicago. The channel empties into the North Branch of the Chicago River and contributes to the flow which eventually reaches the Des Plaines River.

Flow into the river system from Lake Michigan is controlled by locks and sluice gates at both the Chicago River Controlling Works and the O'Brien Controlling Works located on the Calumet River, and by pumping rates at Wilmette Harbor. Capacities of the three diversion points determine the maximum flow into the waterway system. At Wilmette the maximum flow is 700 cfs; at the Chicago River Controlling Works, 5508 cfs; and at O'Brien Locks, 3560 cfs; for a maximum diversion of approximately 10,000 cfs

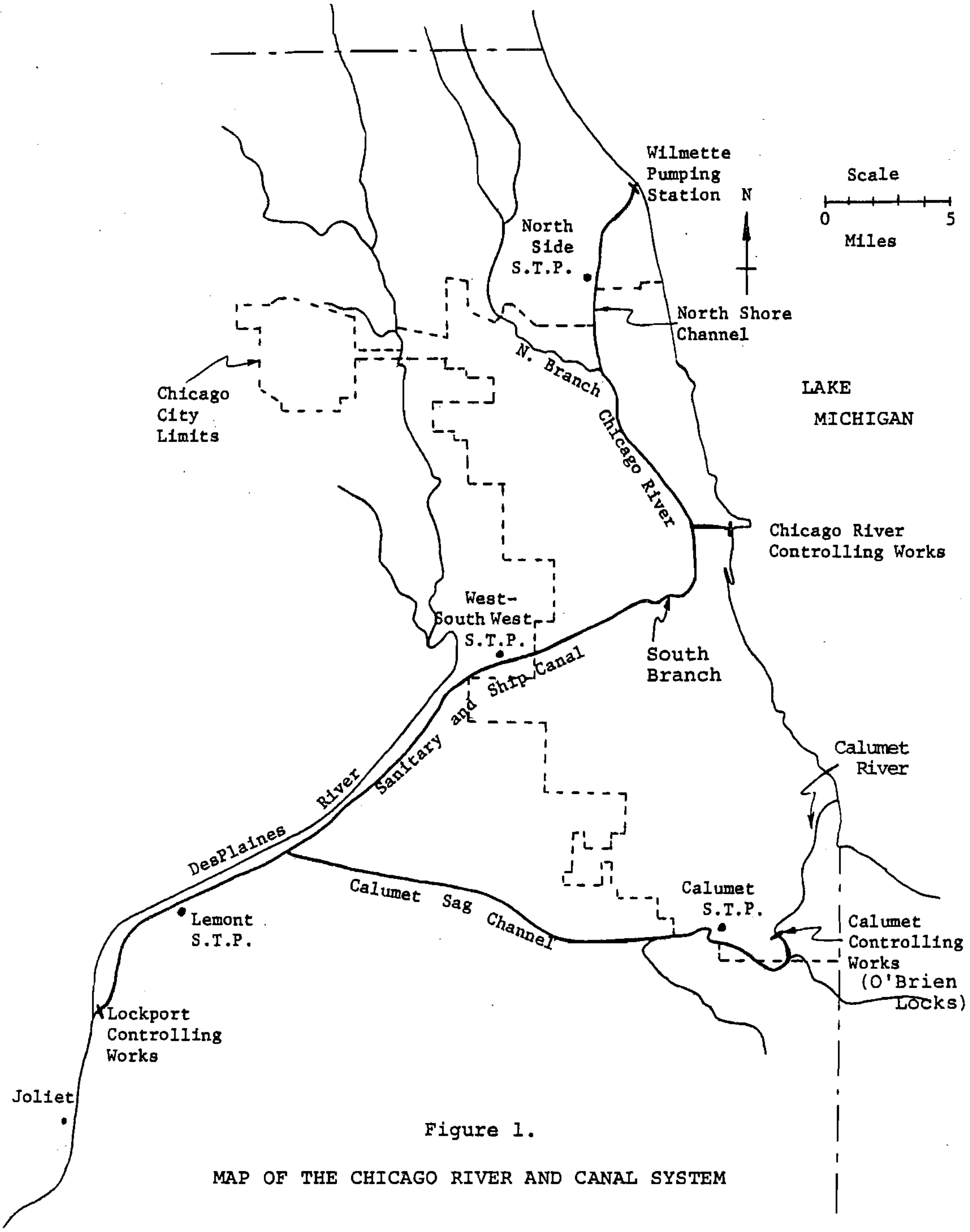


Figure 1.

MAP OF THE CHICAGO RIVER AND CANAL SYSTEM

(Metropolitan Sanitary District of Greater Chicago, 1976).

Flow leaving the system is controlled by lock and sluice gates at the Lockport Controlling Works, located near Lockport, Illinois (35 miles southwest of Lake Michigan). The controlling works regulate flow into the Des Plaines River.

Water flowing through the three diversion points is termed direct diversion and is attributed to (1) leakage at the sluice gates and Wilmette pumps, (2) lockage for watercraft at the Chicago River and O'Brien Locks, (3) a small amount of navigational makeup water, and (4) dilution water to help maintain water quality. The lockage, leakage, and navigational makeup water are considered fixed and termed nondiscretionary while dilution water is considered discretionary. Both nondiscretionary and discretionary diversions provide relatively good quality dilution water, but only the discretionary portion can be varied in response to prevailing water quality conditions.

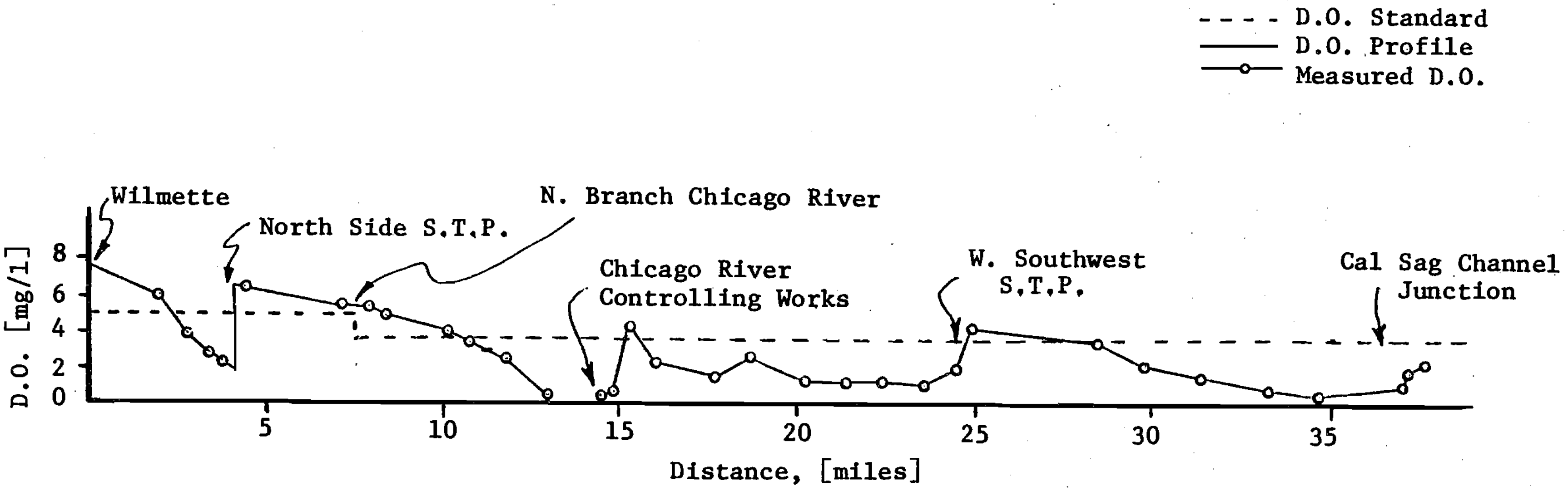
In addition to the discretionary and nondiscretionary direct diversions at the three controlling works, is the water diverted for Chicago's municipal water supply and storm runoff diverted from the Lake Michigan watershed. The total diversion from Lake Michigan, therefore, includes direct diversions, municipal water supply, and stormwater runoff. Storm runoff constitutes the major uncontrolled inflow into the waterway. More will be said about runoff collected in combined sewers in conjunction with the sewage treatment plants.

Three major sewage treatment plants contribute effluent to the river and canal system. The North Side Sewage Treatment Plant (350 MGD) effluent flows into the North Shore Channel. The Sanitary and Ship Canal receives effluent from the West Southwest Sewage Treatment Plant (870 MGD), and the Calumet Treatment Plant (210 MGD) effluent flows into the Calumet River above its junction with the Cal Sag Channel. Each of these plants provides a high degree of treatment, generally around 85-90 percent removal of BOD. Chicago, however, has a combined sewer system and therefore the treatment plants cannot treat the large flow volumes which accompany major storms in the area. In such instances the treatment plants are bypassed and effluent is discharged directly to the waterways system after chlorination. These discharges occur on the average of once in every four or five days. Such intermittent loadings contribute greatly to the poor water quality of the river and canal system in two ways. The first is the oxygen depletion due to the high concentration of BOD in the waste. More important, however, are the resulting benthic deposits which continue to demand oxygen after the periodic discharges of waste.

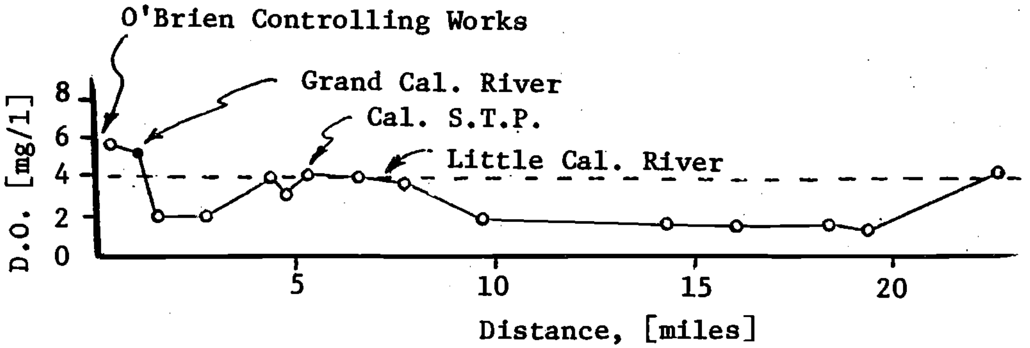
Current dissolved oxygen levels are often substandard, and during summer months some sections of the waterways system are anaerobic. Figure 2 shows a typical summer dissolved oxygen profile (August 8, 1973). Proper allocations, in conjunction with remedial measures will allow maintenance of the dissolved oxygen standard.

REGULATIONS

Several statutes govern the operation of the Chicago River and Canal System, including the maintenance of navigable waterways, the maintenance of water quality standards, and a restriction on water diverted from Lake Michigan.



North Shore Channel and Chicago River



Calumet Sag Channel

Figure 2. Dissolved Oxygen Profile (Illinois State Water Survey 1974)

Navigation

Title 33 of the Federal Code of Regulations defines the elevations to be maintained for navigation in both the Chicago River and O'Brien Controlling works. Water levels must remain between -2.0 feet CCD (Chicago City Datum) and -0.5 CCD, except during times of storm runoff or low lake levels. If the lake level falls below -1.5 CCD then river levels at these locations are to be kept 0.5 feet below the lake level. Again during times of heavy storm runoff this constraint is relaxed.

Water Quality

The Water Pollution Regulations of Illinois (1973) designate three different standards for the Chicago River and Canal System, depending on the section of the system in question. The North Branch of the Chicago River above its confluence with the North Shore Channel falls into the general use category and must maintain dissolved oxygen (DO) levels not less than 6.0 mg/l during at least 16 hours of any 24-hour period, and not less than 5.0 mg/l at any time. The North Shore Channel must maintain DO levels not less than 5 mg/l during 16 hours of any 24-hour period and not less than 4 mg/l at any time. The remainder of the system falls into the restricted use category which prior to December 31, 1977, required DO levels to be not less than 3.0 mg/l during at least 16 hours in any 24-hour period nor less than 2.0 mg/l at any time. Effective December 31, 1977, the restricted use DO standard was raised to 4 mg/l at all times.

Diversion Restriction

Effective March 1, 1970, the U. S. Supreme Court ruled that the State of Illinois is restricted to a total diversion from the Lake Michigan Watershed of 3,200 cfs, on an annual average. The ruling allowed the use of a five-year accounting period but restricted average flow to no more than 3,520 cfs in any one year. The ruling resulted from a suit brought by the other states bordering the five Great Lakes and was initiated during the middle 1960's,when lake levels were extremely low. However, in the years following the ruling lake levels were exceptionally high, resulting in extensive shore erosion. Consequently, with the passage of the Water Resources Development Act of 1976, Illinois was allowed to divert up to 10,000 cfs. However, the problem of allocating the water is only slightly lessened. The increase is allowed for a trial five-year period, only when lake levels are above the historical average, and when there is no threat of downstream flooding. There is still a great need for an operating policy which will satisfy the various constraints on the waterways system.

Allotment of Diverted Water

On April 29, 1977, the state of Illinois announced new allocations of the available diversion water (Illinois Department of Transportation 1977). Of the 196 communities applying for lake water for municipal use, 43 were denied allocations. In addition, 320 cfs was allocated for discretionary diversion. Table 2 shows the origin of this amount.

Table 2. Allotment of Lake Michigan Water for Discretionary Diversion, in cfs*

	Spring	Summer	Fall	Winter	Annual Average
Wilmette	55	101	55	0	
Chicago River	0	753	18	0	
O'Brien Locks	0	293	3	0	
TOTAL	55	1147	76	0	320

*Source: (Illinois Department of Transportation 1977).

The numbers in Table 2 were based on the results of the studies by MSDGC (1974) and Harza Engineering Company (1976). The Illinois Department of Transportation (IDOT), responsible for the allocations, used parts of both studies in their determination. Their reasoning was based on the fact that, although the procedures used by both were similar, in many cases input data varied considerably. IDOT used the results from the sections of the studies they thought were based on the most accurate data.

CURRENT PRACTICE

Operation of the Chicago River and Canal Systems is under the jurisdiction of the Metropolitan Sanitary District of Greater Chicago. MSDGC regulates the flows in the waterways system with several considerations in mind, including the navigation requirements, water quality standards, federally imposed flow regulations, and flood control. Neglecting storm runoff, the water levels are maintained as high as the navigational and streamflow regulations will permit, in order to increase the dissolved oxygen level of the system. Because of higher DO levels during colder weather, the average monthly flows are usually higher during summer months.

In order to prevent flooding as a result of heavy storm runoff, the MSDGC lowers the water level at the Lockport Controlling Works and ceases diversions from Lake Michigan. Reduction of the water level prior to a storm is performed on the basis of rainfall predictions. Water levels are lowered significantly below the navigation standard before the onset of a severe storm and generally rise above the standard following it. Occasionally, high levels in the waterway system necessitate discharging water back into Lake Michigan at the Chicago River Controlling Works. This discharge takes place when high water levels threaten flooding of low elevations.

For the years 1971 through 1976 direct diversions have averaged 777 cfs. The values during the last three years of this period, however, were substantially below this average. Table 3 shows the direct diversions in relation to the total water diversion.

Table 3. Lake Michigan Diversions by Illinois, cfs*

Type of Diversion	1971	1972	1973	1974	1975	1976
Direct Diversion	726	1322	958	640	541	475
Storm Runoff	679	157	857	774	888	977
Domestic Pumping	1677	1657	1652	1699	1670	1658
TOTAL:	3082	3154	3467	3113	3099	3110

*Source: The Metropolitan Sanitary District of Greater Chicago, Maintenance and Operation Annual Report (1975, 1976).

FUTURE IMPROVEMENTS

The Metropolitan Sanitary District of Greater Chicago has proposed a sequence of capital improvements for the waterway system. The projects will have significant impact on the water quality of the river and canal system and therefore reduce the necessary direct diversion.

Instream Aeration

The project currently under construction is the installation of ten instream aeration stations. These aerators will be placed at critical areas throughout the system as shown in Table 4. Each of the diffused air stations is anticipated to raise the DO concentration to within 90 percent of the saturation concentration (Macaitis, Povilaitis, and Cameron 1977).

Tertiary Treatment

The three major wastewater treatment plants will be upgraded to provide tertiary treatment by providing both filtration and nitrification. The

Table 4. Location of Aeration Stations*

Aeration Station	Milepoint**
North Shore Channel:	
A	334.8
North Branch Chicago River :	
B	328.8
Ship and Sanitary Canal :	
C	325.6
D	313.6
E	302.2
Cal Sag Channel:	
F	324.0
G	319.5
H	316.0
J	311.0
K	308.5

*Personal Communication, Thomas M. Edwards,MSDGC

**Mileages are referenced from Grafton.

improvements are not expected to have a significant effect on the water quality above Lockport, however, since the current effluent concentrations are fairly low. In addition, the travel times to Lockport are generally shorter than the time for nitrogenous BOD exertion.

Tunnel and Reservoir Plan

The most ambitious project involves the construction of 125 miles of large diameter tunnels to act as a reservoir for combined sewer overflow. The Tunnel and Reservoir Plan (TARP) will effectively control the combined sewer wastewater currently overflowing into the waterways when stormflows exceed treatment plant capacities. The overflow will be stored and gradually pumped to expanded wastewater treatment plants. The project has been divided into two phases with completion of Phase I expected in 1982. Implementation of the plan will eliminate not only contamination immediately following overflows but also the continuing effect of benthic deposits resulting from the overflows.

SOLUTION PROCEDURE

The procedure developed in this chapter determines the minimum average monthly diversions necessary to maintain water quality standards. The formulation of the solution procedure is accomplished in two basic steps. The first is the development of an expression to predict the DO concentration for various sections of the waterway, given certain flow rates. The DO profiles are calculated using the Streeter-Phelps equation. The second step is to utilize the DO equation to tabulate possible DO concentrations resulting from different diversion values for various sections of the waterway. The flow and DO concentration values are incorporated into a network, or matrix, in such a way that the links in the network represent diversion values and the nodes represent discrete DO concentrations. Once the network is established, an efficient network algorithm is applied to determine the minimum total diversion. To represent the different monthly conditions, the optimization is run 12 times.

The steps for determination of one month's diversion are detailed in the following sections.

SECTIONING THE WATERWAY SYSTEM

To model the system, the river and canal network was divided into four sections with each section subdivided into reaches. Locations of the 11 reaches are tabulated in Table 5 and shown schematically in Figure 3. The small segment of the mouth of the Chicago River was ignored in the sectioning and the inflow at the Chicago River Controlling Works was assumed to be at the junction of the North and South branches.

The four sections were established to correspond to segments of the waterway affected by certain diversions. In other words, if Q_1, Q_2 and

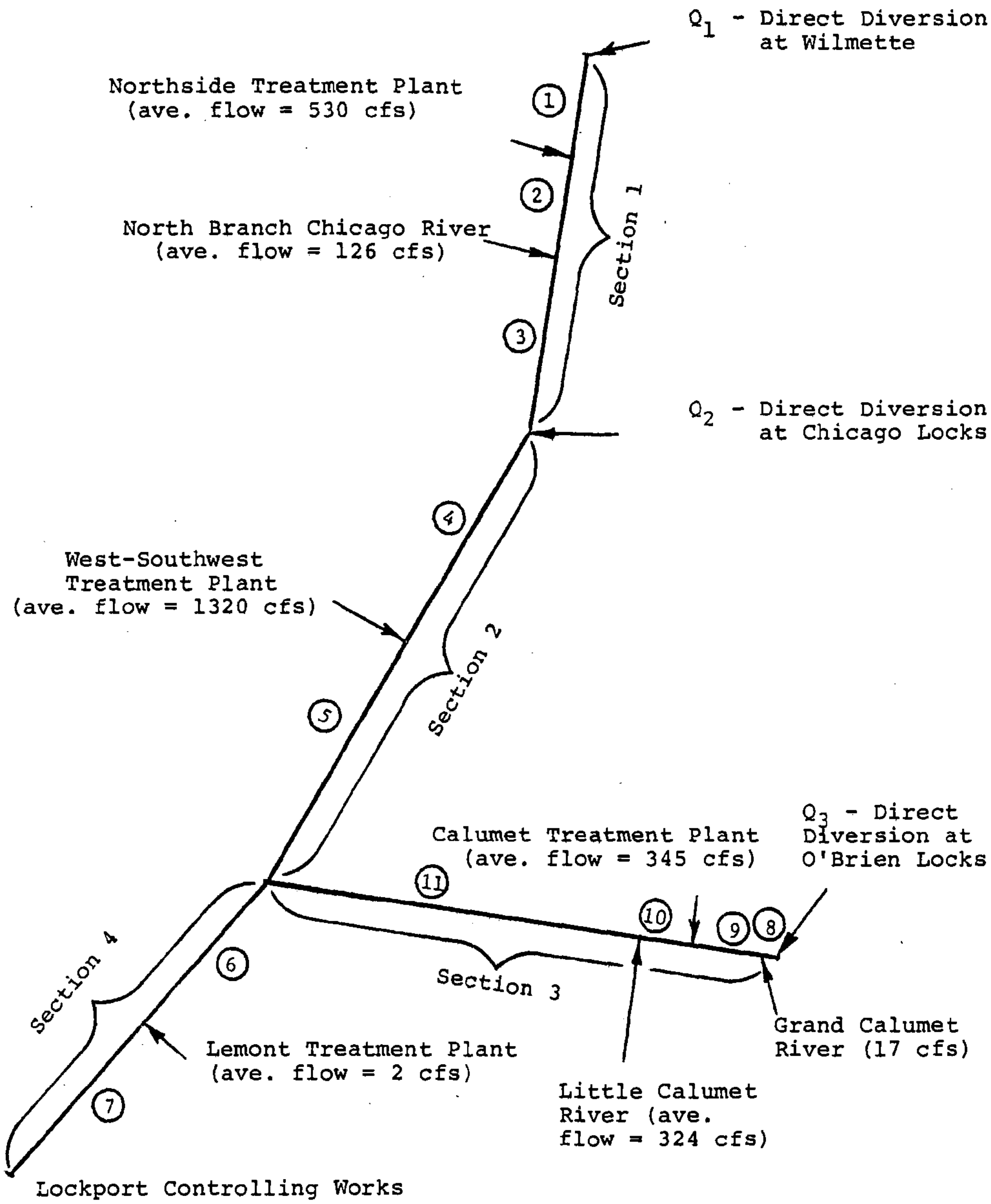


Figure 3.
Schematic Diagram of Chicago River and Canal System
(Ave. flows from 1973 data)
(Circled numbers represent reach numbers.)

Table 5. The Four Sections of the Chicago River and Canal System

Section Number	Section Start and End Points	Reaches Within Section
1	Wilmette Pumping Station-Chicago River Controlling Works	1, 2 and 3
2	Chicago River Controlling Works-Calumet Sag Junction with main channel	4 and 5
3	O'Brien Controlling Works-Calumet Sag Junction with main channel	8, 9, 10 and 11
4	Calumet Sag Junction with main channel-Lockport Controlling works	6 and 7

Q_3 represent the diversions at Wilmette, the Chicago River and O'Brien Locks respectively, and assuming all other parameters are constant, then varying Q_1 will affect the DO concentration in section 1 and Q_1 and Q_2 will affect the concentration in section 2. Likewise varying Q_3 will affect the DO concentration at any point in section 3, and Q_1, Q_2, and Q_3 will all impact the concentration in section 4.

Reaches within each section were designated whenever significant changes in the river depth, cross-sectional area, deoxygenation coefficient, or flow occurred. In all but one case (reach 7), each started at the discharge of a tributary or a wastewater treatment plant, or at a point of diversion from Lake Michigan. Reach 7 accommodates a change in cross-sectional area. Although it also coincides with the Lemont Treatment Plant, the small flow contributed by the plant was not incorporated. Detailed physical characteristics of the reaches are listed in Appendix A. When utilizing the solution procedure to evaluate the effect of the instream aeration stations, ten additional reaches were added, each beginning with an aeration station. Appendix F lists the characteristics with the addition of these reaches.

MATHEMATICAL EXPRESSIONS

DO concentrations in the sections of the waterway system are calculated on the basis of the Streeter-Phelps equation:

$$DC_t = \frac{K_1 L_o}{K_2 - K_1} \left(e^{-K_1 t} - e^{-K_2 t}\right) + DC_o \left(e^{-K_2 t}\right) \qquad (1)$$

where:

DC_t = dissolved oxygen deficit at time, t, [mg/l]

L_o = concentration of organic matter at t = 0, [mg/l]

K_1 = coefficient of deoxygenation, [days^{-1}]

K_2 = coefficient of reaeration, [days^{-1}], and

t = time of travel, [days]

In this equation, no specific term is incorporated to account for the sludge oxygen demand present in certain sections of the river and canal system. Instead, the SOD is incorporated into the deoxygenation rate constant based on the procedure used by Butts (1974) for determining the values of K_1. In equation (1), K_2 is calculated using (O'Connor and Dobbins 1956):

$$K_2 = \frac{(D_M \; V)^{1/2}}{2.303 \; H^{3/2}} \qquad (2)$$

where:

H = average depth in reach, [ft]

D_m = molecular diffusivity of oxygen in water @ 20°C, [ft^2/day], and

V = stream velocity, [ft/day]

The dissolved oxygen concentration is determined by subtracting the deficit from the saturation concentration, determined by (Committee on Sanitary Engineering Research 1960):

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

where

T = water temperature, [^oC.]

The deoxygenation and reaeration coefficients also depend on temperature and are corrected using the following formula:

$$K_T = K_{(20^oC)}\theta^{(T-20)} \qquad (4)$$

θ = 1.0241 for K_2,

θ = 1.047 for K_1, and

T = water temperature, [^oC.]

Degradation of biochemical oxygen demand (BOD) was calculated using a first order decay:

$$L_t = L_o\, e^{-k_1 t} \qquad (5)$$

Travel times to the end of a reach were determined using the flow rate, cross-sectional area, and length of the reach. The critical time (time to the maximum DO deficit) was determined by:

$$t_c = \frac{1}{K_2 - K_1} \quad \ln \frac{K_2}{K_1} \left[1 - \frac{(K_2 - K_1)DC_o}{K_1 L_o} \right] \qquad (6)$$

The BOD exertion by benthic deposits, or sludge oxygen demand (SOD) was studied extensively by Butts (1974). SOD values are reported for certain areas of the waterway; specifically in the North Shore Channel above the North Side Treatment Plant and in the North Branch of the Chicago River just below the North Shore Channel inflow. The benthic deposits tend to occur where low streamflows allow sedimentation. These locations agree with Velz's (1970) observations that velocities above 0.6 ft/sec scour deposits.

It is assumed that the effect of nitrogenous deoxygenation is insignificant and is neglected. The assumption is based upon the fact that nitrogeneous deoxygenation effects are noticeable approximately ten days after introducing organic loads to the river system. Generally, the longest travel time for this model is less than ten days.

In each section, the DO concentration at two points is of prime concern: the point where the critical deficit occurs and at the end of the section. The critical deficit is important to determine whether the DO standard is violated or not. The concentration at the end of the section is used to calculate the initial conditions at the beginning of the next section.

The DO profile for the entire section is made up of individual profiles for the reaches comprising the section. For each reach, initial conditions are calculated by mass balance and assumed to be completely mixed. Flow rate and temperature are assumed constant throughout the reach. BOD degrades according to equation (5) and the DO concentrations are determined using equations (1) through (4).

For each monthly period the only nonconstant inputs affecting the DO concentration are Q_1, Q_2 and Q_3, the diversion rates at the head of sections 1, 2 and 3. Therefore, for each section, the resulting DO concentration will depend on the flowrate into the head of the section. This flowrate will depend on different factors, depending upon the section, but will be a function of one or more diversions plus a constant (average monthly) tributary inflow. For example, the flow at the beginning of section two will depend on Q_1, Q_2 and constant tributary flows into section one.

Varying the diversion flow rates will affect the DO profile by either raising the DO concentrations for a high flow rate (more dilution water) or vice versa. The results of the calculation can be shown in graphical form and are illustrated in Figure 4a. In this case the effects of five possible diversions are shown, each with the same initial conditions (DO, temperature and BOD). Each possible diversion results in a different DO curve and therefore different critical and end values of DO.

Given this configuration, there are three possible outcomes of a diversion. First, the DO concentration of the end of the section and all points in between are greater than the minimum DO standard. Second, the DO concentration at the end of the section is in violation of the DO standard and third, the end DO concentration is not in violation of the standard, but the critical deficit occurs before the end of the section and does violate the standard. The first case is shown by the upper three curves in Figure 4a. The second and third cases are shown by the curves labeled "20 cfs" and "40 cfs" respectively.

FORMULATION OF NETWORK STRUCTURE

The network developed in this section consists of nodes representing the DO concentration at the end of each stream section, and arcs representing the appropriate diversion value resulting in that concentration. To exemplify the procedure used in the development, a portion of the network is shown in Figure 4b. This section of the network corresponds to the DO curves in Figure 4a. Node 18 in Figure 4b represents a discrete DO concentration

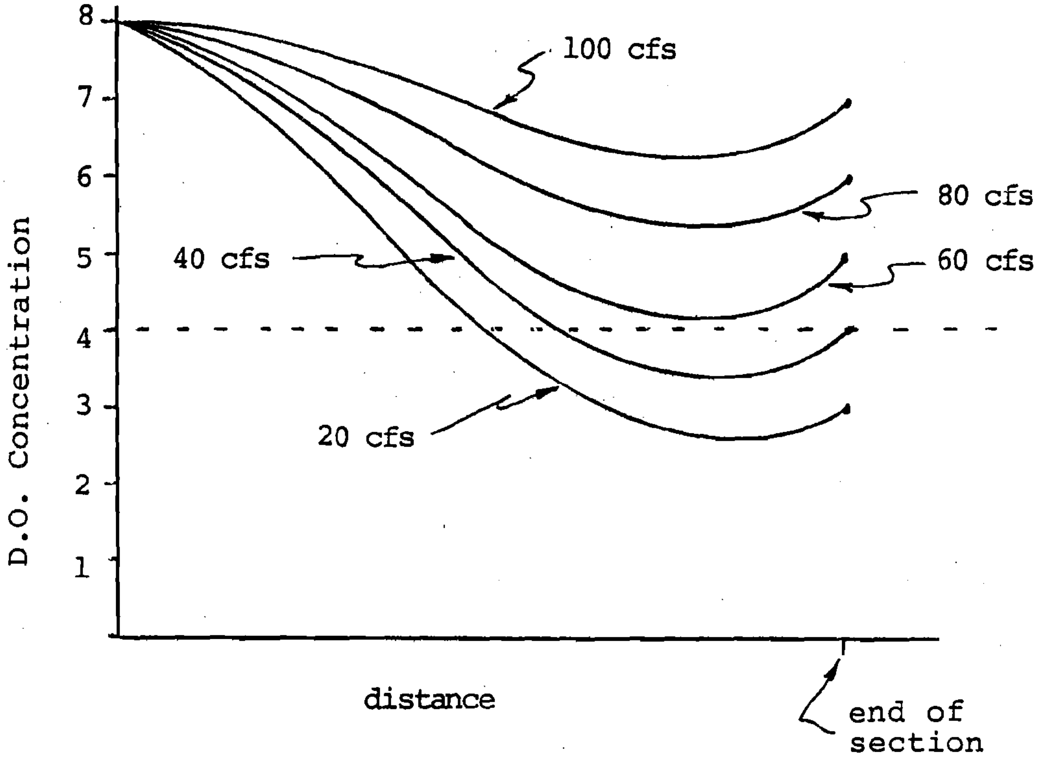


Figure 4a. Dissolved Oxygen Profiles

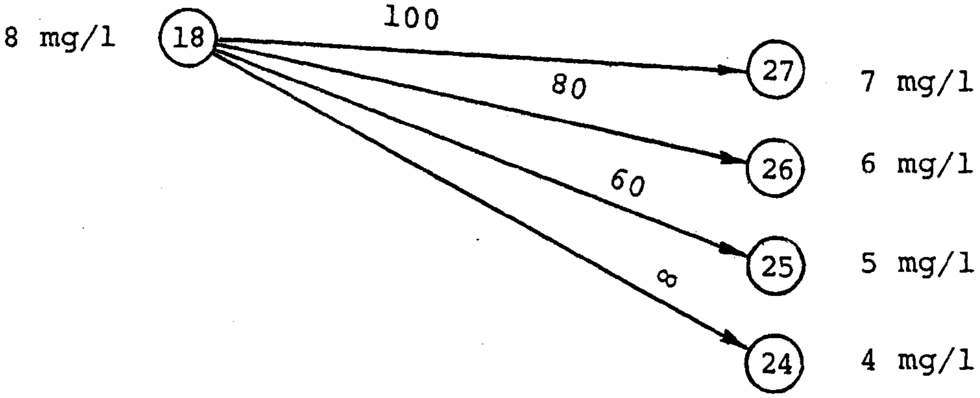


Figure 4b. Network Representation

Figure 4. Conversion from a Graphic to Network Representation

at the beginning of a section of the waterway system. Nodes 24, 25, 26, and 27 represent discrete DO concentrations at the end of the section resulting from specific diversion values at the beginning of the section. The actual value of the diversion is recorded as the value of the arc between node 18 and the appropriate resulting node. Therefore, the value of arc 18-26 equals the diversion (80 cfs) at the beginning of the section resulting in a DO concentration (6 mg/l) at the end of the section, given an initial DO concentration (8 mg/l).

The diversion value is most often not the only flow in the river section. In most cases flow will enter from an upstream section, tributary, or treatment plant and for all cases the total flow is used in the calculations. However, all flows except the diversion are constant for the initial node, and therefore only the diversion value is shown in the network.

The arcs and nodes in the network in Figure 4b reflect the three possible outcomes outlined at the end of the previous section (and shown in Figure 4a). In the first case the arc is included as described. In the second case no node exists representing a DO concentration below the standard, therefore no arc can be created. For the third case, an arc does exist between the two appropriate nodes, but it is given a value of infinity, representing an infeasible possibility because the DO standard has been violated.

This process can be repeated for different discrete values of initial DO (different initial nodes) to determine DO concentrations resulting from different diversions. Consequently, for each section, a range of possible DO concentrations (nodes in the network) can exist at both the beginning and end of the section. The beginning concentrations depend on circumstances above the section in question. The end concentrations depend on the initial concentration (node at the beginning of the section) and the flow rate through the section. The flow rate is in turn the sum of the flow from upstream section(s) and the diversion into the section (the value on the arc in the network). This expanded network is illustrated in a simplified manner in Figure 5, where the first column of nodes represents possible DO concentrations at the beginning of the section and the second column represents possible resulting DO concentrations.

The arcs are included on the basis of equations (1) through (4). For example, if the DO concentration at the beginning of the section was 6 mg/l, a range of diversions from 20 to 200 cfs can be used to calculate the DO concentrations at the end of the section. If the concentration resulting from a 20 cfs diversion is 4 mg/l, then an arc with a weight of 20 connects nodes 16 and 24. Likewise if 200 cfs produced an end concentration of 17 mg/l, an arc with weight 200 connects nodes 16 and 27.

Dissolved oxygen, however, is not the only initial condition which affects the eventual concentration in the river section. Others are temperature, BOD and the flowrate. For this application temperature and BOD are assumed constant for each monthly application of the model. This assumption is reasonable since both vary only slightly during the monthly time frame. The flowrate, however, has a greater effect. Because of the configuration of the problem at hand, this impact can be easily incorporated into the network structure. This will be described further as the entire network is developed.

The overall network is constructed on the basis of the previous description. For each stream section there may be a number of possible, initial DO values. Therefore, the network in Figure 5 will be "repeated" for each

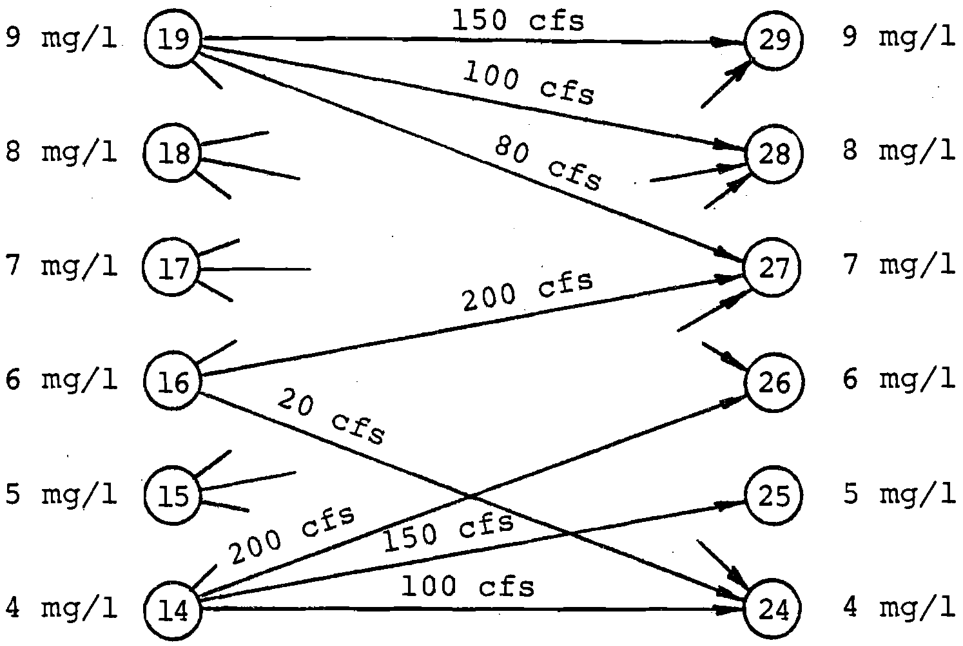


Figure 5. The Network Structure for One Section

section.

Figure 6 illustrates the entire network. In the network there are three segments, corresponding to river sections 1, 2 and 4. The segments are delineated by columns of nodes, with only one node in the first and last "columns." Each column represents a range of possible discrete DO concentrations with values chosen to emphasize the lower concentrations. Consequently, the DO concentrations were incremented every 0.1 mg/l between DO concentrations of 4.0 and 4.9, every 0.2 mg/l between DO concentrations of 5.0 and 7.0, and every 0.5 mg/l between DO concentrations of 7.0 and 11.0. Each node, therefore, represents a small range of DO concentrations. For example, any actual DO concentration between 5.1 and 5.3 is represented in the network by a single node having a DO concentration of 5.2 mg/l.

As can be seen from the illustration, the node at the end of one segment becomes the initial node for the next segment. The DO concentration at the end of one section cannot, however, be used as the initial DO concentration for the next section without making adjustments dependent upon the characteristics of the diversion at the beginning of the downstream section. One of these characteristics is the value of the diversion itself. Knowing the diversion, a weighted average (mass balance) can be determined for the DO concentration in order to determine the initial conditions for the second section. Following this determination the end DO can be calculated as before.

At the beginning of section 1, an average DO is assumed for each month representing the DO concentration at the Wilmette Pumping Station. Consequently, the first column of nodes contains only one node as shown in Figure 6. At the end of the first section, each DO concentration obtained is associated with a particular diversion from the Wilmette Pumping Station and is assigned

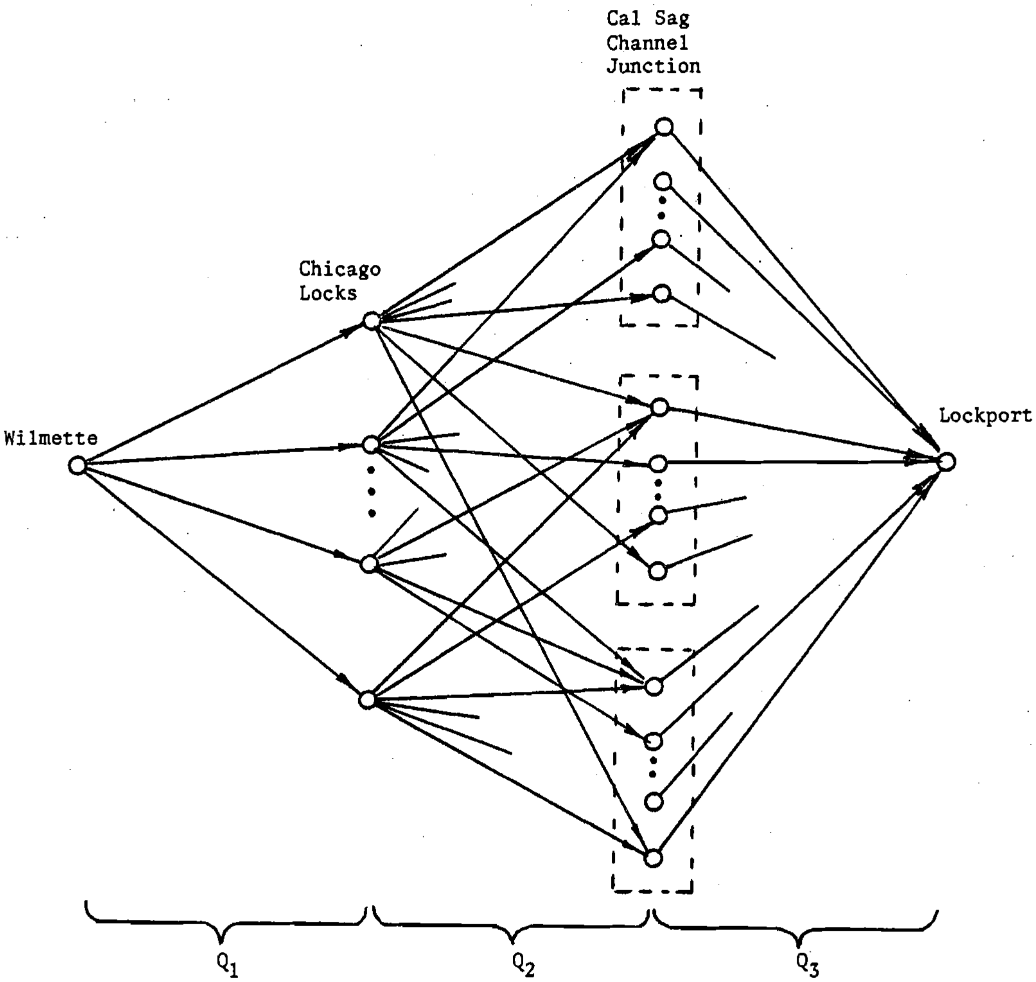


Figure 6. Network Representation of Flow Alternatives with Nodes representing Dissolved Oxygen Concentrations.

a node representing its final DO concentration. The group of nodes at this point make up the second column in the network. Each node represents a DO concentration and total flow to that point in the waterway system.

The value of the arc from node 1 to any particular node in the second node column is equal to the diversion required from the Wilmette Pumping Station to obtain a specific DO concentration at the end of the first section represented by this particular node.

The second column of nodes is not complicated because the DO and flow are calculated from the initial DO and diversion at Wilmette. However, the third column requires a more complex structure because the DO at the end of the second section can result from different combinations of Wilmette diversions (Q_1) and Chicago River diversions (Q_2), and consequently a different total flow. Since the total flow at this point has an impact on the downstream (Section 4) DO concentration, its value must be contained in the nodes. This is done by dividing the third node column into three subgroups, representing a range of possible flows. The ranges are determined by anticipating the minimum and maximum flowrates at this point and dividing the column into three ranges. Each node represents a very small range of DO concentrations, and a range of flowrates, depending upon the subgroup it is in.

The last column in the network contains one node representing the DO concentration at the Lockport Controlling Works. Several nodes could be shown representing a range of DO values; however, the node representing the minimum DO concentration is used. A higher concentration would result from a larger diversion. The larger diversion, however, would not be chosen in a minimization procedure. This fact allows us to use only one arc, from each node of the beginning of the section, representing the diversion necessary to just maintain the DO standard.

The diversion value placed on the arcs leading to the last node is that from the O'Brien Locks, Q_3. The use of Q_3 in this way allows us to ignore section three in the construction of the network, which is possible because any diversion at the O'Brien Locks must satisfy the DO standard in section three before it is considered in the computations for section four. In other words, values of Q_3 must satisfy the DO standards in section three and contribute to the total flow in section four to maintain the standard there. If either standard is violated, the flow is not used. The minimum Q_3 capable of maintaining standards in both sections is used as the value on each arc in segment four of the network.

USE OF THE NETWORK

Because of the configuration of the network, any sequence of arcs (a path) from the first node (1) to the last node (160) will include 3 arcs, one representing each of the three direct lake diversions. If the shortest path is determined, then the sum $Q_1 + Q_2 + Q_3$ will be minimized. Once the network is completed, a shortest path algorithm (Pierce 1975) is applied to determine the shortest path between the nodes 1 and 160. The average monthly direct diversion is obtained by summing the three diversions.

The procedure is very similar to solving the problem using discrete dynamic programming, where the state variables are the DO concentrations and flowrates, and the stages are the three sections of the network. Liebman and Lynn (1966) and Meier and Beightler (1967) used dynamic programming to solve similar water quality problems. The branched dynamic programming approach used by Meier and Beightler is similar to the incorporation of section three into the network. This application is simplified, however, since section three consists of only one stage.

The number of feasible arcs generated between each node column depends on the number of diversions tested at each diversion point and the number resulting in feasible DO concentrations. In order to minimize the number of diversions tested, an iterative procedure was developed. Liebman and Lynn (1966) describe a similar procedure when using a discrete dynamic programming solution. However, they reduced the number of nodes necessary to solve the problem. This application requires a reduction in the number of arcs generated for use in the network. The reduction in the number of arcs, however, must not interfere with the solution procedure or eliminate the optimal solution. A procedure was used where a wide range of diversions were tested and refinements made during successive iterations. For the first iteration a number of different values for each of Q_1, Q_2, and Q_3 were tested, ranging from very low to very high diversion flows. The resulting "minimum" values of Q_1, Q_2, and Q_3 were used as a basis for the second iteration. Their use is based on the reasoning provided in the following example, illustrated in Figure 7. If four diversion values were tested, the resulting DO concentrations at the end of the section might be 8.0 mg/l, 6.2 mg/l, 5.1 mg/l, and 3.9 mg/l. The flow rate yielding the 3.9 concentration (100 cfs) is not feasible and therefore not included in the solution. The lowest feasible diversion rate is 200 cfs. It is quite possible, however, that a 101 cfs diversion flowrate would yield a feasible DO concentration of 4.0 mg/l. In order to narrow the range of the diversion rates, the second iteration would test values between 100 cfs and 200 cfs. A third iteration could further refine the search. Experience with the procedure showed that three iterations were sufficient to narrow the margin of error to within 5 cfs after a reasonable intitial choice.

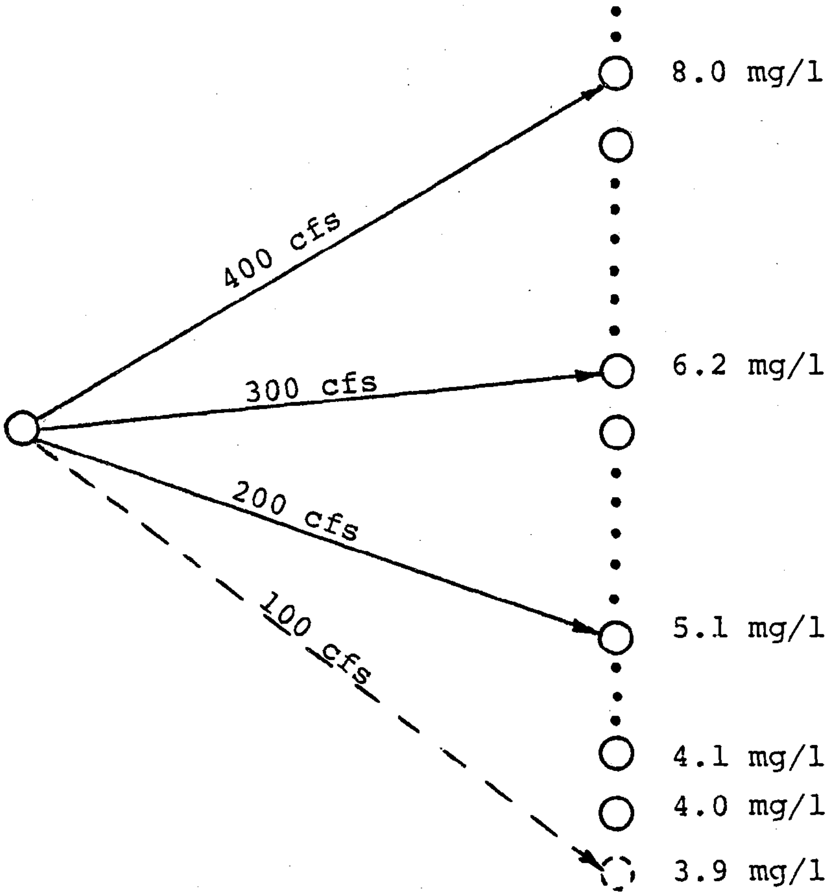


Figure 7. Use of the Tested Diversion Rates to Narrow the Search for Feasible Flow Rates

One caution must be exercised, however, when this approach is actually utilized. It is possible that when conducting the second iteration the arc values in the first section of the network will adversely affect those in the second section. Figure 8 shows a case where the first iteration chose a shortest path of $Q_1 = 200$ and $Q_2 = 200$ (Figure 8a). During the refinement for the second iteration the Q_1 and Q_2 values to be tested would range from 100 to 200. Figure 8b shows the possible outcome. A flow of $Q_1 = 105$ cfs might be the minimum feasible flow for section one. However, from the node representing 4.0 mg/l at the end of section one, no Q_2 flow between 100 and 200 cfs will generate a feasible DO concentration at the end of section 2. It is also possible that the only feasible combination was the sequence determined by the first iteration ($Q_1 = 200$ cfs, $Q_2 = 200$ cfs). However, it is possible that a Q_2 of 290 cfs in conjunction with a Q_1 of 105 cfs would produce feasible results. This combination ($Q_1 + Q_2 = 105 + 290 = 395$) is less than the only one that would have been generated ($Q_1 + Q_2 = 200 + 200 = 400$).

To alleviate this problem the range of flows tested in the second iteration must not be narrowed as drastically for Q_2 and Q_3 flow values. This approach is heuristic in nature and in the cases tested it was found that, if the first iteration yielded feasible flows for 200 and 300 cfs but not for 100 cfs, then the range for the second iteration should be from 100 to 300 cfs.

The procedure has thus far been described using average monthly input data. In order to determine the variations from month to month, the algorithm must be solved for each month, which requires three iterations for each month for a total of 36 applications of the algorithm.

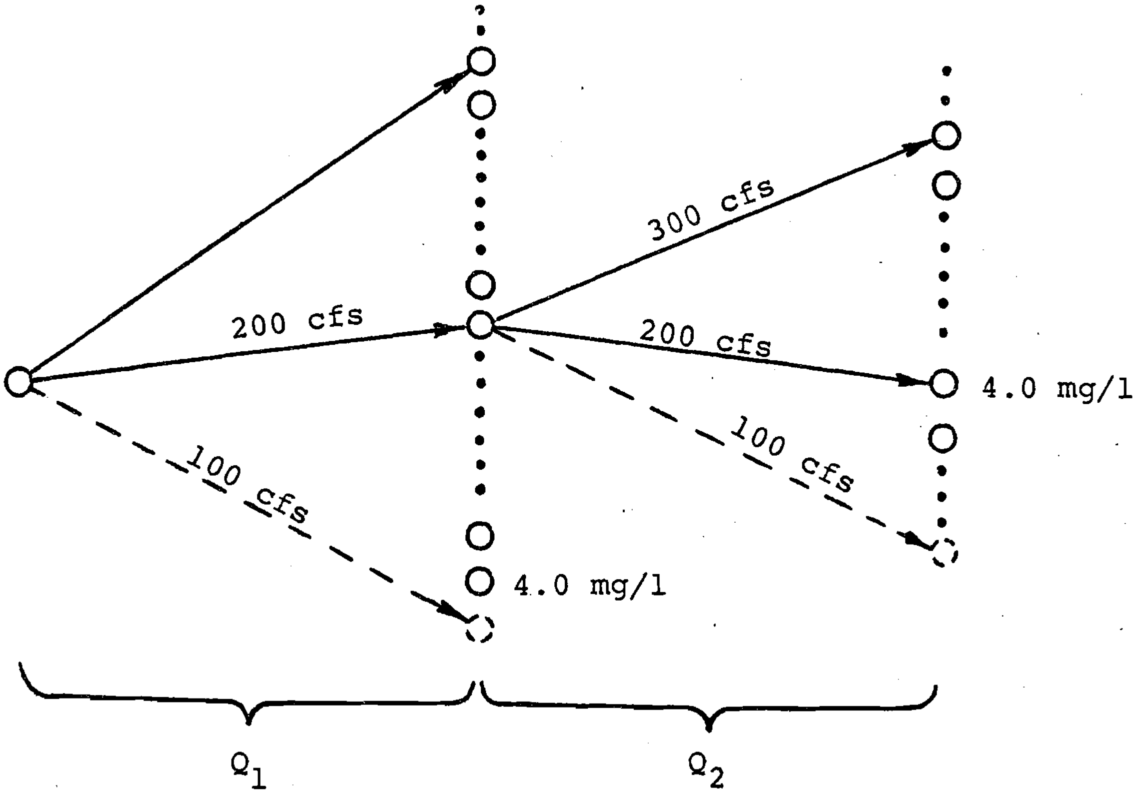


Figure 8a. Possible Results After the First Iteration of the Algorithm

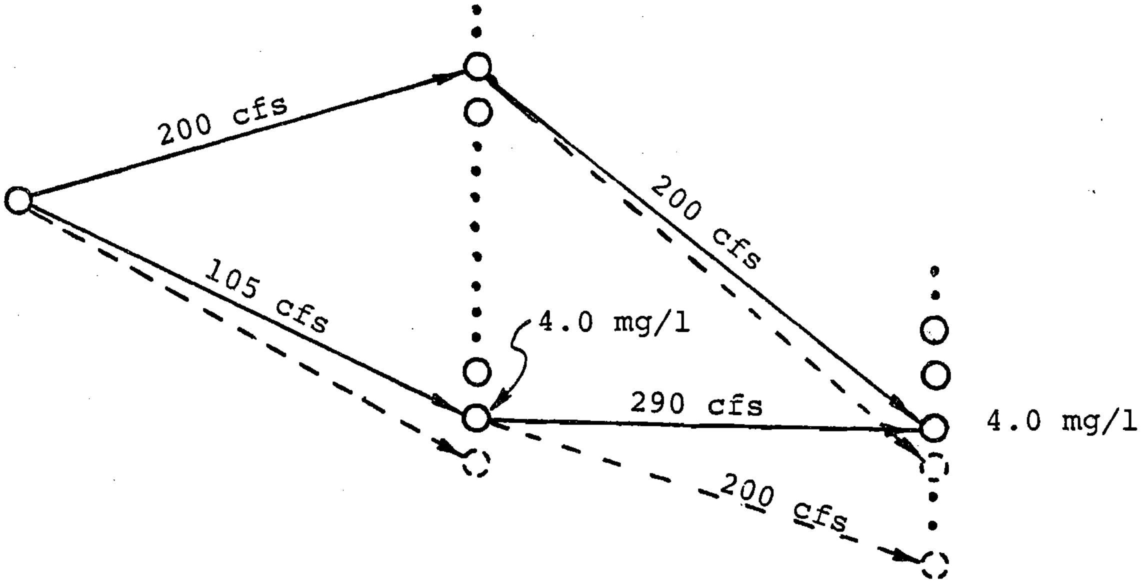


Figure 8b. Potential Conflict During the Second Iteration of the Algorithm

Figure 8. Example of the Resolution of Conflict Occurring Between Iterations of the Algorithm

RESULTS AND DISCUSSION

The optimization procedure was coded in Fortran IV and run on a CDC Cyber 74-18. Average CPU time for one iteration of all 12 months was approximately 6 seconds. Computer size limitations restricted the size of the network to 160 nodes.

Two cases were analyzed using the program: (1) conditions currently existing in the study area and (2) conditions after the installation of the ten instream aeration stations.

EXISTING CONDITIONS

The waterway system described in Chapter II was analyzed to determine the diversions necessary to maintain the dissolved oxygen standards imposed after December 31, 1977, which state that the North Shore Channel must maintain 5 mg/l at least 16 hours of the day and at least 4 mg/l at all times, and the remainder of the system under consideration must maintain 4 mg/l. To simplify the problem the more stringent, 5 mg/l standard was used for the steady state analysis of the North Shore Channel.

The input data used for the evaluation (physical characteristics and influent DO, BOD, temperature, and flow rate) are shown in Appendices A through E. Average monthly flowrates were used for both the wastewater treatment plants and tributary streams. The choice of deoxygenation coefficient values was difficult because of the uncertainty of representative rates. Values were chosen based on data provided by Butts, Evans, and Stall (1974) and calibration of the DO sag curve. Because of the difference in reaches designated for this study and those determined by Butts, Evans, and Stall, the K_1 values may not agree exactly in location. The values for each reach are shown in Table 6. In addition to these values, existing conditions were

Table 6. Deoxygenation Rate Coefficients (K_1) for Reaches in the River and Canal System, in days^{-1}

Reach	K_1
1	.52
2	.52
3	.52
4	.17
5	.32
6	.30
7	.30
8	.70
9	.70
10	.32
11	.32

analyzed with K_1 values approximately 25 percent higher than those in Table 6.

Table 7 shows the results of the anlaysis using the K_1 values shown in Table 6. The average yearly diversion for the entire waterway network is 777 cfs. The diversions using K_1 values 25 percent higher than those in Table 6, are shown in Table 8. The average yearly diversion is considerably higher, at 1022 cfs. In both cases the Calumet Sag Channel requires approximately 72 percent of the dilution water, while the Chicago River needs very little. The large proportion allotted to the Cal-Sag Channel is due to the high K_1 values and poor quality of influent tributaries. The small portion allotted at the Chicago River Controlling Works is in some part due to the solution technique. Formulation of the problem ignores the short section of the Chicago River between the lake and the junction of the North and South Branches. Under these circumstances, dilution water for section two can come from either the Wilmette pumping station (Q_1) or the mouth of the Chicago River (Q_2). Since a certain amount of water must be diverted at Wilmette to meet the standards in section one, this water will also act as dilution water when it reaches section two. Obviously, water diverted from the lake at the Chicago River Controlling Works will be of higher quality than that already receiving waste from section one. However, a lower total diversion (Q_1 + Q_2) is possible with a greater diversion at Wilmette than is necessary in section one. The "excess" water in conjunction with some natural reaeration and the relatively low K_1 values in reach 4 make this situation possible.

In the analyses shown in Tables 7 and 8 no diversions were allowed below the average existing lockage and leakage values for the three diversion points. The values used correspond to those presented by Keifer and Associates (1976) and shown in Table 1. Values for the winter months were

Table 7. Minimum Diversions Under Existing Conditions (Using K_1 Values Shown in Table 6)

Month	Wilmette	Chicago River	O'Brien Locks	Total
January	46	64	85	195
February	46	64	85	195
March	46	135	115	296
April	46	135	275	456
May	46	135	710	891
June	110	157	405	672
July	200	157	500	857
August	220	157	1025	1402
September	130	157	2910	3197
October	270	92	365	727
November	60	92	76	228
December	46	64	100	210
Average	106	117	554	777

Table 8. Minimum Diversion Under Existing Conditions (Using K_1 Values 25 Percent Higher than Shown in Table 6)

Month	Wilmette	Chicago River	O'Brien Locks	Total
January	46	64	100	210
February	46	64	100	210
March	46	140	180	366
April	46	135	310	491
May	90	135	850	1075
June	190	160	500	850
July	200	157	650	1007
August	300	157	1370	1827
September	200	157	4450	4807
October	360	92	450	902
November	115	92	100	307
December	46	64	110	220
Average	140	118	764	1022

used for December, January, and February, spring values were used for March, April and May, summer values for June, July, August, and September and autumn values for October and November. In order to determine what effect the lockage and leakage flows have on the total diversion, the program was run with no lower limit on the amounts to be diverted. The results are shown in Table 9. The analysis was performed with the K_1 values shown in Table 6. A comparison with Table 7 reveals that the yearly average diversion could be reduced by approximately 100 cfs if all lockage and leakage could be eliminated.

INSTREAM AERATION

MSDGC is currently constructing ten insteam aeration stations to help improve the water quality of the Chicago River and Canal system. The solution procedure was modified by adding ten reaches to accommodate instream aeration. The physical characteristics of the modified problem are detailed in Appendix F. Three different analyses were made by varying both the values of the deoxygenation coefficients and the efficiency of the aerators. In all cases the lockage and leakage flows are included. Macaitis, Povilaitis, and Cameron (1977) reported that the diffused air aerators under construction by MSDGC should be capable of raising the DO concentration to approximately 90 percent of the saturation concentration. Table 10 shows results assuming a 90 percent "aeration efficiency" and using K_1 values shown in Table 6. Table 11 shows results using the same K_1 values but assuming only a 70 percent "aeration efficiency." As a "worst case" analysis, a third run was made with a 70 percent efficiency and K_1 values 25 percent greater than shown in Table 6. The results of this analysis are shown in Table 12.

Table 9. Necessary Diversions Under Existing Conditions Without Lockage and Leakage FLows

Month	Wilmette	Chicago River	O'Brien Locks	Total
January	0	0	85	85
February	0	0	85	85
March	0	0	115	115
April	0	0	275	275
May	20	0	710	730
June	110	0	410	520
July	500	0	510	1010
August	220	0	1025	1245
September	130	0	2925	3055
October	310	0	380	690
November	65	0	75	140
December	0	0	100	100
Average	113	0	558	671

Table 10. Minimum Divisions with Instream Aeration Assuming 90 Percent "Aeration Efficiency" (Using K_1 Values Shown in Table 6)

Month	Wilmette	Chicago River	O'Brien Locks	Total
January	46	64	90	200
February	46	64	80	190
March	46	135	112	293
April	46	135	220	401
May	46	135	495	676
June	46	157	345	548
July	46	157	365	568
August	46	157	725	928
September	46	157	2180	2383
October	70	92	90	252
November	46	92	76	214
December	46	64	100	210
Average	48	117	421	576

Table 11. Minimum Diversions with Instream Aeration Assuming 70 Percent "Aeration Efficiency" (Using K_1 Values Shown in Table 6)

Month	Wilmette	Chicago River	O'Brien Locks	Total
January	46	64	90	200
February	46	64	80	190
March	46	135	112	293
April	46	135	220	401
May	46	135	500	681
June	80	157	360	597
July	90	157	380	627
August	240	157	750	1147
September	120	157	2200	2477
October	240	92	90	422
November	46	92	76	214
December	46	64	100	210
Average	91	117	413	621

Table 12. Minimum Diversions with Instream Aeration Assuming 70 Percent Aeration Efficiency (Using K_1 Values 25 Percent Higher than Shown in Table 6)

Month	Wilmette	Chicago River	O'Brien Locks	Total
January	46	64	100	210
February	46	64	90	200
March	46	135	130	311
April	46	135	250	431
May	46	135	590	771
June	140	157	420	717
July	160	157	440	757
August	330	157	980	1467
September	200	157	3250	3607
October	330	92	170	592
November	60	92	76	228
December	46	64	110	220
Average	125	117	551	793

The average annual diversions for the three cases range from 576 to 793 cfs, which indicates a reduction of approximately 200 cfs for instream aeration with a 90 percent "efficiency" (using the lower K_1 values).

POSSIBLE EXTENSIONS

The solution procedure described in this report is based on a steady state analysis using monthly averages. Actual conditions in the River and Canal System are far from steady state. Lockages, storm water overflow, and flood control operations provide flows resembling impulse inputs to the system. Diurnal variations in DO concentrations also complicate the modeling process. A detailed non-steady-state analysis of the River and Canal system would be an enormous undertaking. If it were to be done, a straightforward optimization procedure, such as the one presented here, could be used to provide starting conditions and average monthly flow "goals" for the simulation.

One drawback of the procedure presented in this report is that it provides only the optimal result, and no other feasible, yet close to optimal schemes. In most cases an array of "good" solutions is very valuable in any decision process. To overcome this problem a different shortest path algorithm could be used in the procedure that generated a certain number of paths, starting with the best, then the second best, and so forth.

The use of average monthly flow rates as input to the model was based on the fact that the desired monthly diversion rates are also monthly averages. Adjustment of the diversion rates during a month should reflect existing conditions in the appropriate stream section. In the past, the adjustment has reflected primarily navigation and flood control. In addition, both water quality and the allotted average monthly diversion should influence the decision. The water quality could be predicted for very short time horizons based on considerations such as temperature and tributary flow rate and quality. The average diversion should be used as a target value much as the 3200 cfs value is currently used as a yearly target.

One problem may arise when varying the diversion rates for short term adjustment of the DO concentrations. It may prove advantageous to raise the diversion rate to a very high level over the span of a day or two. This high flowrate, however, may not be possible because of the physical limitation of the diversion structure. Wilmette, in particular, is most subject to this possibility because of the low, 700 cfs capacity. Again, this possibility needs to be explored with more detailed studies.

In some cases it may be advantageous to use the optimization procedure to determine average diversions for periods shorter than a month. This would be beneficial if conditions at the beginning of a month were considerably different from those at the end. The problem of supplying representative data for short time periods, however, might limit this approach.

As a result of the Water Resources Development Act of 1976 Illinois may divert up to 10,000 cfs under the appropriate circumstance. The results of this study are still valid and provide the minimum direct diversions necessary to maintain the current dissolved oxygen standards. It may be advantageous, however, to divert more than the minimum necessary. The benefit of higher diversion, of course, would be a higher overall DO concentration in the waterway. Other factors might also be considered, including (1) reduction in the use of instream aerators, (2) increased navigation capability, and (3) increased hydropower generation at Lockport. Obviously, an increased diversion would be beneficial for all of the considerations listed. The geographic and temporal distribution of the diversions, however, should be determined on the basis of some criterion. The criterion could reflect any combination of one or more of the previous considerations. Examples would be to

(1) maximize the average DO concentration, (2) maximize the minimum DO concentration, (3) minimize energy required for instream aeration, or (4) maximize power generation at Lockport. All of these factors, however, must be considered in the light of potential downstream flooding.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the application of the procedure developed as a part of this study, the following conclusions can be drawn:

1. Under existing conditions a yearly average direct diversion of from 777 to 1022 cfs is necessary to maintain the dissolved oxygen standard of the Illinois Water Pollution Regulations. Assuming an average annual value of 256 cfs for lockage and leakage, approximately 521 to 766 cfs should be designated for discretionary diversion.

2. After completion of the instream aeration stations, an annual average direct diversion of from 576 to 793 cfs will be necessary to maintain the dissolved oxygen standard. This diversion will allow from 320 to 537 cfs for discretionary purposes.

3. In all cases a large percentage of the direct diversion flow should occur during the months of May through October. Slightly less than half of the total annual flow should be concentrated in August and September.

4. Judicious allocation of the direct discretionary diversion flows among the Wilmette Pumping Station, the Chicago River Controlling Works, and the O'Brien Locks is an important factor in minimizing the necessary diversion. The Calumet Sag Channel will require a large percentage of the discretionary diversion even after installation of the instream aerators. Diversions at the Chicago River Controlling Works were lowest of the three locations, often requiring only that attributed to lockage and leakage.

Based on the findings of this research, the following recommendations are made for implementation and further study:

1. The allocation of 320 cfs for discretionary diversion by the Division of Water Resources of the Illinois Department of Transportation should be raised slightly. The lowest value obtained during the study was 320 cfs after installation of instream aeration stations. Although this value may prove to be sufficient, some flexibility is desirable.

2. A procedure for continuous adjustment of diverted flows should be developed. The values reported here are average monthly flows. The actual flow at any specific time should depend on existing conditions within the watershed. The procedure should include the objectives of navigation, flood control, <u>and</u> water quality based on the available monthly average diversions. The continuous operation should allow for conditions within different geographical areas which may dictate different diversion rates.

3. With the enactment of the Water Resources Development Act, allowing an increase in the total diversion by Illinois, procedures should be established for the allotment of water when lake levels are above normal. With specific reference to discretionary diversions, relative diversion rates should be determined for the waterway sections based on factors such as (1) maximizing the average DO concentration, (2) maximizing the minimum DO concentration, (3) minimizing the energy used for artificial aeration, or (4) maximizing power production at Lockport.

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Appendix A

Length, Average Depth, and Cross-Sectional Area of River Reaches Used in the Solution Procedure*

Reach Number	Beginning and Ending Points	Beginning and Ending River Mile **	Average Depth ft.	Average Cross Sect. Area, ft^2	Length of Reach, Miles
1.	Wilmette pump Stat. North Side Treat. P.	340.7 - 336.5	5.7	485.0	4.2
2.	North Side Treat. P. North B.C.R. Junct.	336.5 - 333.4	6.9	771.0	3.1
3.	North B.C.R. Junct. Chicago R.C. Works	333.4 - 325.6	11.9	2462.0	7.8
4.	Chicago R.C. Works W-Southwest T.P.	325.6 - 315.8	16.2	3717.0	9.8
5.	W-Southwest T.P. Calumet Sag Junct.	315.8 - 303.4	17.4	4294.0	12.4
6.	Calumet Sag Junct. Lemont T. Plant	303.4 - 300.5	25.2	4160.0	2.9
7.	Lemont T. Plant Lockport C. Works	300.5 - 291.1	18.4	4288.0	9.4
8.	O'Brien C. Works Grand Cal. R. Junct.	326.5 - 325.6	9.0	4852.0	0.9

Appendix A (Continued)

Reach Number	Beginning and Ending Points	Beginning and Ending River Mile **	Average Depth ft	Average Cross Sect. Area, ft^2	Length of Reach, Miles
9.	Grand Cal. R. Junct. Calumet T. Plant	325.6 - 321.3	10.1	4744.0	4.3
10.	Calumet T. Plant Little Cal. R. Junct.	321.3 - 319.6	10.5	3237.0	1.7
11.	Little Cal. R. Junct. Calumet Sag Junct. With Main Channel	319.6 - 303.4	9.8	2830.0	16.2

*Source; Illinois State Water Survey, May 1974.

**Mileage from Illinois River Mouth at Grafton.

Appendix B

Average Monthly Dissolved Oxygen Concentrations of Major Inputs to Chicago River and Canal System, mg/l*

DISCHARGE SOURCE	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
Direct Diversions:												
Wilmette Pump. Stat.	13.3	12.3	11.3	10.9	10.2	9.8	8.2	8.1	9.1	8.6	10.2	10.9
Chicago R. Cont. Works	12.6	11.9	11.2	10.8	9.7	9.4	8.1	7.9	8.7	8.8	10.5	11.2
O'Brien Cont. Works	9.6	11.6	9.5	9.0	6.6	5.9	6.0	5.0	4.1	7.4	8.3	10.4
Sewage T. Plants Effluent:												
North Side T. Plant	8.4	8.1	7.8	7.6	7.5	7.2	6.9	7.2	7.3	7.4	7.3	7.8
West-Southwest T. Plant	8.6	8.2	8.3	8.3	7.8	7.9	7.6	7.0	7.6	7.6	8.0	8.1
Calumet Treatment Plant	7.9	8.0	7.3	7.8	7.4	7.0	6.8	6.7	6.4	7.0	7.4	7.9
Tributaries:												
North Branch Chicago R.	10.0	11.4	10.7	10.6	8.2	2.9	3.7	2.5	4.3	3.5	4.9	9.7
Grand Calumet River	4.5	6.0	3.5	2.8	0.8	3.3	1.0	0.7	2.5	2.9	3.8	4.7
Little Calumet River	9.2	10.2	8.4	5.3	4.8	4.7	1.3	3.2	3.9	1.6	4.8	9.7

*Source: Metropolitan Sanitary District of Greater Chicago, Annual Maintenance and Operation Reports, 1972-1975.

Appendix C

Average Monthly Values of Biochemical Oxygen Demand of Major Influents to Chicago River and Canal System, mg/l*

DISCHARGE SOURCE	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
Direct Diversions:												
Wilmette Pump. Stat.	2.7	3.0	3.0	2.5	3.0	3.0	3.0	2.0	2.5	2.7	3.7	3.5
Chicago R. Cont. Works	3.0	3.0	3.0	2.0	2.7	3.0	3.0	1.8	2.3	2.7	3.7	3.4
O'Brien Cont. Works	5.0	4.0	5.0	5.0	4.0	3.0	3.0	3.0	4.0	3.0	2.0	4.0
Sewage T. Plants Effluent:												
North Side T. Plant	13.0	14.0	11.0	9.0	10.0	9.0	8.0	9.0	9.0	12.0	10.0	11.0
West-Southwest T. Plant	11.0	14.0	15.0	13.0	13.0	9.0	6.0	6.0	6.0	7.0	7.0	9.0
Calumet Treatment Plant	14.0	14.0	16.0	14.0	14.0	15.0	17.0	16.0	19.0	19.0	17.0	17.0
Tributaries:												
North Branch Chicago R.	8.0	7.0	5.0	10.0	13.0	7.0	7.0	9.0	7.0	14.0	7.0	7.0
Grand Calumet River	11.0	17.5	12.5	16.5	19.0	9.0	14.5	18.0	8.0	7.5	14.0	18.5
Little Calumet River	9.0	11.0	8.0	10.0	8.0	7.0	6.0	8.0	6.0	9.0	3.0	8.0

*Source: Metropolitan Sanitary District of Greater Chicago, Annual Maintenance and Operation Reports, 1972-1975.

Appendix D

Average Monthly Temperatures of Major Influents to the Chicago River and Canal System, °C*

DISCHARGE SOURCE	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
Direct Diversions:												
Wilmette Pump. Stat.	1.0	1.0	4.4	5.6	9.2	10.0	17.8	18.9	18.3	15.6	8.2	5.6
Chicago R. Cont. Works	1.0	2.2	4.4	6.0	10.0	11.6	19.0	19.0	15.0	14.0	7.0	4.4
O'Brien Cont. Works	1.0	2.0	7.0	10.0	16.0	19.0	20.0	22.0	16.0	18.0	6.0	5.0
Sewage T. Plants Effluent:												
North Side T. Plant	10.0	10.0	10.0	12.0	14.0	18.0	20.0	22.0	20.0	19.0	16.0	12.0
West-Southwest T. Plant	12.0	12.0	13.0	14.0	18.0	21.0	23.0	25.0	23.0	21.0	18.0	14.0
Calumet Treatment Plant	12.0	11.0	12.0	12.0	15.0	18.0	20.0	22.0	22.0	20.0	17.0	13.0
Tributaries:												
North Branch Chicago R.	1.0	1.0	4.0	12.0	13.0	18.0	20.0	19.0	14.0	9.0	2.0	0
Grand Calumet River	3.0	8.0	7.0	12.0	17.0	18.0	20.0	21.0	16.0	18.0	6.0	7.0
Little Calumet River	1.0	2.2	4.0	10.0	16.9	18.0	17.3	19.3	13.8	11.3	1.0	2.0

*Source: Metropolitan Sanitary District of Greater Chicago, Annual Maintenance and Operation Reports, 1972-1975.

Appendix E

Average Monthly Flow of the Major Influents to the Chicago River and Canal System, cfs*

DISCHARGE SOURCE	JAN.	FEB.	MAR.	APR.	MAY	JUN.	JUL.	AUG.	SEPT.	OCT.	NOV.	DEC.
Direct Diversions:												
Wilmette Pump. Stat.	91	38	39	44	41	43	45	44	46	43	61	187
Chicago R. Cont. Works	135	294	34	84	81	142	142	148	107	96	78	224
O'Brien Cont. Works	176	330	63	80	178	174	174	185	138	119	121	306
Sewage T. Plants Effluent:												
North Side T. Plant	504	491	554	573	540	526	531	531	497	483	489	509
West-Southwest T. Plant	1271	1254	1391	1457	1390	1367	1422	1424	1295	1227	1199	1239
Calumet Treatment Plant	331	293	349	372	352	339	313	306	281	286	308	332
Tributaries:												
North Branch Chicago R.	185	175	215	255	215	160	80	105	90	80	100	145
Grand Calumet River	53	48	40	63	76	71	34	30	29	26	29	38
Little Calumet River	417	370	304	473	462	485	123	108	114	78	142	180

*Source: Metropolitan Sanitary District of Greater Chicago, Annual Maintenance and Operation Reports, 1972-1975.

Appendix F

Length, Average Depth, and Cross-Sectional Area of River Reaches Used in the Solution Procedure after Instream Aeration*

Reach Number	Ending Points	Beginning and Ending River Mile**	Average Depth ft.	Average Cross-Sect. Area, ft^2	Length of Reach, Miles
1.	Wilmette pump Stat.- North Side Treat. P.	340.7 - 336.5	5.7	485	4.2
2.	North Side Treat.P.- Aeration Station A	336.5 - 334.8	6.9	771	1.7
3.	Aeration Station A- North B.C.R. Junct.	334.8 - 333.4	6.9	771	1.4
4.	North B.C.R. Junct.- Aeration Station B	333.4 - 328.8	11.9	2462	4.6
5.	Aeration Station B- Chicago River Junct.	328.8 - 325.6	11.9	2462	3.2
6.	Chicago River Junct.- Aeration Station C	325.6 - 325.5	16.2	3717	0.1
7.	Aeration Station C- W.Southwest T.P.	325.5 - 315.8	16.2	3717	9.7
8.	W.Southwest T.P. Aeration Station D	315.8 - 313.6	17.4	4294	2.2

Appendix F (Continued)

Reach Number	Ending Points	Beginning and Ending River Miles**	Average Depth ft.	Average Cross-Sect. Area, ft^2	Length of Reach, Miles
9.	Aeration Station D- Calumet Sag Junct.	313.6 - 303.4	17.4	4294	10.2
10.	Calumet Sag Junct.- Aeration Station E	303.4 - 302.2	25.2	4160	1.2
11.	Aeration Station E- Lemont T. Plant	302.2 - 300.5	25.2	4160	1.7
12.	Lemont T. Plant- Lockport C. Works	300.5 - 291.1	18.4	4288	9.4
13.	O'Brien C. Works- Grand Cal. R. Junct.	326.5 - 325.6	9.0	4852	0.9
14.	Grand Cal. R. Junct.- Aeration Station F	325.6 - 324.0	10.1	4744	1.6
15.	Aeration Station F- Calumet T. Plant	324.0 - 321.3	10.1	4744	2.7
16.	Calumet T. Plant- Little Cal. R. Junct.	321.3 - 319.6	10.5	3237	1.7
17.	Little Cal.R.Junct.- Aeration Station G	319.6 - 319.5	9.8	2830	0.1
18.	Aeration Station G- Aeration Station H	319.5 - 316.0	9.8	2830	3.5

Appendix F (Continued)

Reach Number	Ending Points	Beginning and Ending River Miles**	Average Depth ft.	Average Cross-Sect. Area, ft^2	Length of Reach, Miles
19.	Aeration Station H- Aeration Station J	316.0 - 311.0	9.8	2830	5.0
20.	Aeration Station J- Aeration Station K	311.0 - 308.5	9.8	2830	2.5
21.	Aeration Station K- Calumet Sag Junct. With Main Channel	308.5 - 303.4	9.8	2830	5.1

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*Source: Illinois State Water Survey, May 1974.

**Mileage from Illinois River Mouth at Grafton.