Contract Report 526

Reduction in Peak Flows and Improvements in Water Quality in the Illinois Waterway Downstream of Lockport Due to Implementation of Phases I and II of TARP

Volume 1: Hydraulics and Hydrology

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Volume 2: Water Quality

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REDUCTION IN PEAK FLOWS AND IMPROVEMENTS IN WATER QUALITY IN THE ILLINOIS WATERWAY DOWNSTREAM OF LOCKPORT DUE TO IMPLEMENTATION OF PHASES I AND II OF TARP

EXECUTIVE SUMMARY

This study was performed to investigate the reduction in flood peaks and improvement in water quality with the Chicago Tunnel and Reservoir Plan (TARP) Phases I and II downstream of Lockport to Peoria. The reduced peak flows and stages will provide some relief from severe flooding, thus reducing flood damage and posing less danger to the levees along the river. This study also investigated the potential improvement in water quality of the Illinois River from treatment of essentially all combined sewer overflows (CSOs) as envisioned with TARP Phase II. Both hydraulic/hydrologic and water quality analyses were done by using TARP Phase I alone and in conjunction with Phase II. Most of the benefits in the reduction of peak flows downstream of Lockport are due to TARP Phase II, whereas improvements in water quality are due to both phases of TARP.

For TARP Phase I simulations, 6,602 acre-feet of tunnel storage were used. For TARP Phase II simulations the volume included the Chicago Underflow Plan (CUP) reservoir storage capacity (46,700 acre-feet). O'Hare System has been excluded from the simulations.

For the hydraulic/hydrologic analyses, the Lockport flow values were first adjusted to eliminate discrepancies because of different measurement methods used at different time periods. The Illinois River Flow Model, developed for this study, was used to simulate the base conditions along the Illinois Waterway at Marseilles, Kingston Mines, and Meredosia. A storage routing model was also developed to simulate the effects of TARP operation on the Lockport flows. The daily flows entering the water reclamation plants (WRPs) were estimated from the daily Lockport flows by a desegregation model. Several WRP operation scenarios were then used to simulate the expected changes in the Lockport flows as a result of TARP operations. These modified Lockport flows were then input into the Illinois River Flow Model to be routed downstream, and compared with the flows for the base conditions. The results from the hydraulic/hydrologic study were also used in the water quality analyses to investigate the possible impacts of TARP operations on water quality in the Illinois Waterway downstream of Lockport.

Three levels of WRP capacities were used in the simulations. These are the maximum design, 90 percent of maximum design, and average design (80 percent of maximum design). These values are summarized in volume 1, table 12. The effects of TARP Phases I and II on the peak flows downstream of Lockport were analyzed by using the CUP reservoir storage capacity and the maximum design capacity of the WRPs. The results indicate that TARP Phase II operation, with CUP reservoir storage and WRPs operating at maximum design capacity, can significantly reduce the high flows and their durations at and downstream of Lockport. These effects were particularly significant up to Kingston Mines (downstream of Peoria Lake). The most pronounced high-flow reductions at Lockport were seen at 1-, 7-, and 15-day high flows. The reductions in flows for larger durations (15 and 31 days) become less noticeable downstream — obviously due to increased drainage area.

The effects of TARP Phase II operation on the frequency and volume of overflows were simulated for various scenarios. An overflow (or spill) was defined as a condition when flows entering a WRP exceed the plant's designated capacity and the reservoir within that system is full. It was found that TARP Phase II operation, with CUP reservoir storage (46,700 acre-feet), can eliminate most but not all of the CSOs to the Chicago Waterways during the 1958-1988 simulation period, and significantly reduce flood peaks in the Illinois River downstream of Lockport, if the WRPs can operate continuously at their maximum design capacities. These results show that, on the average, overflows in the total service area would occur for about 29 days a year without the TARP, 9 days with Phase I, and only 1 day with Phase II (volume 1, figure 13). Similarly, the average volume of overflows in the total service area would be about 65,000 acre-feet per year without TARP, 25,000 acre-feet with Phase I, and about 1,700 acre-feet with Phase II (volume 1, figure 16).

However, the WRPs may not operate continuously at their maximum design capacities. The results summarized in volume 1, table 12 show that if the WRPs can operate continuously at 90 percent of their maximum design capacity (condition 3), then a storage capacity of 122,200 acre-feet would eliminate all overflows. This is comparable to the 126,630 acre-feet storage capacity initially proposed by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). If the WRPs can operate only at the average design capacity for sustained periods (condition 4, table 12), then storage capacities much larger than the CUP or those proposed by the MWRDGC are needed to eliminate all overflows into the waterways during the simulation period.

The results of water quality studies clearly indicate that significant water quality improvements have been manifested in waters of the Upper Illinois Waterway since the inception of TARP I during the early 1980s. Minimum dissolved oxygen (DO) concentrations observed at Lockport have improved from 0.00 milligram per liter (mg/l) in 1971/72 to 1.71 mg/l in 1989/90, and from 2.30 mg/l to 5.68 mg/l, respectively, for the same periods at Chillicothe. Similarly, the minimum ammonia concentrations at Lockport for the respective periods were 2.45 mg/l and 0.14 mg/l, and the maximum ammonia concentrations were 6.12 mg/l and 1.44 mg/l. Benthic sediments in the Brandon Road and Dresden Island Pools exhibit remarkably lower sediment oxygen demand (SOD) rates now than 20 years ago. The implementation of TARP I has, undoubtedly, been instrumental in producing this remarkable improvement. Results of the biochemical oxygen demand/dissolved oxygen (BOD/DO) water quality modeling indicate that the implementation of TARP Phase I may have raised the minimum DO levels in the Peoria Pool by at least 1.50 mg/l during very high CSO conditions. Similar improvements are indicated for Brandon Road and. Dresden Island Pools. DO improvements in Marseilles and Starved Rock Pools have not been as significant, but these pools traditionally exhibit high DO levels.

Implementation of TARP Phase II would ensure maximum wasteload reduction irrespective of the magnitude of the CSOs, since this phase is designed as a flood control system that will retain most (if not all) of the overflow for treatment. This will result in persistent wasteload reductions of 90 percent or greater.

The simulations show drastic reductions in CSOs with the completion of TARP Phase II, which will further ensure not only that the water quality in the Chicago Waterways will be improved and residential flooding will be minimized, but also that the probability of CSOs emptying into Lake Michigan will be a thing of the past. The completion of both phases of TARP will have significant benefits to communities along the Illinois Waterway from Lockport to Peoria in terms of 1) reduction of high flood peaks and reduction in duration of high water stages, which will provide relief from floods, and 2) improvement in water quality for water users, aquatic habitats, and recreation. Inclusion of these benefits can considerably improve the benefit-cost ratio for the TARP project.

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REDUCTION IN PEAK FLOWS AND IMPROVEMENTS IN WATER QUALITY IN THE ILLINOIS WATERWAY DOWNSTREAM OF LOCKPORT DUE TO IMPLEMENTATION OF PHASES I AND II OF TARP

Volume 1: Hydraulics and Hydrology

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CONTENTS

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Volume 1: Hydraulics and Hydrology

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INTRODUCTION

The city of Chicago began building its first sewers in 1850, mainly to drain stormwater away from the dirt roads common in those days. After the Chicago Fire of 1871, new brick sewers were constructed to replace the old wooden conduits. By the late 19th century the stormwater sewers had been turned into combined sewers, carrying both storm runoff and sanitary sewage directly into the rivers and into Lake Michigan. In the early 1900s, the construction of sewage treatment plants (STPs) began. By 1930, Chicago and its suburbs were almost completely developed, covering an area of 375 square miles. New intercepting sewers were constructed *to* capture the combined sewage during dry weather, but the interceptors and the plant capacities were exceeded during high runoff periods. Although separate sewer systems have been constructed since 1930 for storm runoff and sanitary sewage, the combined sewers built before 1930 still remain. Because of these combined sewers and the increasing concentration of people and industries within the 375-square-mile metropolitan area, about 100 spills of raw sewage and stormwater enter the Chicagoland waterways every year, causing major pollution problems (Robison, 1986). The more intense storms cause residential and business flooding, and may even cause backflows into Lake Michigan.

The Chicago Tunnel and Reservoir Plan (TARP) was conceived by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC), formerly the Metropolitan Sanitary District of Greater Chicago (MSDGC), primarily to eliminate the pollution and flooding caused by the combined sewer overflows (CSOs) to the Chicagoland waterways. To reduce CSOs into the waterways, runoff from rainfall will be stored in tunnels (ranging in size from 9 to 33 feet in diameter) and reservoirs, and then gradually passed through existing water reclamation plants (WRPs) before being discharged to the waterways. The benefits of TARP have been considered for the 375-square-mile project area, but the propagation of these benefits to the Illinois Waterway downstream of Lockport to its confluence with the Mississippi River has not yet been investigated.

This study was performed to investigate the reduction in peak flow and improvement in water quality with TARP Phases I and II, and to investigate the propagation of these effects downstream of Lockport to Meredosia. The reduced peak flows and stages will provide some relief from severe flooding, thus reducing flood damage and posing less danger to the levees along the river. The runoff from the urbanized Chicago area will be treated at the water reclamation plants before its release to the waterways. This study also investigated the potential improvement in water quality of the Illinois River as a result of treatment of practically all CSOs as envisioned with TARP. TARP will also significantly reduce the sedimentation in the waterways.

TARP is one of the largest public works projects ever undertaken at a cost of about $3.67 billion (in 1991 dollars). TARP has the following goals: 1) protect water quality in Lake Michigan, 2) improve water quality in the Chicago and Illinois Waterways, and 3) reduce urban flooding to a greater extent. Because of the immensity of the overall project, TARP was designed in two phases (figure 1). Phase I, at a cost of $2.51 billion, will primarily control pollution using tunnels, shafts, and pumps; and Phase II, at a cost of $1 .16 billion, will provide for flood control by using additional tunnels and storage reservoirs. Within the service area, TARP was

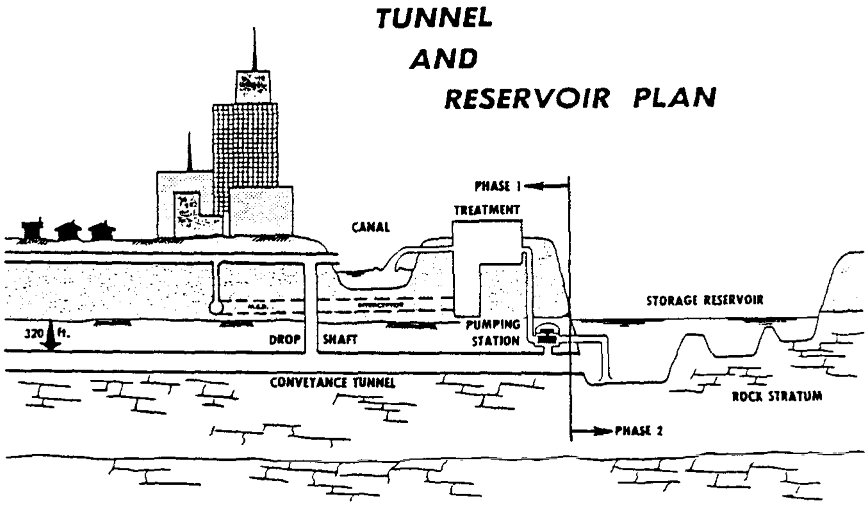


Figure 1. Components of Phases I and II of TARP (Courtesy of MWRDGC)

subdivided into four separate subsystems: Mainstream, Des Plaines, Calumet, and O'Hare (or Upper Des Plaines). The general location of TARP service area and the Illinois Waterway are shown in figure 2.

TARP Phase I

TARP Phase I will capture CSOs from the 375-square-mile service area, containing about 13,500 miles of sewers (U.S. Amy Corps of Engineers (COE), 1986; MWRDGC personal communication, 1989). The components of Phase I consist of collecting structures, drop shafts, tunnels, and pumping stations. The drop shafts range in diameter from 4 to 17 feet, depending on the required inflow capacity. The tunnels range in diameter from 9 to 33 feet and are bored 150 to 350 feet below ground. Of Phase I's 109 miles of completed and proposed tunnels, the largest is the Mainstream Tunnel, which conveys the combined sewer flows to the Mainstream pumping station located at the end of the tunnel in Hodgkins, Illinois. The pumping station operates at a dewatering rate that allows a full tunnel to be emptied within two to three days (COE, 1986). The Mainstream System has 40.3 miles of tunnels, of which 31.2 miles have been completed (MWRDGC, 1990). The Des Plaines System has 25.8 miles of tunnels, of which 3.5 miles have been completed and 13.4 miles are under construction (Ibid.). The Des Plaines System is also dewatered by the Mainstream pumping station. The Calumet System has 36.3 miles of tunnels, of which 9.2 miles have been completed (Ibid.). The Calumet pumping station, located at the Calumet Water Reclamation Plant in Chicago, was designed to handle all Phase I Calumet System discharges. When its six pumps are operational, the Calumet pumping station will have a capacity of 535 cubic feet per second (cfs), which can dewater the Calumet System in two days (COE, 1986). Phase I of the O'Hare System has been completed and consists of 6.6 miles of tunnels.

To summarize, TARP Phase I consists of 109 miles of tunnels, of which 75.4 miles have been completed or under construction, and 33.6 miles remain to be constructed. Upon completion, TARP Phase I will have 6,815 acre-feet of tunnel storage capacity (MWRDGC, 1987): Mainstream System = 3,697 acre-feet, Des Plaines System = 1,267 acre-feet, Calumet System = 1,638 acre-feet, and O'Hare System = 213 acre-feet. According to the latest project status there are minor updates in those tunnel capacities (MWPDGC personal communication, 1991): Mainstream System = 3,170 acre-ft, Des Plaines System = 1,206 acre-ft, and Calumet

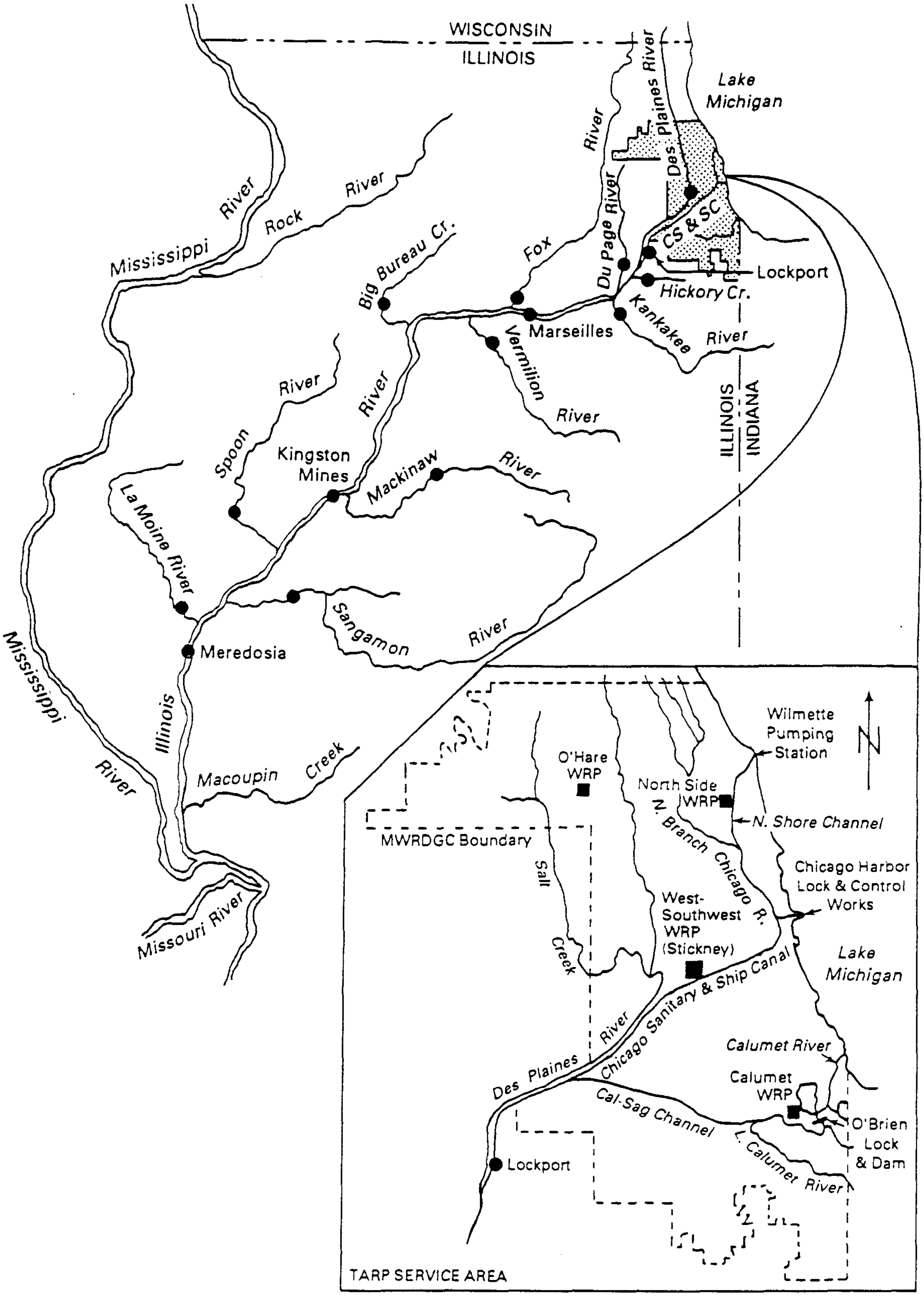


Figure 2. The general location of TARP service area and the Illinois Waterway

System = 1,667 acre-ft. Previous capacity values were used in the simulations because the updated information was not yet available.

TARP Phase II

TARP Phase II was initially planned to consist of additional conveyance tunnels (Mainstream and Calumet Systems), an on-line reservoir, and three terminal reservoirs located at the downstream ends of the Mainstream/Des Plaines, Calumet, and O'Hare tunnel systems. The terminal reservoirs will capture more CSO volume for flood control. The Mainstream/Des Plaines and Calumet reservoirs will be located in the McCook and Thornton quarries, respectively. Both quarries are still being mined by their owners, but MWRDGC has begun acquiring land. The storage capacities proposed by the District for the McCook, Thornton, and O'Hare reservoirs are 83,190,40,840, and 1,600 acre-feet, respectively. However, a COE study (Chicago Underflow Plan (CUP)) has recommended significantly reduced storage capacities. for TARP Phase II reservoirs (COE, 1986).

The CUP recommendation for the McCook reservoir involves constructing a 32,100-acre-foot reservoir that will provide 30,100 and 2,000 acre-feet of flood storage for the Mainstream and the Des Plaines Systems, respectively. The CUP recommendation for the Thornton reservoir and the O'Hare System are 14,600 and 1,050 acre-feet of reservoir storage, respectively. Therefore, the total reservoir capacity proposed by MWRDGC (125,630 acre-feet) is reduced to 47,750 acre-feet. In addition to the reservoir storage, there will be 2,342 acre-feet of storage due to 21.5 miles of Phase II tunnels. The Mainstream and Calumet Systems will have 17.3 miles (1,984 acre-feet) and 4.2 miles (358 acre-feet) of Phase II tunnels, respectively.

Outline

The main emphasis of this study was to investigate the propagation and attenuation of the benefits of TARP for the Illinois Waterway downstream of Lockport. This area is significant since the basin of this waterway covers almost half of Illinois and affects about 9 million people.

The next section explains the compilation and adjustment of Lockport flows, which were collected from different sources. Successive sections then explain the model development and parameter estimation procedures for the Illinois River Flow Model. This model was used to analyze the hydrologic impacts of TARP downstream of Lockport by simulating and comparing the flows in the Illinois Waterway with and without TARP operation. The waterway was divided into three reaches with control stations at Lockport, Marseilles, Kingston Mines, and Meredosia. The flows at Lockport and other major tributaries were input into the model.

The effects of different TARP operations on the flows at Lockport, (the most upstream input to the Illinois River Flow Model) were simulated by using **a** storage routing algorithm. These effects are explained in detail following the section on the Illinois River Flow Model. A separate section presents the statistics of these effects on the flows and their variability at Lockport and downstream of Lockport.

Acknowledgments

This study was jointly supported by the Metropolitan Water Reclamation District of Greater Chicago and the Illinois State Water Survey. John Variakojis of the Water Reclamation District served in a liaison capacity during this study. This report was prepared under the general direction of Richard G. Semonin (Chief) and John M. Shafer (Head of Hydrology Division), Illinois State Water Survey. More than 30 years of Lockport flow data, obtained from the U.S. Army Corps of Engineers, were entered into computer files by Olga Fishman and Irina Kosinovsky. Roman Waupotitsch prepared the computer programs for the Illinois River Flow Model, and assisted in the generation of most of the tables and graphics. Eva Kingston edited the report, and David Cox helped with the graphics.

ANALYSIS AND ADJUSTMENT OF LOCKPORT FLOWS

The daily flows at Lockport are one of the main inputs into the Des Plaines River, which is included in the Illinois Waterway. The flows at Lockport were reported by MWRDGC until 1984. Since then the flows at Lockport have been recorded at Romeoville (5.2 miles upstream of Lockport) by an acoustic velocity meter (AVM). The flows at Lockport are significant for the State of Illinois because this station provides the flow data essential to manage the allowed diversion of Lake Michigan water (3,200 cfs) for water supply, navigation, and effluent dilution purposes.

To eliminate the bias that might stem from using flow data from different sources, adjustments were made in the historical Lockport flows (prior to AVM installation in June 1984, at Romeoville) to bring them in line with the AVM measurements since then. Although future reported flows at Lockport will correspond to

AVM flows, it will also be possible to use the adjusted historical flows with the Illinois River Flow Model.

Regression Equations

Lockport flow adjustments were made by using regression equations that correlate historical MWRDGC reported flows to the AVM flows. The development of these flow regression equations was based on the studies conducted by COE (1989), Harza Engineering Co. (1986), and U.S. Geological Survey. COE first used these regression equations to estimate the missing AVM values due to equipment malfunctions from the flow values reported by MWRDGC at Lockport.

The COE study suggests that the regression equations require the implementation of three different components of flow recorded at Lockport: 1) flow through the powerhouse turbines (including leakage and lockage losses), 2) flow through the powerhouse sluice gates, and 3) flow through the control works sluice gates. Previous studies had used flow threshold levels for different regression equations. The values of the flow components were obtained from COE's Chicago District office as hard copy, dating back to 1955.

The basis for the regression equations developed by COE was that the change in flow patterns at Lockport was highly correlated to the flow components mentioned above. Therefore, COE developed three regression equations to estimate the missing AVM values from the reported Lockport flow components. Equation (1) would be used if the flows at Lockport were from turbine flows including leakage and lockage losses. Equation (2) would be used with turbine and powerhouse sluice gate flows. Equation (3) would be used if all three flow components existed.

$$Q_{AVM} = 1.084\ Q_{TLL} + 88.130 \qquad \left\{ \text{Turbine flow only} \right. \tag{1}$$

$$Q_{AVM} = 1.140\ Q_{TLL} + 0.796\ Q_{PH} + 31.143 \qquad \left\{ \begin{array}{l} \text{Turbine and powerhouse} \\ \text{sluice gate flows} \end{array} \right. \tag{2}$$

$$Q_{Avm} = 0.963\ Q_{TLL} + 0.659\ Q_{PH} + 1418.79 \qquad \left\{ \begin{array}{l} \text{Turbine, powerhouse sluice} \\ \text{gate, and control works} \\ \text{sluice gate flows} \end{array} \right. \tag{3}$$

where Q_{Avm} = AVM flows, Q_{TLL} = combined turbine flows (including leakage and lockage losses), and Q_{PH} = powerhouse sluice gate flows. If these equations had proved satisfactory, they could have been applied to the historical Lockport flows to bring them in line with the new AVM records. However, COE equations for Romeoville AVM flows did not appear to be satisfactory when flows passed through the control works.

COE (1989) developed the equations by integrating the three components of the reported Lockport flows mentioned above with the measured AVM flows at Romeoville for the June 1984 - March 1988 period . In our analysis, we found that while equations (1) and (2) yielded satisfactory results, equation (3) showed significant variation (when flow passed through the control works). Therefore, a new form of the control works equation had to be developed.

It should be noted that although equation (3) was used when flow passes through the control works, Q_{PH} is the independent variable because it showed a higher correlation with Q_{AVM}. According to COE (1989), Q_{PH} and control works sluice gate flows (Q_{cw}) were highly correlated, therefore, both variables could not be used in the same regression equation. However, when Q_{cw} values were plotted against Q_{PH} values (figure 3), Q_{cw} values ranging to 1,250 cfs had no significant functional relationship to Q_{PH}. Therefore, equations (2) and (3) were modified by using a threshold value Q_{CW} = 1,250 cfs). Parameters for equation (3) were re-estimated by using the independent variable Q_{PH} that corresponds to Q_{CW} values greater than 1,250 cfs. Equation (2) was also modified to include Q_{cw} values less than 1,250 cfs, using an independent variable (Q_{pH} + Q_{cw}). The final form of the regression equations used in this study was:

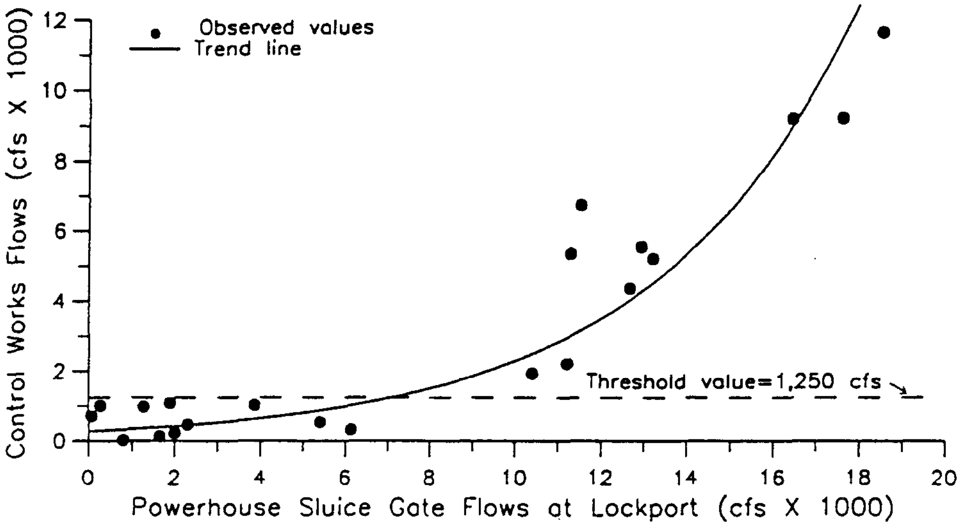


Figure 3. Powerhouse sluice gate flows at Lockport versus flows through control works

Turbine Only

$$Q_{AVM} = 1.08387 \times Q_{TLL} + 88.12987 \tag{4}$$

Turbine, Powerhouse, and/or Control Works

$$Q_{AVM} = 1.12833 \times Q_{TLL} + 0.76528\ (Q_{PH} + Q_{CW}) + 109.73206 \quad (\text{if } Q_{cw} \leq 1{,}250\text{cfs}) \tag{5}$$

$$Q_{AVM} = 0.14728 \times Q_{TLL} + 0.42562 \times Q_{PH} + 7068.01331 \qquad (\text{if } Q_{CW} > 1{,}250 \text{ cfs}) \tag{6}$$

Since the flows passed through the control works on only 21 days during the AVM monitoring period (June 1984 - March 1988), all data were used for parameter estimation. The new equations could not be verified.

Adjustment of Historical Lockport Flows

Historical Lockport flows were defined as flows that began in 1955. By using the modified regression equations, these flows were adjusted to correspond to the AVM flows. These adjustments were necessary because future flows at Lockport will be measured by AVM and because the Illinois River Flow Model will be applicable to both historical and future flows. Flow statistics at Lockport also had to be revised based on the AVM data, so that flow measurements would be comparable.

Due to the nature of the regression equations, adjustment of the historical flows required use of the three flow components reported at Lockport prior to 1984. Data available fom the U.S. Geological Survey's WATSTOR database did not distinguish between these components and therefore could not be used. "Provisional" Lockport flow data obtained from COE's Chicago District Office were entered into computer files for future analysis. The regression equations were developed by using "preliminary" data reported by MWRDGC since June 1985. Analysis of an overlapping two-year period for which both preliminary and provisional data were available indicated only slight differences between them. This period was also used to develop relationships necessary to convert provisional flows to preliminary flow components (turbine, powerhouse, and control work sluice gate flows). If a preliminary flow component could not be obtained, the provisional values were used. The adjusted flows were used to generate the pertinent flow statistics at Lockport and also as the base conditions for analyzing the impacts of TARP operation downstream of Lockport.

ILLINOIS RIVER FLOW MODEL

Flow Imbalances in the Illinois River Basin

Estimation of parameters of the Illinois River Flow Model was complicated by unexpected problems regarding the imbalances of the flows in the Illinois Waterway and its sub-basin gaging stations. Attempts to identify and remedy these flow imbalances in cooperation with the U.S. Geological Survey were not successful; the imbalances could not be explained without conducting a long-term investigation. Examples of these imbalances for all three reaches in the study are shown in tables 1-3, for the period 1985 - 1988. Preliminary analyses also revealed that these imbalances varied over time. Therefore, use of these flows in the model would have violated two basic assumptions of the model: continuity of flow within a reach (mass balance) and stationarity of the flow time series. Since the cause of the problem could not be determined and the needed flow adjustment could not be made, the model was modified to accommodate these unexplained imbalances.

One of the solutions was to divide the flow series into several shorter time periods, thus alleviating the impact of nonstationarity. This obviously also increased the number of simulations needed for parameter estimation (four time periods for the most upstream reach which showed the highest nonstationarity, and three time periods for the two downstream reaches). The flow imbalances were then handled by using flow correction coefficients, based on the magnitude of the imbalances in the reach, and proportioning of the gaged and ungaged drainage areas. The accounting of the flows from the ungaged areas was also incorporated into the same correction coefficients. Ideally, the bottom line in tables 1 - 3 should be zero. A negative flow indicates that the sum of the inflows exceeds the sum of the outflows for that year within that reach. The procedure for estimating the flow correction coefficients will be explained in the next section.

Estimation of Flows from Ungaged Areas and Flow Correction Coefficients

In all three reaches, a significant part of the drainage area remains ungaged. For example, the ratios of the total ungaged area to the total drainage area for each reach were 10.3, 35.8, and 21.4 percent, respectively. Consequently, the totals of all tributary inflows in a reach should be smaller than the outflows from that reach. However, for periods of imbalances the total of all tributary inflows in a reach were greater than the outflows. Therefore, an accounting and correction procedure was

Table 1. Mean Annual Flows (cfs) at the Illinois River at Marseilles and the Gages Upstream, and Their Annual Water Budgets

Streamgage	Area (sq mi)	Mean annual flows in water year (cfs) 1985	1986	1987	1988
Illinois River at Marseilles (05543500)	8,259	10,273	11,160	9,355	8,211
Gages upstream of Marseilles					
CS&SC at Romeoville (05536995)	740	3,789	3,823	3,900	3,392
Des Plaines River at Riverside (05532500)	630	658	867	856	648
Hickory Creek at Joliet (05539000)	107	82	69	67	66
Du Page River at Shorewood (05540500)	324	311	303	364	323
Kankakee River near Wilmington (05527500)	5,150	5,737	6,095	4,751	3,801
Mazon River near Coal City (05542000)	455	341	475	263	193
Sum of gaged area and flows (upstream of Marseilles)	7,406	10,918	11,632	10,201	8,423
(Flow at Marseilles) – (Sum of gaged flows)		–645	–472	–846	–212
[†] Estimated flow from ungaged area	853	783	964	872	692
(Flow at Marseilles) – (Sum of gaged flows) – (Estimated flow from ungaged area)		–1,428	–1,436	–1,718	–904

[†] The flow from the ungaged area was estimated based on the sum of average annual discharges from Mazon River, Du Page River, Hickory Creek, and Des Plaines River, divided by their area (1,516 sq mi), and multiplied by 853 sq mi.

Table 2. Mean Annual Flows (cfs) and the Water Budget for the Illinois River between Stations at Marseilles and Kingston Mines

Streamgage	Area (sq mi)	Mean annual flows in water year (cfs) 1985	1986	1987	1988
Illinois River at Kingston Mines (05568500)	15,818	16,698	19,107	15,701	13,616
Gages upstream of Kingston Mines					
Fox River at Dayton (05552500)	2,642	2,108	2,692	2,418	2,056
Vermilion River near Leonore (05555300)	1,251	714	1,209	807	512
Big Bureau Creek at Princeton (05556500)	196	152	178	126	149
Mackinaw River below Congerville (05567500)	767	575	675	553	169
Illinois River at Marseilles (05543500)	8,259	10,273	11,160	9,355	8,211
Sum of gaged area and flows (upstream of Kingston Mines)	13,115	13,822	15,914	13,259	11,097
(Flow at Kingston Mines) - (Sum of gaged flows)		2,876	3,193	2,442	2,519
† Estimated flow from ungaged area	2,703	1,975	2,646	2,173	1,606
(Flow at Kingston Mines) - (Sum of gaged flows) - (Estimated flow from ungaged area)		901	547	269	912

† The flow from the ungaged area was estimated based on the sum of average annual discharges from Fox River, Vermilion River, Big Bureau Creek, and Mackinaw River divided by their area (4,856 sq mi), and multiplied by 2,703 sq mi.

Table 3. Mean Annual Flows (cfs) and the Water Budget for the Illinois River between Stations at Kingston Mines and Meredosia

Streamgage	Area (sq mi)	Mean annual flows in water year (cfs) 1985	1986	1987	1988
Illinois River at Meredosia (05585500)	26,028	25,156	26,145	21,165	15,842
Gages upstream of Meredosia					
Illinois River at Kingston Mines (05568500)	15,818	16,698	19,107	15,701	13,616
Spoon River at Seville(05570000)	1,636	1,361	1,319	1,112	636
Sangamon River near Oakford (05583000)	5,093	3,391	4,328	2,777	2,132
La Moine River at Ripley (05585000)	1,293	1,260	1,385	948	191
Sum of gaged area and flows (upstream of Meredosia)	23,840	22,710	26,139	20,538	16,575
(Flow at Meredosia) – (Sum of gaged flows)		2,436	6	627	–733
†Estimated flow from ungaged area	2,188	1,640	1,918	1,319	807
(Flow at Meredosia) – (Sum of gaged flows) – (Estimated flow from ungaged area)		796	–1,912	–692	– 1,540

† The flow Corn the ungaged area was estimated based on the sum of average annual discharges from Spoon River, Sangamon River, and La Moine River, divided by their area (8,022 sq mi), and multiplied by 2,188 sq mi.

developed. This procedure was based on the difference between the reach drainage area and the gaged tributary area, and the difference between the historic average outflow and the sum of the historic average gaged tributary flows. A typical reach is shown in figure 4, where G_1 and G_2 are two gaging stations with drainage areas A_1 and A_2 and long-term average flows Q_1 and Q_2, respectively. Similarly, A_{down} and A_{up}, and Q_{down} and Q_{up}, are the drainage areas and the average flows at the downstream and upstream points of the reach, respectively. The overall ratio of the unaccounted flow to unaccounted area (l) is

$$\lambda = \frac{Q_{down} - (Q_{up} + Q_1 + Q_2)}{A_{down} - (A_{up} + A_1 + A_2)} \tag{7}$$

The flow to area ratio for each tributary gaging station (l_1 and l_2) can also be given as

$$\lambda_1 = \frac{Q_1}{A_1}\ ; \qquad \lambda_2 = \frac{Q_2}{A_2} \tag{8}$$

If DA_1 and DA_2 are the ungaged areas that can be accounted by gages G_1 and G_2, respectively, then the flow correction coefficients (y_1 and y_2) for each tributary gaging station can be written as

$$\Psi_1 = \frac{\lambda}{\lambda_1} \times \frac{\Delta A_1}{A_1} + 1 \tag{9}$$

and

$$\Psi_2 = \frac{\lambda}{\lambda_2} \times \frac{\Delta A_2}{A_2} + 1 \tag{10}$$

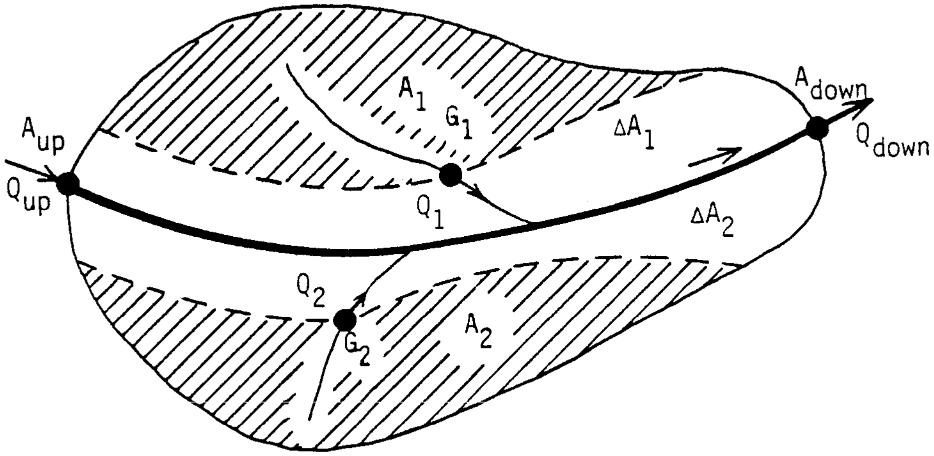


Figure 4. Illustration of a typical reach with gaged and ungaged areas

It must be noted that Ψ_{up} is unity ($\Delta A_{up} = 0$) because the mainstream flow hydrology is much different than the tributary flow hydrology. It was assumed that the flow from the ungaged areas will follow the distribution of the flows at the nearby gages. Therefore, if the parameters of the model are estimated by using the tributary gage flows, the parameters of each tributary need to be multiplied by that gage's flow correction coefficient. For each tributary gage, table 4 shows the drainage area (A), the ungaged drainage area contributing to that tributary (ΔA), and the flow correction coefficient (Ψ), for the different periods used in the model.

Structure and Development of the Illinois River Flow Model

The Illinois River Flow Model was used for flow routing in the Illinois Waterway between Lockport and Meredosia. The software for the model has already been developed and tested during the early stages of the study. The model is based on the concept of discrete, multi-input, linear drainage systems, which enables the use of all available flow data to construct a correlative, linear black-box model. In this type of model a long river system is usually divided into shorter segments, or reaches, at intermediate gaging stations. The upstream and downstream endpoints of each segment are marked by gaging stations. Figure 5 shows a black-box diagram of a simple reach with two tributaries and one outflow.

A simple mathematical representation of this system can be made as follows:

$$\hat{Q}_t = \sum_{i=1}^{p} a_i I_{t-i} + \sum_{j=1}^{q} b_j T_{t-j} \tag{11}$$

where $\hat{Q}_t$ is the estimate of the system output at time t, I and T are the tributary inflows to the system, a_i and b_j are the model parameters, and p and q are the time lags for each tributary inflow. When p = 3 and q = 2, we find that

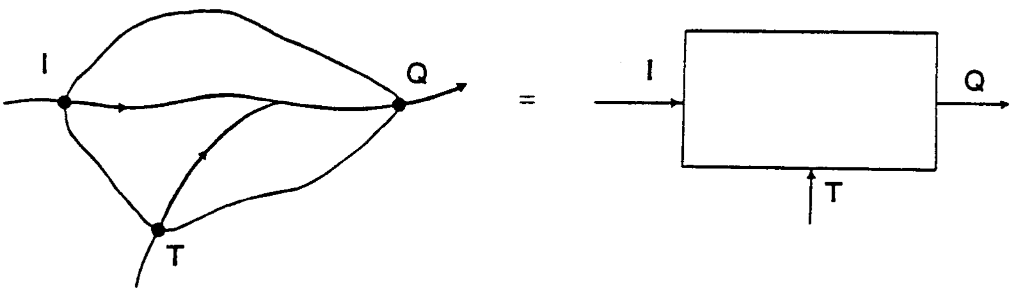


Figure 5. A simple reach and its black-box representation

Table 4. Flow Correction Coefficients of the Streamflow Gages

Streamgage	A (mi^2)	ΔA (mi^2)	Flow correction coefficients, (Ψ)			
			1955 - 1965	1966 - 1974	1975 - 1983	1984 - 1988
Lockport	740	0.0	1.0000	1.0000	1.0000	1.0000
Des Plaines	630	75.0	1.0907	1.0949	1.0614	0.9434
Hickory	107	115.9	1.7488	1.9293	1.5496	0.1419
Du Page	324	66.4	1.1342	1.1626	1.0981	0.8854
Kankakee	5150	254.7	1.0308	1.0384	1.0243	0.9725
Mazon	455	341.0	1.6422	1.6580	1.4045	0.4410

Streamgage	A (mi^2)	ΔA (mi^2)	Flow correction coefficients, (Ψ)		
			1955 - 1966	1967 - 1977	1978 - 1988
Marseilles	8259	0	1.0000	1.0000	1.0000
Fox	2642	155	1.0497	1.0658	1.0687
Vermilion	1251	449	1.3716	1.4330	1.4462
Big Bureau	196	1213	6.4053	8.4387	8.7183
Mackinaw	767	887	2.2567	2.4213	2.5435

Streamgage	A (mi^2)	ΔA (mi^2)	Flow correction coefficients, (Ψ)		
			1955 - 1966	1967-1977	1978 -1988
Kingston Mines	15819	0	1.0000	1.0000	1.0000
Spoon	1636	844	1.6212	1.4924	1.3874
Sangamon	5093	835	1.2058	1.1457	1.1249
La Moine	1293	508	1.4696	1.4124	1.2905

$$\hat{Q}_t = (a_1 I_{t-1} + a_2 I_{t-2} + a_3 I_{t-3}) + (b_1 T_{t-1} + b_2 T_{t-2}) \qquad (12)$$

If N is the number of observations, the model parameters a_i and b_j can be estimated by minimizing the sum of squares (S) of the model residuals ($e_t = Q_t - \hat{Q}_t$) between the observed and the estimated flows as:

$$\text{Minimize} \quad S = \sum_{t-1}^{N} (e_t)^2 \qquad (13)$$

This simple model suffers from frequent estimation of negative flows and lack of long-term water balance in the reach. Moreover, the solution matrix is frequently ill-conditioned, resulting in unstable solutions (Abadie, 1970).

Several researchers have developed improved versions of this model. Natale and Todini (1974) have shown that good estimations of parameters a and b can be obtained by introducing some constraints on the solution of this linear system, which provides nonnegativity, mass balance, and parameter stability. Yazicigil et al. (1980) used these constrained models on large river basins and observed high serial correlations in the model residuals, which indicates unexplained variance in the model. Nakashima and Singh (1983) tried to use an additional autoregressive term in the model to explain the serial residual correlation without using constraints due to the increased complexity of parameter estimation. Durgunoğlu and Rao (1985) used a quadratic programming technique to estimate the parameters of the constrained system with autoregressive terms. The present model is an improved version of the Nakashima-Singh and Durgunoğlu-Rao models.

A computer program was written to integrate the hydrological data into the quadratic programming algorithm. The user may choose either a model with or without an autoregressive parameter. The model is also capable of integrating data on uniformly distributed precipitation over the reach, if precipitation data are available. If the precipitation option is selected, an infiltration loss coefficient is computed in the program, based on the long-term total precipitation and runoff in the reach. The loss coefficient is then incorporated into the model constraints to maintain the water balance. The program also checks the difference between the total inputs and output of the system, and, if necessary, adjusts the model parameters to compensate for the difference. This difference usually occurs either due to systematic measurement biases or due to unmeasured inflows from ungaged areas within the reach.

For this study, the Illinois Waterway between Lockport and Meredosia was divided into three reaches (figure 6). The mathematical representation of each reach can be shown as

Reach 1

$$(\hat{Q}_{MAR})_t = \beta 1\,(Q_{MAR})_{t-1} + \sum_{i=0}^{p_1-1} a1_i\,(Q_{MAZ})_{t-i} + \sum_{j=0}^{q_1-1} b1_j\,(Q_{KAN})_{t-j} + \sum_{k=0}^{r_1-1} c1_k\,(Q_{DUP})_{t-k} + \sum_{l=0}^{s_1-1} d1_l\,(Q_{HIC})_{t-l} + \sum_{m=0}^{v_1-1} f1_m\,(Q_{DES})_{t-m} + \sum_{n=0}^{z_1-1} g1_n\,(Q_{LOC})_{t-n} \tag{14}$$

Reach 2

$$(\hat{Q}_{KM})_t = \beta 2\,(Q_{KM})_{t-1} + \sum_{i=0}^{p_2-1} a2_i\,(Q_{MAC})_{t-i} + \sum_{j=0}^{q_2-1} b2_j\,(Q_{BB})_{t-j} + \sum_{k=0}^{r_2-1} c2_k\,(Q_{VER})_{t-k} + \sum_{l=0}^{s_2-1} d1_l\,(Q_{FOX})_{t-l} + \sum_{m=0}^{v_2-1} f1_m\,(Q_{MAR})_{t-m} \tag{15}$$

Reach 3

$$(\hat{Q}_{MER})_t = \beta 3\,(Q_{MER})_{t-1} + \sum_{i=0}^{p_3-1} a3_i\,(Q_{LAM})_{t-i} + \sum_{j=0}^{q_3-1} b3_j\,(Q_{SAN})_{t-j} + \sum_{k=0}^{r_3-1} c3_k\,(Q_{SPN})_{t-k} + \sum_{l=0}^{s_3-1} d3_l\,(Q_{KM})_{t-l} \tag{16}$$

where

Q_{LOC} = Flow at Lockport
Q_{DES} = Flow from Des Plaines River
Q_{HIC} = Flow from Hickory Creek
Q_{DUP} = Flow from Du Page River
Q_{KAN} = Flow from Kankakee River
Q_{MAZ} = Flow from Mason River
Q_{MAR} = Flow at Marseilles
Q_{FOX} = Flow from Fox River
Q_{VER} = Flow from Vermilion River
Q_{BB} = Flow from Big Bureau Creek
Q_{MAC} = Flow from Mackinaw River
Q_{KM} = Flow at Kingston Mines
Q_{SPN} = Flow from Spoon River
Q_{SAN} = Flow from Sangamon River
Q_{LAM} = Flow from La Moine River
Q_{MER} = Flow at Meredosia

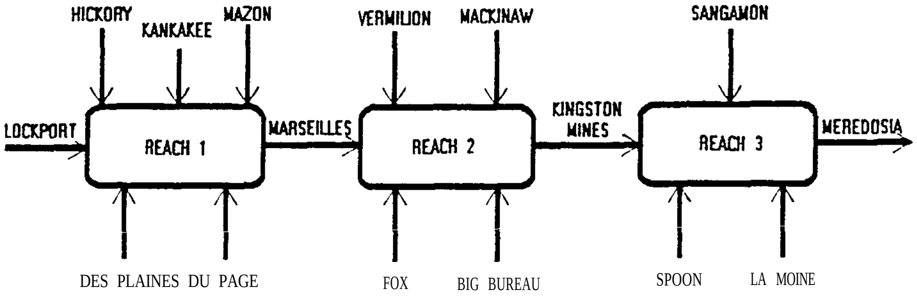


Figure 6. A schematic diagram of three reaches of the Illinois River between Lockport and Meredosia

Flow subscript t indicates the discrete time interval (usually days for large rivers); p, q, r, s, and v indicate the number of lags used in the model for each tributary flow; and ß is the autoregressive parameter. The numbers following these parameters indicate the reach (e.g., $\beta 1$ is the autoregressive parameter for Reach 1). It must be noted that in this model the outflow at time t is correlated to tributary inflows at time t. This configuration is useful for simulation purposes. A slightly different version, which is also built into the program, can correlate outflows at time t to inflows at time t-1 for forecasting purposes. The parameters a, b, c, d, f, g, and β should satisfy the following constraints for each reach:

$$\sum a = (1-\beta) \quad \text{for all a, b, c, d, f, and g} \tag{17}$$

and

$$1 \geq \beta \geq 0 \tag{18}$$

These parameters basically guarantee that the long-term mass balance is preserved (equation (17)) and the estimated flows are stationary and nonnegative (equation (18)).

Model Parameters and Simulation Results

The parameters of the three reaches were estimated by using the quadratic programming procedure and the improved model structure. The objective function of the quadratic program, given by equation (13), was minimized under the constraint of equations (17) and (18). The error term in the objective function (e_t) was obtained for each reach by equations (14), (15), or (16). Tables 5-7 give the model's estimated parameters. Because it was necessary to use three or four time periods, the estimation procedure took a long time. The optimum set of model parameters for each reach was selected by using a subjective criterion because there was no objective method available. The criterion used here was based on the parsimony and the expected lag of flows between the gaging stations and the tributaries. To better understand the analytical form of the model, the analytical model equation of Reach 3, based on the model parameters given in table 7,is given below for the period from 1978 - 1988.

Table 5. Model Parameters for Reach 1

LAG	Lockport	Des Plaines	Hickory	Du Page	Kankakee	Mazon	Marseilles
Years 1955 - 1965							
0	0.57550	0.74740	–1.86741	1.72848	0.78057	1.07459	0.00000
1	0.10970		3.00164	–0.95127	–0.07425	0.05067	0.31481
2			0.06407				
Years 1966 - 1974							
0	0.51552	1.72752	–0.00381	1.22747	0.85380	0.23986	0.00000
1	–0.03211	–2.32017	2.55347	–0.13210	–0.53996	0.78372	0.69782
2	–0.03986	0.92378	–1.95694	–0.74291		–0.42843	
3	–0.02770					–0.08351	
4	–0.05552					–0.01214	
5	–0.05816						
Years 1975 - 1983							
0	0.56500	0.28267	–1.20681	3.09214	0.75952	0.58151	0.00000
1	–0.02562		1.61109	–2.80041	–0.48553	0.86119	0.73197
2	–0.27135					–1.07793	
Years 1984 - 1988							
0	0.55013	0.34723	–5.09811	4.13209	0.83107	0.23484	0.00000
1	–0.18210		5.15035	–3.80623	–0.47315	–0.07252	0.63197

$$(\hat{Q}_{\text{MER}})_t = 0.89215\ (Q_{\text{MER}})_{t-1} + 0.13918\ (Q_{\text{LAM}})_t + 0.15231\ (Q_{\text{SAN}})_t \qquad (19)$$

$$-\ 0.31424(Q_{\text{SAN}})_{t-1} + 0.28326(Q_{\text{SAN}})_{t-2} + 0.14963(Q_{\text{SPN}})_t$$

$$+\ 0.4892\ (Q_{\text{KIN}})_t - 0.38125\ (Q_{\text{KM}})_{t-1}$$

The analytical model equations for other time periods and reaches can be written similarly. Table 8 gives the values of the observed and the simulated flows at certain flow durations for three stations. All the results indicate a very good match.

It must be noted that the simulated flow duration values (table 8) were estimated during the parameter estimation process of the model. These flows will yield the minimum achievable errors (for observed and simulated flows) defined by the objective function (equation (13)). This mode of simulation, the “forecasting mode,” is possible only if the flow for the previous day (Q_{t-1}) is available to estimate today’s flow ($\hat{Q}_t$) and is useful for analyzing the accuracy of the parameter estimation. However, since the flows downstream of Lockport are not known under TARP

Table 6. Model Parameters for Reach 2

LAG	Marseilles	Fox	Vermilion	Big Bureau	Mackinaw	Kingston Mines
Years 1955-1966						
0	0.12965	0.35936	0.04323	-0.09946	0.25827	0.00000
1	-0.04617	-0.30027	-0.02590	0.68145	-0.08486	0.89076
2	0.07735	0.20278	0.16089	-0.07811	-0.00299	
3	-0.02230	-0.14305	-0.04382	0.07262	-0.07387	
4	-0.01426	0.00868	0.01362	0.17157		
5	-0.01504	0.10120		-0.24912		
6		-0.08779		0.16309		
7		0.06246		-0.16380		
8		-0.07303		0.21992		
9		-0.01565				
Years 1967-1977						
0	0.15279	0.14047	0.45417	-0.21663	0.06480	0.00000
1	-0.06420	-0.09023	-0.71449	0.26516	0.40847	0.91603
2	0.07891	0.14596	0.38830	0.15569	-0.10969	
3	-0.02194	0.02357	-0.00766	-0.02819	-0.16026	
4	-0.02648	-0.00938		0.07953		
5	-0.00426	-0.04735		-0.22785		
6	-0.01007	-0.06177		0.22200		
7	-0.02077	0.04149		0.23097		
8		-0.02782		0.04799		
9		-0.02545		0.17990		
Years 1978-1988						
0	0.16634	0.20365	0.22740	-0.52035	-0.03700	0.00000
1	-0.09755	-0.07785	-0.10000	0.34534	0.23562	0.91737
2	0.12178	-0.05613	0.10713	0.75871	0.01157	
3	-0.01099	-0.05936	-0.13948	0.13674		
4	-0.06635	0.15938	0.02446			
5	-0.04828	-0.06012				
6	0.03922	0.14469				
7	0.00195	-0.19101				
8	-0.02441	0.09344				
9	0.00092	-0.06838				

Table 7. Model Parameters for Reach 3

LAG	Kingston Mines	Spoon	Sangamon	LaMoine	Meredosia
Years 1955 - 1966					
0	0.14488	0.31196	0.17199	0.34380	0.00000
1		−0.07663		−0.13284	0.85512
Years 1967 - 1977					
0	0.13731	0.29351	0.15733	0.39169	0.00000
1		−0.08858		−0.19774	0.86269
Years 1978 - 1988					
0	0.48920	0.14963	0.15231	0.13918	0.00000
1	−0.38135		−0.31424		0.89215
2			0.28326		

operation, the model has to be used in a “simulation mode,” where $\hat{Q}_t$ values are estimated based on the simulated $\hat{Q}_{t-1}$ values. This mode can also be called the “no-feedback” or “self-generating” mode. Statistically, the results from this mode cannot be more accurate than the results obtained from the “forecasting” mode.

Figures 7-9 compare observed and estimated flows for Marseilles, Kingston Mines, and Meredosia, respectively. Typical dry, average, and wet years were selected for comparison. It can be seen from these figures that the differences between the observed and estimated daily flows are almost indistinguishable.

The Illinois River Flow Model was used in a “simulation” mode with the adjusted historical Lockport flows (without TARP) to generate the flows at the three downstream stations. These flow series represent the base conditions that would have existed without TARP. All the changes that were simulated under any TARP operation were compared with these base conditions.

EFFECT OF TARP ON LOCKPORT FLOWS

Implementation of Phases I and II of TARP will alter the pattern of flows in the Chicago Sanitary and Ship Canal (CS&SC) and the Calumet-Sag Channel, and consequently the flow patterns at Lockport. The effects of these changes downstream of Lockport were then analyzed by using these modified Lockport flows as inputs to the

Table 8. Observed and Simulated Flow Duration Values (cfs)

Probability of exceedance (%)	Marseilles		Kingston Mines		Meredosia	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
99	3210	3254	3300	2809	4200	4253
98	3450	3488	3700	3526	4834	4872
97	3625	3673	4000	4021	5220	5226
96	3760	3800	4210	4331	5550	5537
95	3880	3897	4400	4506	5800	5789
94	3981	4000	4530	4711	5990	5950
93	4080	4120	4700	4934	6160	6127
92	4170	4224	4860	5096	6350	6331
91	4250	4311	5000	5263	6520	6499
90	4320	4388	5100	5395	6700	6683
85	4670	4743	5770	6082	7500	7499
80	4980	5069	6350	6643	8368	8379
75	5310	5388	6880	7167	9460	9404
70	5620	5704	7420	7736	10500	10447
65	5940	6046	8000	8349	11700	11637
60	6310	6412	8720	9096	13000	12938
55	6760	6828	9550	9876	14455	14411
50	7260	7349	10500	11000	16200	16249
45	7880	7967	12000	12459	18400	18364
40	8610	8681	13900	14473	21800	21841
35	9430	9501	16500	17294	24900	24924
30	10500	10528	19000	19482	27600	27661
25	11700	11720	21000	21485	30900	31072
20	13400	13423	23360	23876	34200	34393
15	15800	15761	26700	27111	38600	38591
10	19000	18850	31000	31671	46700	46828
9	19700	19568	32400	33090	48800	48859
8	20600	20461	33900	34451	51500	51254
7	21800	21503	35400	35992	54400	54299
6	23100	22921	37000	37521	58400	58103
5	24705	24322	38800	39674	62100	61972
4	27000	26695	41300	42058	65800	65599
3	30243	29396	44000	45447	71843	71413
2	34600	33758	48300	50230	79062	77930
1	41381	40238	57433	58727	90481	89781
Average flow	10006	9994	15274	15720	22803	22795

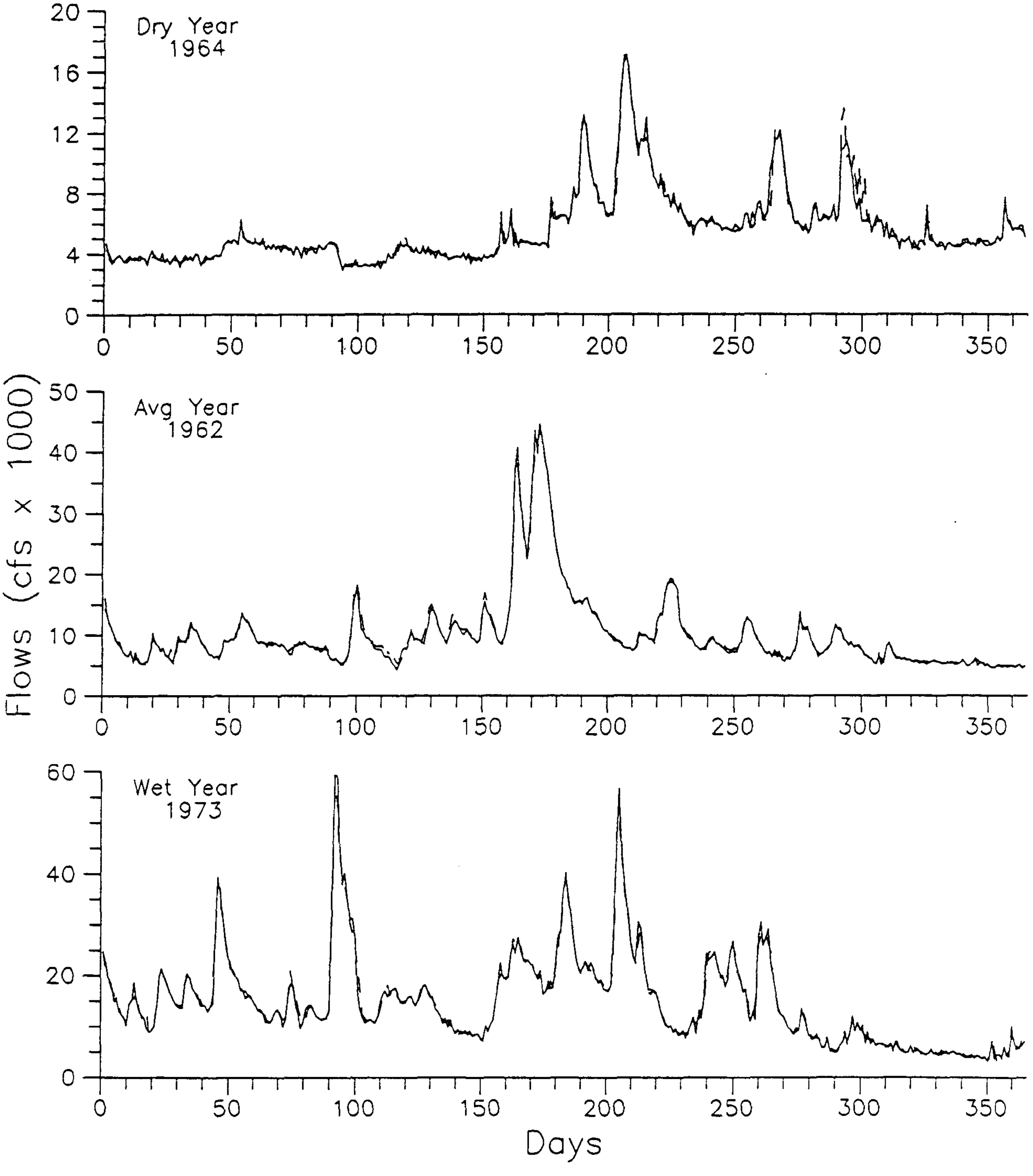


Figure 7. Observed flows (solid line) versus estimated flows (dashed line) for a typical dry, average, and wet year for Marseilles

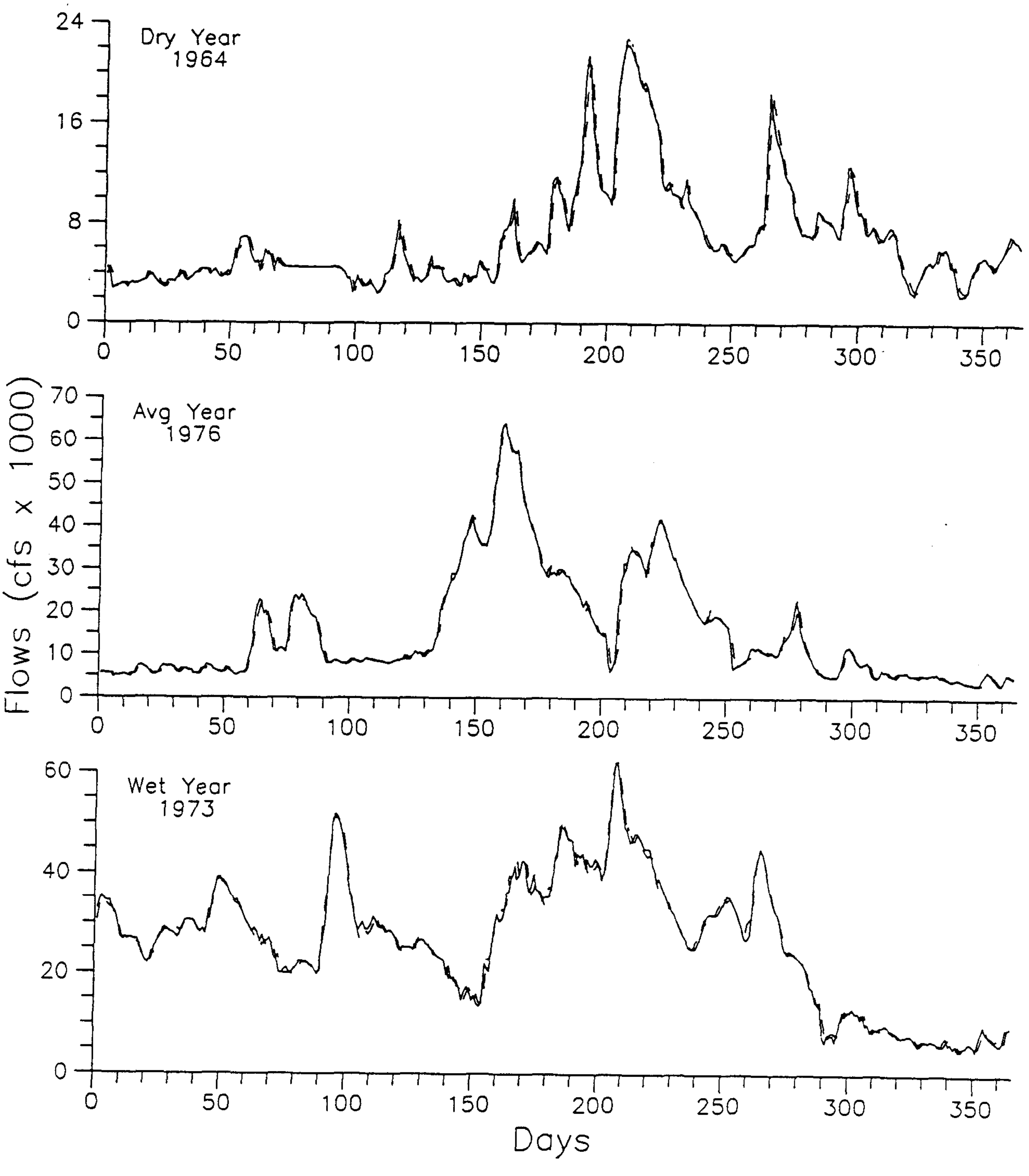


Figure 8. Observed flows (solid line) versus estimated flows (dashed line) for a typical dry, average, and wet year for Kingston Mines

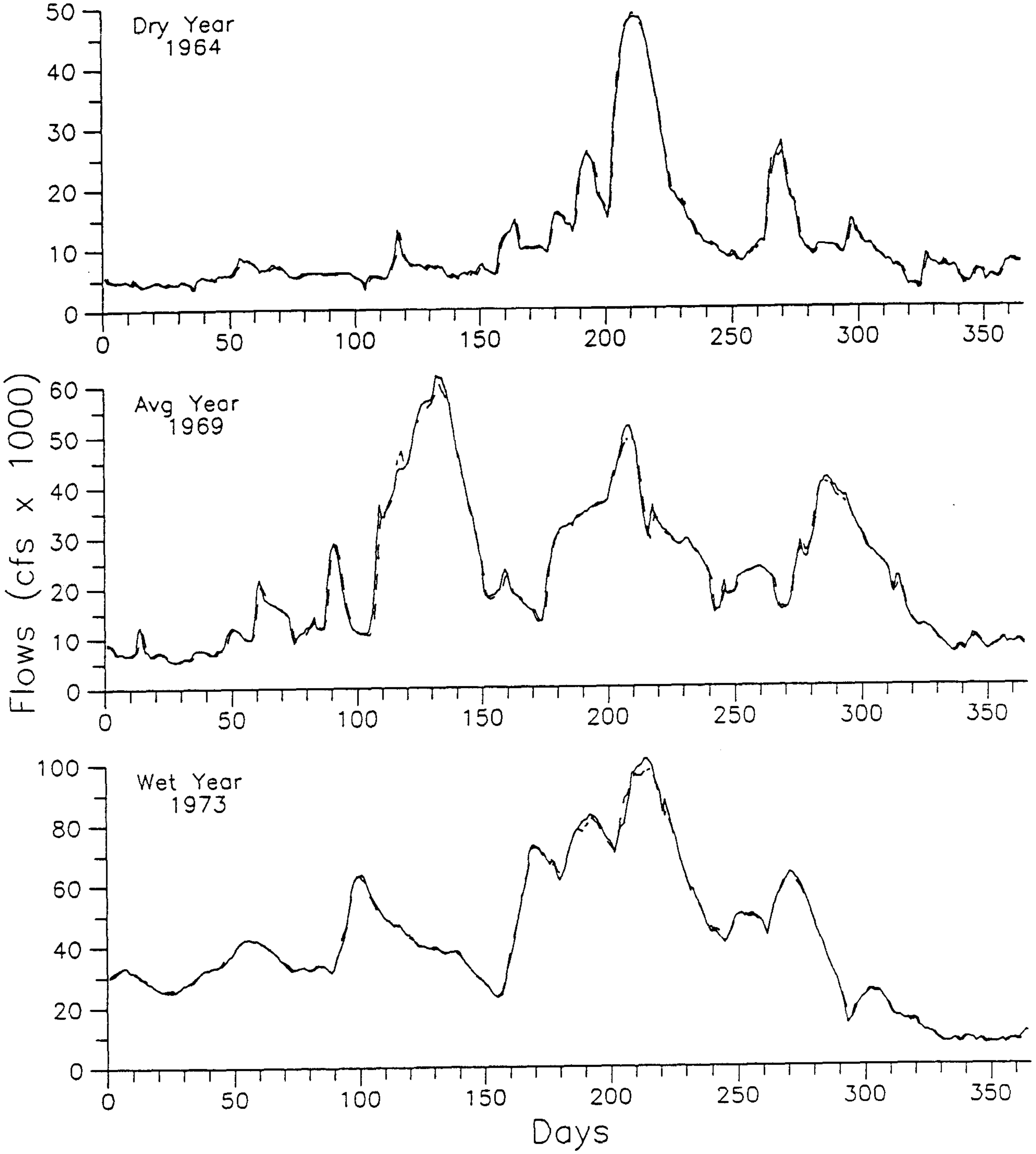


Figure 9. Observed flows (solid line) versus estimated flows (dashed line) for a typical dry, average, and wet year for Meredosia

Illinois River Flow Model. Modification of the Lockport flows as a result of TARP operation requires obtaining the daily flow values in the CS&SC and Calumet-Sag Channel at or near the WRP locations. The average daily flow series at Lockport were then simulated by routing these CS&SC and Galumet-Sag flows under three operating conditions of TARP: 1) without TARP storage, 2) with TARP Phase I tunnel storage, and 3) with TARP Phase II tunnel and reservoir storage.

Since the measured daily flows at CS&SC and Calumet-Sag channel were not available, it was attempted to correlate these flows to the historical daily flows at Lockport by using the flow data at FULEQ nodes 24 and 45, the most appropriate nodes for this purpose (Figure 9-2, Volume-B, COE, 1986). However, COE could not provide this data. Therefore, a method was developed to extract the daily flows at the canals, based on the average monthly diversions and WRP releases, daily Lockport flows, and the partial drainage areas of the Mainstream and Calumet Systems, in proportion to the total area above Lockport. MWRDGC provided the monthly WRP releases and Lake Michigan diversions for the period from0 1971-1985 (table 9). It was assumed that the WRP releases would equal the inflows.

The method used here was based on the assumption that the natural surface runoff can be correlated to the drainage area. Therefore, it was necessary to subtract from the Lockport flows all the flows that did not originate corn surface runoff. These include the raw sewage portion of the combined sewer flows (natural surface runoff plus the raw sewage) entering the WRPs, and the Lake Michigan diversions. Thus, the Lockport flows can be expressed as follows:

$$Q_{LOCKPORT} = Q_{SR} + \sum Q_{DIVERSION} + \sum Q_{SEWAGE} \tag{20}$$

where

$Q_{LOCKPORT}$ = daily Lockport flows
Q_{SR} = surface runoff contributed from upstream of Lockport (740 sq mi)
$Q_{DIVERSION}$ = average monthly diversion flows
Q_{SEWAGE} = estimated monthly raw sanitary sewage flows.

For Q_{SEWAGE} values, the lowest WRP releases for each month for a 15-year period (1971-1985) were used (lower portion of table 9), assuming that the lowest values would include negligible runoff. This allowed the use of a different Q_{SEWAGE} value for each month. Overall average monthly WRP releases could not be used directly because they include combined sewer flows.

Table 9. Average Monthly Water Reclamation Plant (WRP) Releases and Lake Michigan Diversions (DIV), in cfs

Year	WRP&DIV		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
'71	North Side	WRP	424	500	532	454	461	526	518	513	506	440	422	468	480
	Stickney	WRP	1106	1261	1264	1100	1111	1304	1247	1204	1253	1060	1040	1190	1178
	Calumet	WRP	248	288	315	260	270	281	312	274	284	236	228	294	274
	Chicago	DIV	56	25	4-4	126	406	276	894	1484	776	784	616	139	469
	O’Brien	DIV	175	123	34	97	472	511	1127	1895	1027	1038	835	225	630
	Wilmette	DIV	37	26	132	274	213	329	381	460	276	326	158	40	221
‘72	North Side	WRP	453	432	524	578	531	524	531	575	551	516	545	368	511
	Stickney	WRP	1227	1202	1351	1423	1345	1303	1502	1464	1253	1242	1270	1216	1317
	Calumet	WRP	306	236	310	346	304	282	287	328	308	312	364	338	310
	Chicago	DIV	29	76	121	275	403	496	816	840	758	211	79	46	346
	O’Brien	DIV	122	141	143	328	455	551	995	1170	1348	324	245	61	490
	Wilmette	DIV	32	56	43	67	206	357	233	271	235	41	44	40	135
‘73	North Side	WRP	538	506	582	588	536	538	546	522	503	507	477	539	532
	Stickney	WRP	1219	1213	1368	1419	1295	1326	1375	1400	1280	1238	1133	1238	1292
	Calumet	WRP	345	310	368	390	356	345	310	300	272	292	266	337	324
	Chicago	DIV	45	31	551	469	477	621	436	266	134	115	57	41	270
	O’Brien	DIV	81	55	663	489	581	768	535	218	145	116	71	51	314
	Wilmette	DIV	40	44	125	63	39	40	46	45	43	42	41	38	51
‘74	North Side	WRP	523	536	556	553	556	519	519	497	437	425	445	482	504
	Stickney	WRP	1272	1267	1267	1287	1355	1317	1348	1306	1150	1106	1103	1136	1243
	Calumet	WRP	343	334	367	380	396	389	341	198	264	254	294	322	323
	Chicago	DIV	39	34	35	85	111	137	167	154	111	96	107	408	124
	O’Brien	DIV	49	54	59	95	141	164	207	200	135	116	154	553	161
	Wilmette	DIV	37	39	41	42	41	45	46	45	45	42	81	339	70
‘75	North Side	WRP	514	511	541	573	544	535	506	512	459	428	465	531	510
	Stickney	WRP	1187	1205	1167	1354	1312	1454	1382	1403	1208	1207	1239	1352	1289
	Calumet	WRP	333	302	318	455	417	388	323	326	309	280	286	346	340
	Chicago	DIV	231	33	84	554	150	148	158	143	104	99	48	40	149
	O’Brien	DIV	304	67	66	607	215	184	201	171	141	123	88	60	186
	Wilmette	DIV	146	38	46	37	40	41	43	43	46	43	40	35	50
‘76	North Side	WRP	431	582	559	514	516	486	469	461	430	417	391	395	471
	Stickney	WRP	1159	1309	1479	1238	1255	1235	1239	1247	1225	1150	1040	961	1211
	Calumet	WRP	290	352	398	344	374	383	316	299	282	268	263	249	318
	Chicago	DIV	497	781	83	130	179	251	185	191	111	96	200	777	290
	O'Brien	DIV	689	909	132	145	91	151	212	187	134	129	375	823	331
	Wihnette	DIV	37	55	35	46	47	128	67	45	43	40	162	108	68
‘77	North Side	WRP	395	444	502	478	459	493	481	477	484	406	390	457	455
	Stickney	WRP	984	1117	1323	1215	1177	1313	1349	1335	1422	1191	1143	1190	1230
	Calumet	WRP	258	275	314	318	293	316	335	328	351	317	309	340	313
	Chicago	DIV	1112	1411	113	104	102	121	204	123	110	88	94	58	303
	O’Brien	DIV	1152	994	155	170	186	273	381	232	127	125	37	61	324
	Wihnette	DIV	165	84	31	95	172	167	162	148	137	30	19	2	101
‘78	North Side	WRP	389	369	516	548	480	493	502	438	473	389	411	445	454
	Stickney	WRP	1021	1020	1380	1546	1331	1397	1485	1328	1380	1064	1086	1162	1267
	Calumet	WRP	368	319	381	378	361	331	337	348	337	303	313	356	344
	Chicago	DIV	48	151	186	81	86	472	727	705	710	405	48	35	305
	O’Brien	DIV	44	157	228	112	91	495	689	500	693	316	54	37	285
	Wilmette	DIV	3	3	2	2	4	103	82	121	108	27	3	3	38

Table 9. Concluded

Year	WRP&DIV		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG
'79	North Side	WRP	407	441	583	552	478	485	477	544	429	386	403	435	468
	Stickney	WRP	1106	1318	1796	1533	1331	1334	1283	1656	1233	1218	1224	1170	1350
	Calumet	WRP	342	328	362	374	364	343	330	382	328	306	323	350	344
	Chicago	DIV	33	59	60	89	99	454	622	560	593	305	59	39	248
	O’Brien	DIV	47	74	132	103	133	531	787	749	882	656	147	49	358
	Wilmette	DIV	2	3	2	3	4	50	105	72	186	64	4	3	42
'80	North Side	WRP	423	411	483	565	433	456	449	482	458	381	351	410	442
	Stickney	WRP	1142	1165	1304	1372	1184	1382	1309	1473	1362	1156	1032	1198	1256
	Calumet	WRP	333	317	398	415	353	381	348	393	404	342	317	354	363
	Chicago	DIV	39	34	39	79	234	431	741	574	721	345	59	49	279
	O’Brien	DIV	61	45	74	168	219	365	763	647	1045	348	99	87	327
	Wilmette	DIV	3	3	3	3	4	132	172	79	155	68	3	3	52
'81	North Side	WRP	340	424	372	463	522	515	469	491	451	385	404	411	437
	Stickney	WRP	1009	1179	1092	1351	1389	1413	1419	1419	1208	1187	1185	1136	1249
	Calumet	WRP	299	345	328	384	387	368	354	339	306	269	282	279	328
	Chicago	DIV	106	52	51	114	118	515	626	675	952	187	76	43	293
	O’Brien	DIV	119	78	84	190	186	492	697	596	966	186	61	51	309
	Wilmette	DIV	3	2	3	2	6	32	80	132	267	44	3	3	48
'82	North Side	WRP	420	429	532	520	432	420	496	445	388	357	458	498	450
	Stickney	WRP	1170	1238	1536	1476	1263	1253	1456	1317	1173	1116	1329	1524	1321
	Calumet	WRP	261	291	390	399	336	340	362	330	288	268	331	359	330
	Chicago	DIV	30	25	112	60	241	441	499	834	703	311	68	111	286
	O’Brien	DIV	41	20	32	58	225	408	599	669	538	324	86	90	258
	Wilmette	DIV	2	1	0	2	8	52	58	114	117	59	2	2	35
'83	North Side	WRP	388	428	473	544	511	444	463	431	446	404	462	468	455
	Stickney	WRP	1135	1222	1328	1574	1467	1281	1372	1247	1187	1103	1142	1162	1268
	Calumet	WRP	313	303	318	348	412	365	403	350	361	335	350	382	353
	Chicago	DIV	39	37	49	74	135	511	678	562	498	343	110	38	256
	O’Brien	DIV	55	52	69	101	171	312	590	652	524	342	140	75	257
	Wilmette	DIV	3	3	3	2	3	100	188	263	122	70	3	2	64
'84	North Side	WRP	365	453	475	521	497	443	420	415	400	398	399	426	434
	Stickney	WRP	982	1198	1198	1270	1229	1162	1128	1157	1105	1170	1040	1126	1147
	Calumet	WRP	336	376	392	409	394	378	365	353	326	325	310	325	357
	Chicago	DIV	35	46	46	94	199	522	794	662	440	485	78	56	288
	O'Brien	DIV	100	63	70	117	213	487	685	608	485	477	66	76	287
	Wilmette	DIV	3	2	3	3	8	61	130	119	51	53	3	3	37
'85	North Side	WRP	402	441	518	473	414	408	409	424	388	406	549	419	437
	Stickney	WRP	1065	1158	1349	1162	1116	1102	1209	1160	1069	1157	1606	1125	1190
	Calumet	WRP	344	354	370	371	354	333	356	354	341	382	397	400	363
	Chicago	DIV	48	72	65	150	300	526	788	726	815	447	171	64	348
	O'Brien	DIV	79	99	74	123	177	355	577	696	745	421	135	95	298
	Wilmette	DIV	8	3	3	4	4	36	53	65	82	38	4	4	25

Minimum WRP and Average DIV Values

	WRP & DIV		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Min.	North Side	WRP	340	411	372	454	414	408	409	415	388	357	351	368	
	Stickney	WRP	982	1020	1092	1100	1111	1102	1128	1157	1105	1060	1032	961	
	Calumet	WRP	248	275	310	260	270	281	287	198	264	236	228	249	
Av.	Chicago	DIV	159	191	109	166	216	395	356	567	502	288	125	129	
	O’Brien	DIV	208	195	134	194	237	403	603	613	596	336	173	160	
	Wilmette	DIV	34	24	31	43	53	112	123	135	127	66	38	42	

Total surface runoff (Q_{SR}) was further divided into two components, contributed from the TRAP combined sewer area (Q_{S1}) and from the rest of the downstream non-TARP area (Q_{S2}) as

$$Q_{SR} = Q_{S1} + Q_{S2} \tag{21}$$

This division was necessary because the land-use and surface runoff characteristics of these two regions are quite different. Considering equal distribution of precipitation over the drainage areas, it is possible to write the following relations

$$Q_{S1} \propto A_1 C_1 \tag{22}$$

and

$$Q_{S2} \propto A_2 C_2 \tag{23}$$

where

A_1 = total combined sewage area of TARP
A_2 = remaining area upstream of Lockport (740 sq mi - A_1)
C_1 and C_2 = runoff coefficients for areas A_1 and A_2 (not the same areas shown in figure 4)

From equations (21), (22), and (23) Q_{S1} and Q_{S1} can be obtained as

$$Q_{S1} = \frac{Q_{SR} A_1 C_1}{A_1 C_1 + A_2 C_2} \quad \text{and} \quad Q_{S2} = Q_{SR} - Q_{S1} \tag{24}$$

If Q_{S1} was negative, which can happen due to the use of average flows, a Q_{S1} value of zero was used.

The TARP area can be further divided into Mainstream and Calumet areas, with contributing areas of A_M and A_C, respectively (see figure 10), and with different runoff coefficients (C_M and C_C).This condition should be satisfied by the following constraints:

$$A_1 = A_M + A_C \tag{25}$$

and

$$A_1 C_1 = A_M C_M + A_C C_C \tag{26}$$

The total surface runoff from TARP area (Q_{s1}) should then be

$$Q_{S1} = Q_{S1M} + Q_{S1C} \tag{27}$$

where Q_{S1M} and Q_{S1C} are the portions of the surface runoff contributed from the Mainstream and Calumet combined sewer areas, respectively. Therefore, by proportioning,

$$Q_{S1M} = Q_{S1} \frac{A_M C_M}{A_M C_M + A_C C_C} = Q_{S1} \frac{A_M C_M}{A_1 C_1} \tag{28}$$

and

$$Q_{S1C} = Q_{S1} \frac{A_C C_C}{A_M C_M + A_C C_C} = Q_{S1} \frac{A_C C_C}{A_1 C_1} \tag{29}$$

where

A_1 = 342 sq mi
A_2 = 398 sq mi (740 sq mi above Lockport - 342 sq mi of TARP area)
A_M = 252 sq mi (North Side + Stickney WRPs including Des Plaines)
A_C = 90 sq mi (Calumet WRP service area)

Since Q_{S1} is also a function of daily Q_{SR} values (which is effectively a function of the Lockport flows), the daily runoff values at the Mainstream and Calumet Systems can be estimated directly from the daily Lockport flows.

C_1, C_2, C_M, and Cc values were estimated from the limited information on mean annual storm runoffs developed by the Northeastern Illinois Planning Commission (NIPC). This study (NIPC Memorandum, 1987) estimated the mean annual runoff yields from a region covering about 678 square miles (MWRDGC combined sewer area, Plum Creek, almost all of the Calumet area, and North Branch) for the period 1949 - 1979. Yields from three different land covers (forest, grass, and impervious areas) were considered. Using the land-use percentages in this study, and analyzing the most recent topography maps, approximate land usages for the areas of interest in the study were developed (table 10).

Table 10. Land-Use Ratios for Areas Upstream of Lockport

Region	Area (sq mi)	Land cover (as a ratio of the area)		
		Forest	Grass	Impervious
Calumet	90	0.000	0.850	0.150
Mainstream	252	0.000	0.510	0.490
Total TARP area	342	0.000	0.597	0.403
Downstream of TARP	398	0.065	0.870	0.065
Total study area	740	0.037	0.745	0.218

The ratios for "Total TARP area" were obtained by the area-weighted summation of the Calumet and Mainstream ratios. Similarly, the area-weighted summations of the "Total TARP area" and "Downstream of TARP" ratios gave the ratios for the "Total study area." These ratios were then multiplied by the annual runoff yields of forest, grass, and impervious areas to obtain the average annual yield for a particular year. The annual runoff coefficients were then calculated by dividing the average annual yield by the annual precipitation. The overall mean of these runoff coefficients gave C values. This process was performed for all areas of interest. All other necessary information used in the estimation of C values is shown in table 11. For example, the runoff yield of the total TARP area for the year 1949 (12.85 inches) was obtained by adding the weighted runoffs from the forest, grass, and impervious areas (0.0 × 2.38; 0.597 × 6.26; and 0.403 × 22.62, respectively). The land-use ratios (0.0, 0.597, and 0.403) were taken from table 10. That runoff yield was then divided by the annual precipitation to obtain the average runoff coefficient (C_1) of "Total TARP area" for the year 1949 (12.85 ÷ 29.87 = 0.430). Figure 10 shows these runoff coefficients and the drainage areas to which they apply.

After all these parameters were estimated, the modified daily flow values at Lockport could be reconstructed by using the new releases from the WRPs:

$$Q_{LOCKPORT} = \sum \text{ of releases Mainstream and Calumet WRPs} + \sum Q_{DIVERSION} + Q_{s2} + \text{overflows} \tag{30}$$

For the $\sum Q_{DIVERSION}$ values prior to 1971, the mean monthly diversion values were used, as given at the bottom of table 9.

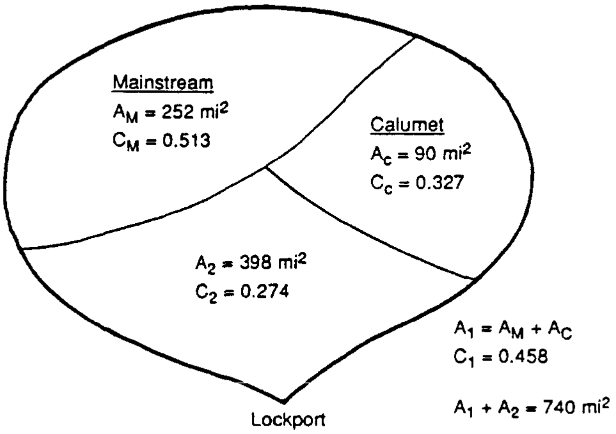


Figure 10. Runoff coeficients used in the Lockport Flow Simulation Model and their applicable areas

Table 11. Runoff Yields and Runoff Coefficients for the Areas Upstream of Lockport

Year	Precip.	Runoff yields from land cover			Calumet System		Mainstream System		Total TARP area		Downstream of TARP		Total study area	
		Forest	Grass	Imperv.	Yield	C_C	Yield	C_M	Yield	C_1	Yield	C_2	Yield	C_T
1949	29.87	2.38	6.26	22.62	8.72	0.292	14.28	0.478	12.85	0.430	7.07	0.237	9.69	0.324
1950	44.28	6.88	13.77	37.60	17.34	0.392	25.45	0.575	23.37	0.528	14.87	0.336	18.71	0.423
1951	39.54	8.36	12.15	32.85	15.26	0.386	22.29	0.564	20.49	0.518	13.25	0.335	16.52	0.418
1952	32.41	10.16	12.03	25.17	14.00	0.432	18.47	0.570	17.33	0.535	12.76	0.394	14.83	0.457
1953	29.15	1.19	4.71	21.13	7.18	0.246	12.76	0.438	11.33	0.389	5.55	0.190	8.16	0.280
1954	36.39	1.88	6.24	27.56	9.44	0.259	16.69	0.459	14.83	0.408	7.34	0.202	10.73	0.295
1955	39.26	4.70	10.32	30.94	13.42	0.342	20.43	0.520	18.63	0.475	11.30	0.288	14.61	0.372
1956	26.71	0.83	4.09	18.01	6.18	0.231	10.91	0.408	9.70	0.363	4.78	0.179	7.00	0.262
1957	39.34	3.61	8.99	31.11	12.31	0.313	19.83	0.504	17.91	0.455	10.08	0.256	13.61	0.346
1958	29.90	2.17	4.97	19.81	7.20	0.241	12.24	0.409	10.95	0.366	5.75	0.192	8.10	0.271
1959	35.08	2.64	7.44	27.71	10.48	0.299	17.37	0.495	15.61	0.445	8.45	0.241	11.68	0.333
1960	31.65	3.55	8.50	26.31	11.17	0.353	17.23	0.544	15.68	0.495	9.33	0.295	12.20	0.385
1960	39.92	1.47	6.64	30.07	10.32	0.259	18.22	0.456	16.20	0.406	8.00	0.200	11.71	0.293
1961	26.49	5.63	8.60	20.81	10.43	0.394	14.58	0.550	13.52	0.510	9.20	0.347	11.15	0.421
1962	28.20	0.11	1.58	18.51	4.12	0.146	9.87	0.350	8.40	0.298	2.58	0.092	5.21	0.185
1963	26.21	0.23	1.96	17.95	4.35	0.166	9.79	0.374	8.40	0.321	2.88	0.110	5.38	0.205
1964	38.80	2.43	8.06	30.70	11.46	0.295	19.16	0.494	17.19	0.443	9.17	0.236	12.79	0.330
1965	33.47	5.78	11.09	25.60	13.26	0.396	18.20	0.544	16.94	0.506	11.69	0.349	14.06	0.420
1966	40.38	5.47	11.89	33.99	15.20	0.376	22.72	0.563	20.79	0.515	12.91	0.320	16.47	0.408
1967	31.35	2.28	6.55	21.73	8.83	0.282	13.99	0.446	12.67	0.404	7.26	0.232	9.70	0.309
1968	38.47	3.50	9.55	28.47	12.39	0.322	18.82	0.489	17.17	0.446	10.38	0.270	13.45	0.350
1970	43.15	4.57	9.97	34.62	13.66	0.317	22.05	0.511	19.90	0.461	11.22	0.260	15.14	0.351
1970	32.06	5.04	9.42	23.22	11.49	0.358	16.18	0.505	14.98	0.467	10.03	0.313	12.27	0.383
1972	37.39	1.82	6.86	27.36	9.94	0.266	16.90	0.452	15.12	0.404	7.87	0.210	11.14	0.298
1973	40.30	11.23	17.16	31.70	19.34	0.480	24.28	0.603	23.02	0.571	17.72	0.440	20.11	0.499
1974	40.38	9.48	15.64	31.91	18.08	0.448	23.61	0.585	22.19	0.550	16.29	0.404	18.96	0.469
1975	40.70	8.05	13.35	32.46	16.22	0.398	22.72	0.558	21.05	0.517	14.25	0.350	17.32	0.426
1976	37.98	4.27	9.12	29.17	12.12	0.319	18.94	0.499	17.20	0.453	10.10	0.266	13.31	0.350
1977	38.59	1.05	5.87	28.91	9.33	0.242	17.16	0.445	15.16	0.393	7.06	0.183	10.72	0.278
1978	32.55	7.77	11.19	26.66	13.51	0.415	18.77	0.577	17.42	0.535	11.97	0.368	14.43	0.443
1979	38.36	8.51	15.09	34.52	18.00	0.469	24.61	0.642	22.92	0.597	15.92	0.415	19.08	0.497
Average:						0.327		0.503		0.458		0.274		0.357

Notes: Precipitation and all yields are in inches.

C_C, C_M, C_1, C_2, and C_T are the runoff coefficients for the Calumet System, Mainstream System, total TARP area, downstream of TARP, and total study area, respectively.

Storage capacities for TARP Phases I and II will determine the new releases from the WRPs and the CSOs. The storage capacities of the Mainstream and Calumet systems are handled separately. Under condition 1 (without TARP), there was no storage capacity; therefore, whenever the flows entering the WRPs exceeded the assumed WRP capacity, the excess flow is spilled untreated. Under condition 2 (with TARP Phase I), 4,964 and 1,638 acre-feet of TARP Phase I tunnel storage were used for the Mainstream and Calumet Systems, respectively. Tunnel storage from the Des Plaines System was included in the Mainstream tunnel storage. Under condition 3 (with TARP Phase II, and using CUP storage capacities), a total storage capacity of 39,048 acre-feet for the Mainstream System (32,100 acre-feet for McCook Reservoir and 6,948 acre-feet for tunnel storage which includes 1,984 acre-feet of TARP II relief tunnel storage), and 16,596 acre-feet for the Calumet System (14,600 acre-feet for Thornton Reservoir and 1,996 acre-feet tunnel storage which includes 358 acre-feet of TARP II relief tunnel storage) were used. However, it is possible that the relief tunnels may not be constructed until the full TARP II reservoirs are built. These values were obtained through personal communication with John Variakojis, and from the Facilities Planning Study (Appendix E, revised March 1989, MWRDGC, 1987).

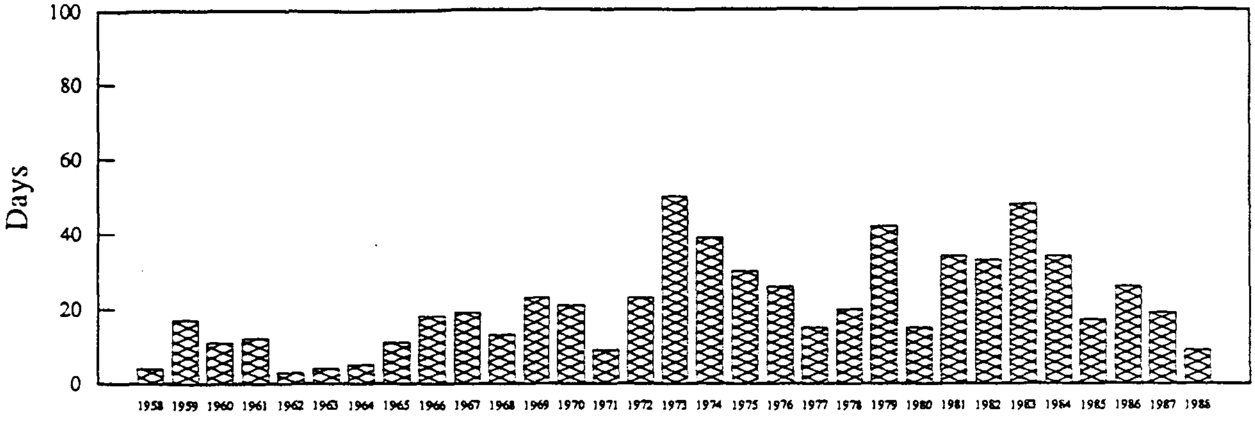
Under condition 1, the Lockport flows do not change, but it is possible to determine how much water would have spilled if the current treatment plant capacities also existed in the past. The daily simulations for 31 years (1958 - 1988) for conditions 2 and 3 were performed to obtain the daily reservoir volumes, WRP releases, and spills for the Mainstream and Calumet Systems. These releases and spills were then summed with the average sanitary sewage and diversion flows, and the natural flow contributed from 398 square miles of drainage area between TARP service area and Lockport, to obtain the modified Lockport flows. These modified Lockport flows were then used with the Illinois River Flow Model to simulate the effects of TARP storage on flows at Marseilles, Kingston Mines, and Meredosia, and then compared with the base condition. The flow model was executed in a cascade mode: the output from one reach is input to the downstream reach.

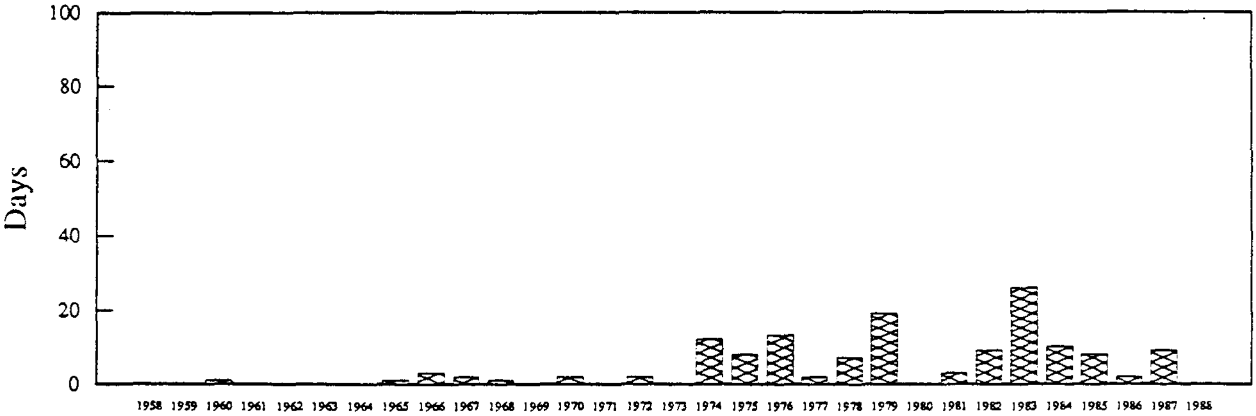
For the storage routing and dewatering algorithm, it was assumed that each WRP could operate at its maximum design capacity. For example, if on any day Q_{S1C} plus the raw sanitary effluents at Calumet (average of that month) exceeded the Calumet WRP maximum capacity (430 million gallons per day (mgd)), then the excess flow was routed into the Thornton Reservoir, provided that there was enough storage to accommodate this overflow. Otherwise, the excess untreated flow would overflow into the canal. As the flow peak receded, the WRP would still operate at its maximum capacity until all the reservoir storage was treated and released into the canal. The same procedure would apply to the Mainstream System as well. However, for the Mainstream System, both the North Side and the Stickney plants were assumed to function as a single unit, because they are both connected to McCook Reservoir. The maximum design capacities of the WRPs used in the simulation were: Mainstream System (Stickney and North Side WRPs) = 1,890 mgd and Calumet System = 430 mgd.

Figures 11 - 16 show the impacts of the TARP operation on the number of days with spills and the volume of these spills within the TARP area. These results were obtained by assuming that the WRPs can operate at maximum design capacities for a sustained period (about 60 - 90 days). The results are presented in bar charts for the total number of days with spills at the Calumet System, the Mainstream System, and the total service area (figures 11 - 13). Similarly, figures 14 - 16 show the total yearly spill volumes. The number of days with spills used in these figures indicate the total number of days where the inflow to the WRPs exceeded plant capacity.

As can be seen from the bar charts, if the CUP storage was used, the only spills expected to occur would be in the Mainstream System. The simulations also show that increasing the McCook reservoir storage capacity from 32,100 acre-feet (CUP capacity) to 70,400 acre-feet would eliminate all spills if the historical conditions were routed through TARP Phase II storage (assuming maximum design capacity for the WRPs). The TARP Phase II storage capacities mentioned here refer to the simulated reservoir capacities and *not* to the MWRDGC's planned final Phase II capacities (McCook = 83,190 acre-feet, and Thornton = 40,840 acre-feet). Obviously, by further assuming that the WRPs could not operate at their full maximum design capacities for sustained periods, the required reservoir capacity would be increased. Reservoir storage capacities necessary to eliminate all spills were also simulated for other WRP treatment capacities.

By assuming that the WRPs can operate only up to 90 percent of their maximum design capacities for a sustained period, the following additional storage capacities would be needed to avoid any spills: 72,100 and 3,400 acre-feet for the McCook and Thornton Reservoirs, respectively. This means that the McCook and Thornton Reservoirs would have 104,200 and 18,000 acre-feet of storage capacity to avoid any spills, respectively. By further assuming that the WRPs can operate only at their average design capacities, then to avoid any spills the McCook and Thornton Reservoirs would have about 139,000 and 23,300 acre-feet, respectively. Table 12 shows the summary of the results for three different WRP operations. If the WRPs could operate at their maximum design capacities under CUP storages


Number of Days with Spills at Calumet without TARP


with TARP I

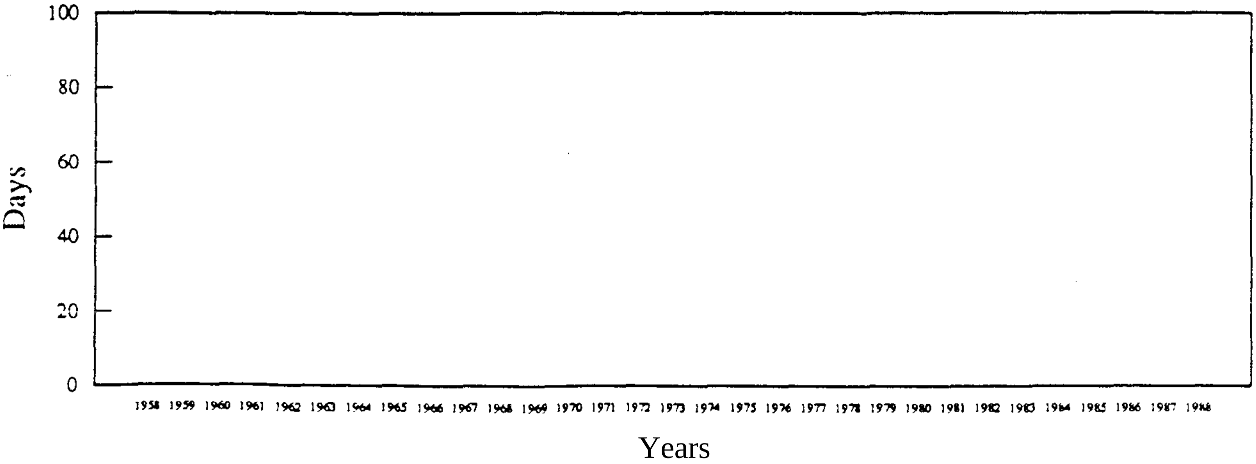
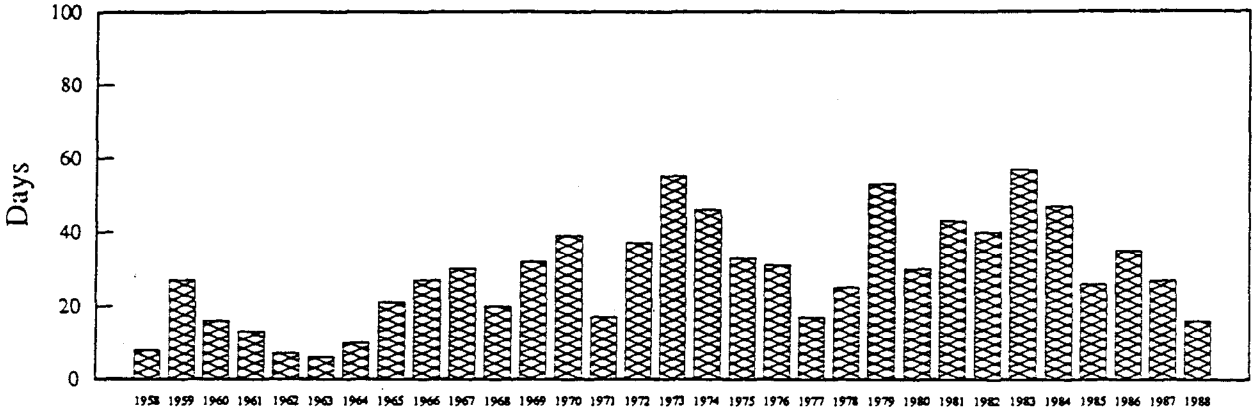
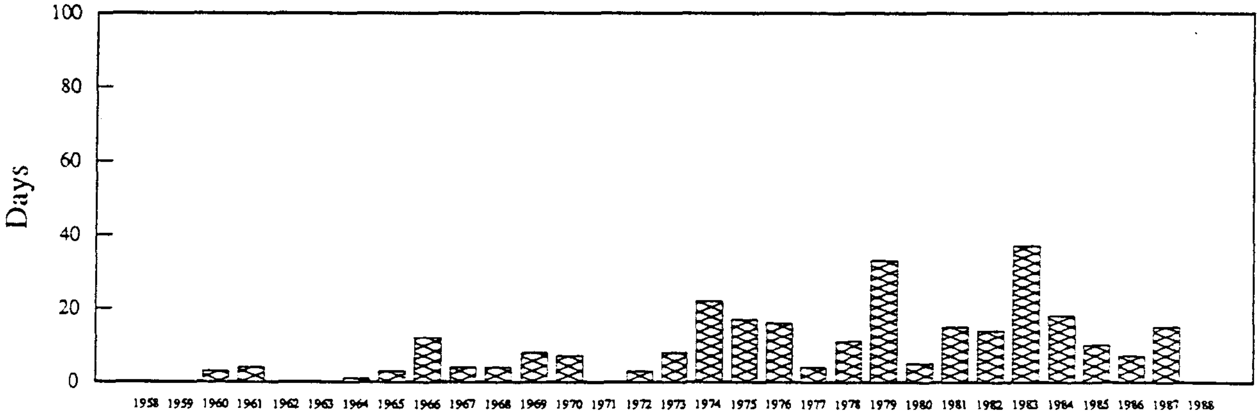

with TARP II

Figure 11. Number of days with spills at Calumet System

Number of Days with Spills at Mainstream without TARP



with TARP I



with TARP II

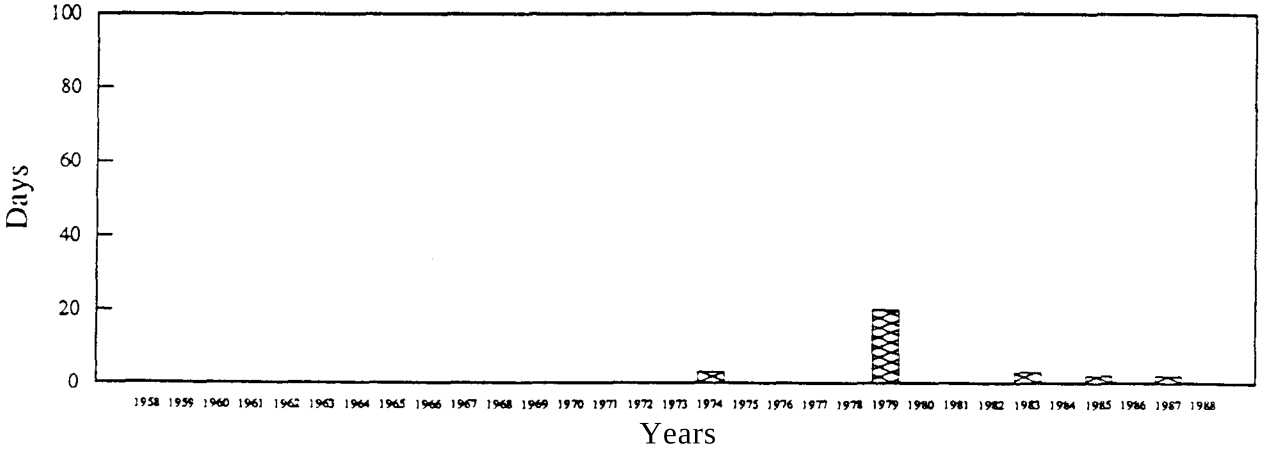


Figure 12. Number of days with spills at Mainstream System

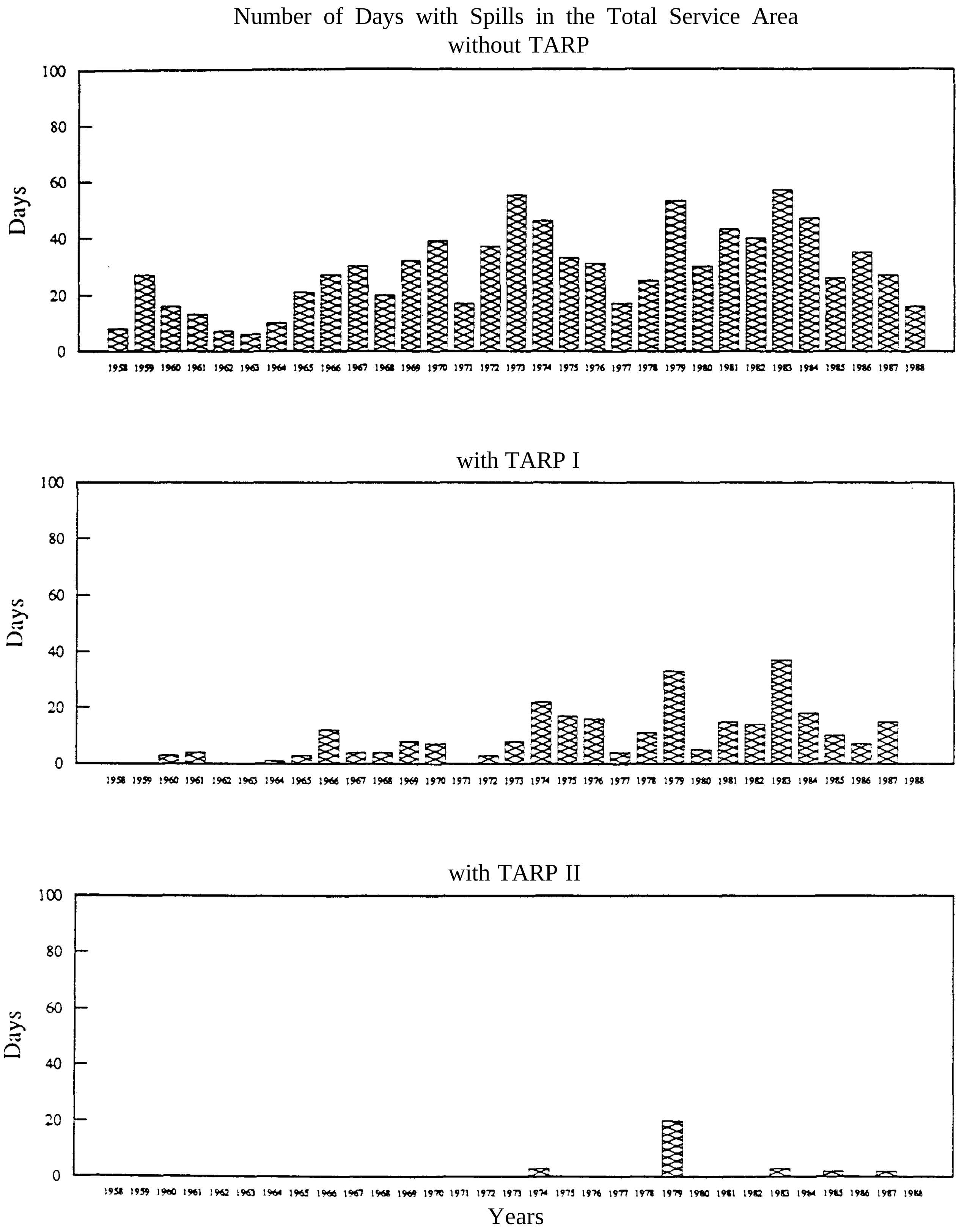
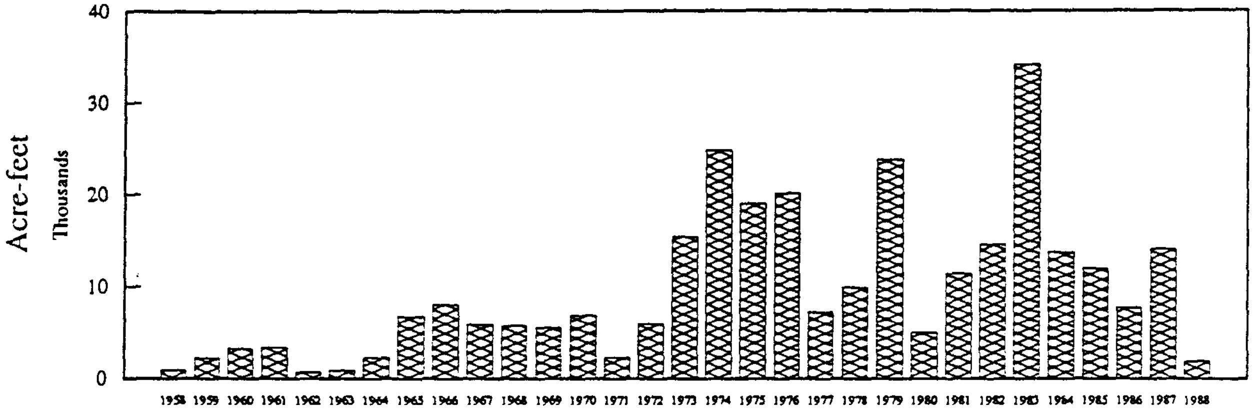
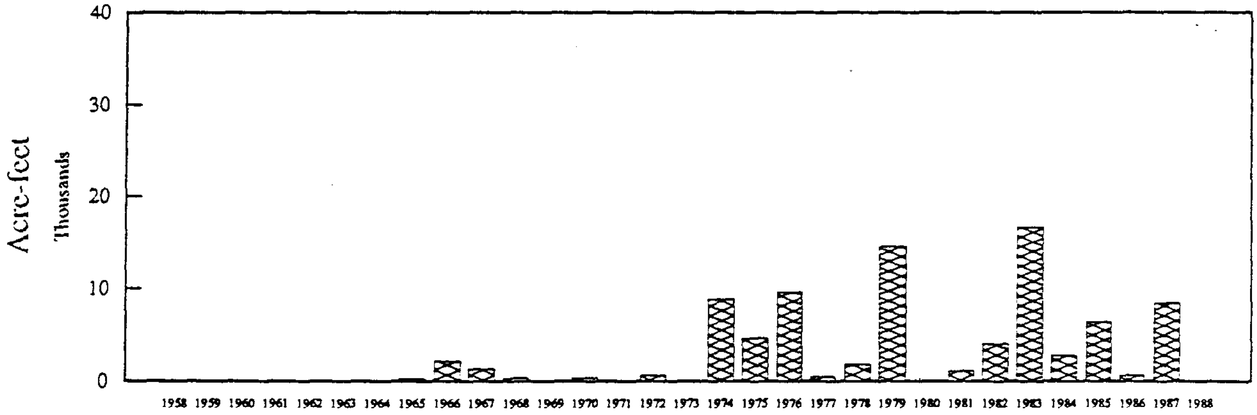


Figure 13. Number of days with spills in the total service area

Volume of Spills at Calumet
without TARP



with TARP I



with TARP II

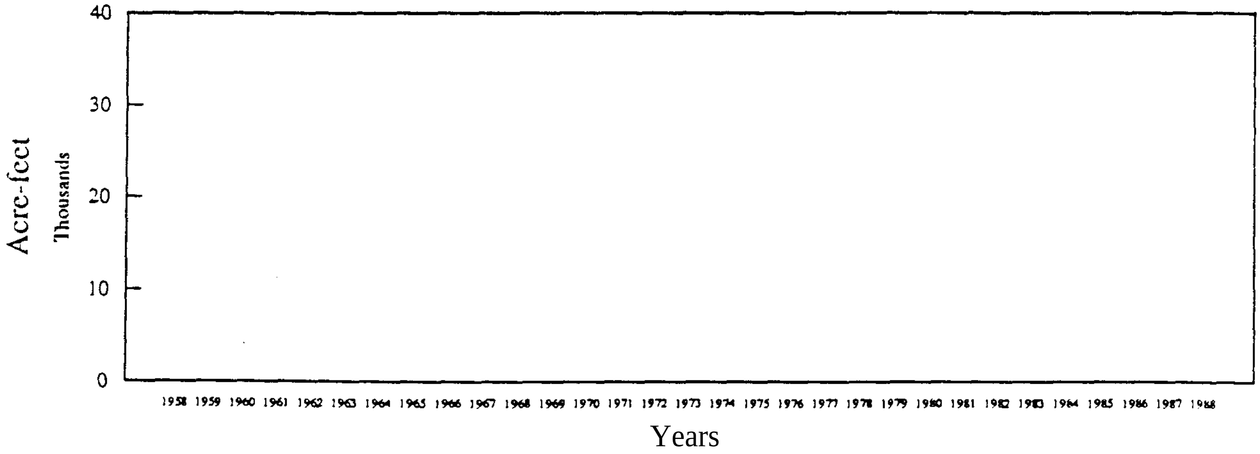
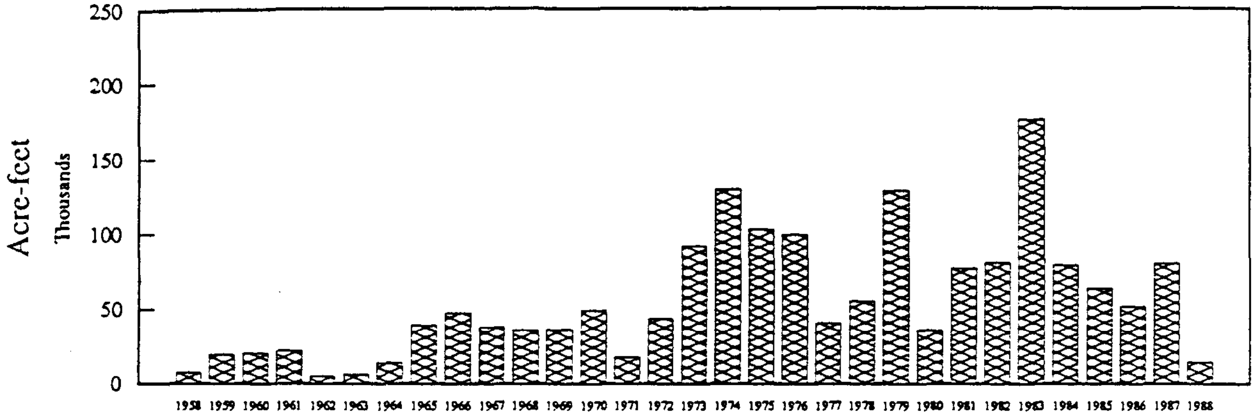
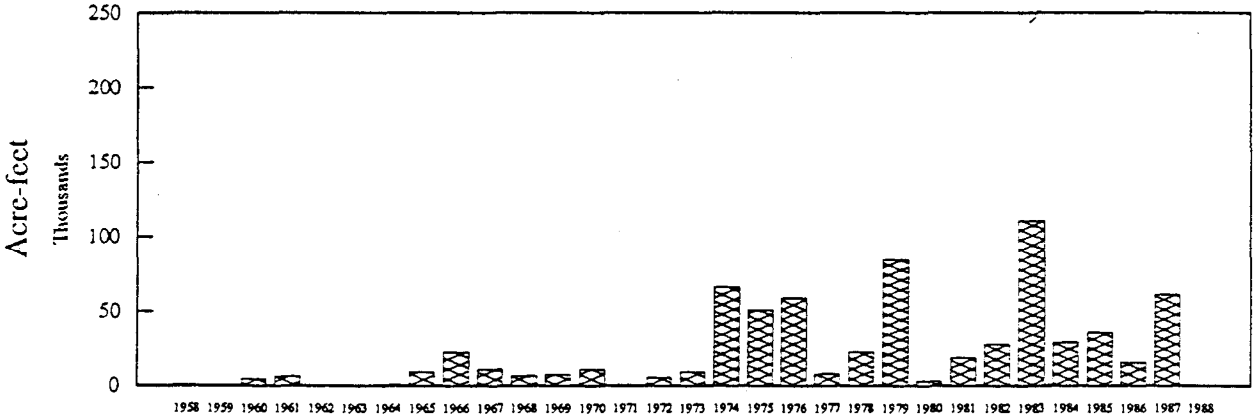


Figure 14. Volume of spills at Calumet System

Volume of Spills at Mainstream
without TARP



with TARP I



with TARP II

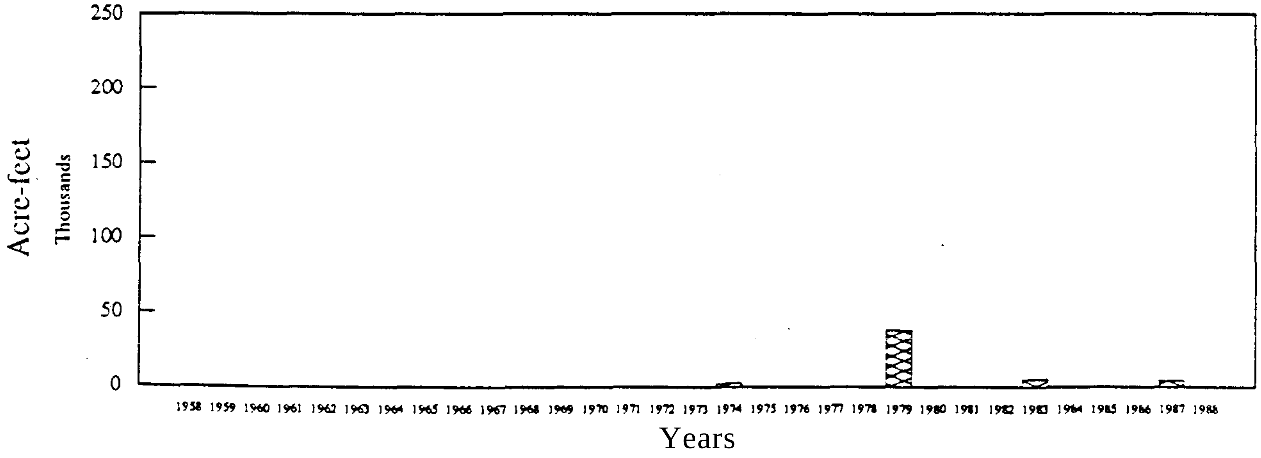
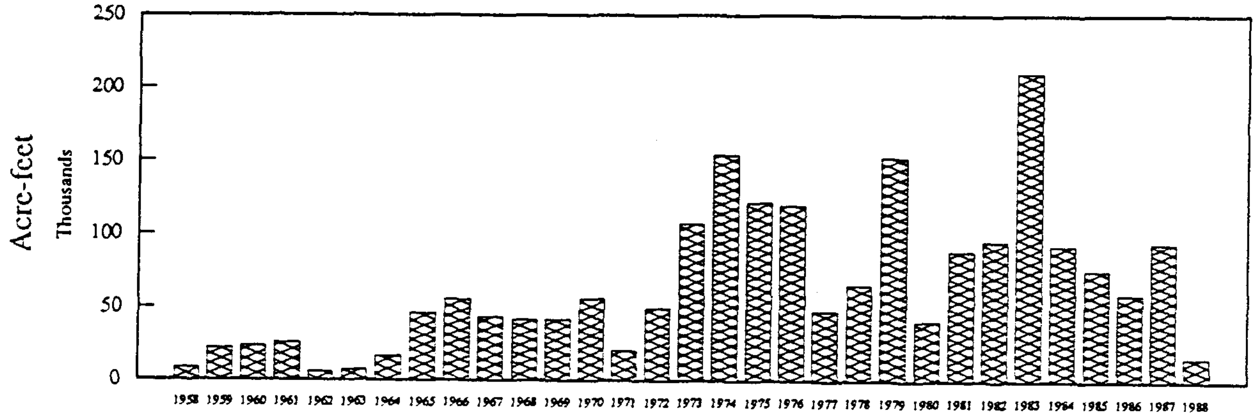
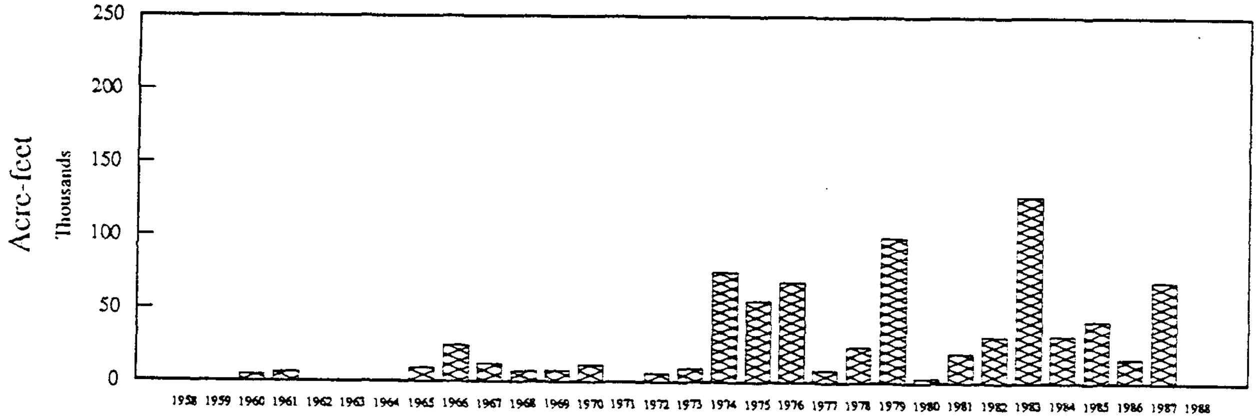


Figure 15. Volume of spills at Mainstream System

Volume of Spills in the Total Service Area
without TARP



with TARP I



with TARP II

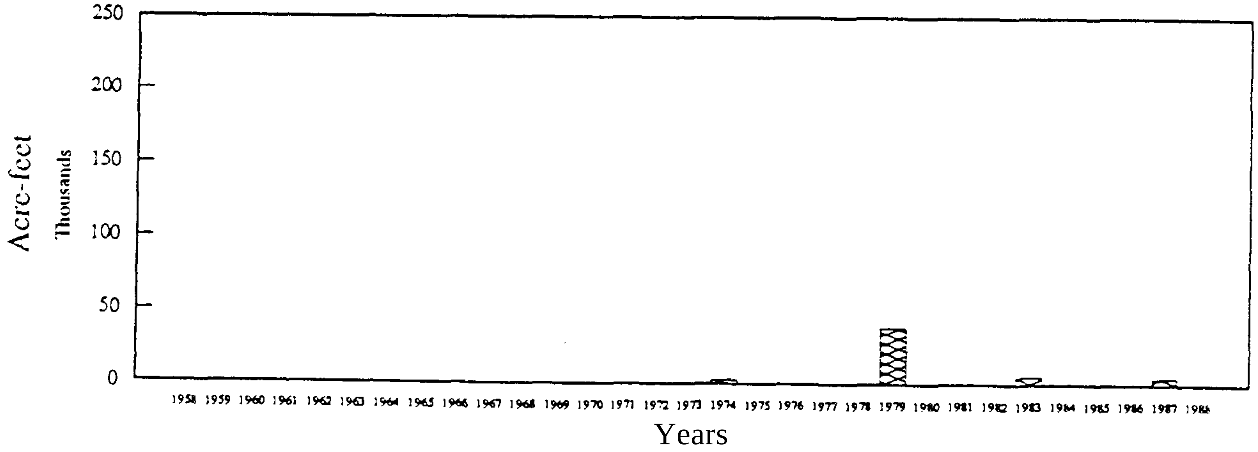


Figure 16. Volume of spills in th.e total service area

(condition 1), the Mainstream would have 52,526 acre-feet of spills. On the other extreme, if the WRPs could operate only at their average design capacities for sustained periods (condition 4), the total reservoir storage capacity necessary to avoid any spills would be 162,300 acre-feet (139,000 and 23,300 acre-feet for McCook and Thornton Reservoirs, respectively). The maximum design capacities of the Stickney, Calumet, and the North Side WRPs are 1,440,430, and 450 mgd, respectively. Similarly, the average design capacities of the Stickney, Calumet, and the North Side WRPs are 1,200,354, and 333 mgd, respectively.

Table 12. Reservoir Storage Capacities Necessary to Avoid any Spills with Different WRP Treatment Capacities

Condition	WRP treatment capacity (mgd)		Reservoir storage capacity (acre-feet)			1958-1988 total volume of spills (acre-feet)	
	Stickney + N.S.	Calumet	McCook	Thornton	Total	Mainstr.	Calumet
1 Max. Des.	1,890 (1,440+450)	430	32,100	14,600	46,700	52,526	0
2 Max. Des.	1,890 (1,440+450)	430	70,400	14,600	85,000	0	0
3 90% Max. Des.	1,701 (1,296+405)	387	104,200	18,000	122,200	0	0
4 Average Des.	1,533 (1,200+333)	354	139,000	23,300	162,300	0	0

The following sections summarize and discuss the statistics of TARP's effects on the Lockport flows and the downstream stations on the Illinois River.

EFFECT OF TARP ON FLOWS DOWNSTREAM OF LOCKPORT

The effects of Phases I and II of TARP on flows downstream of Lockport at Marseilles, Kingston Mines, and Meredosia were simulated by using the Illinois River Flow Model with the modified Lockport flows and then compared with the flows representing the conditions without TARP operation. Also included is the summary of TARP's effect on the Lockport flows, the main input to the model. The results of the flow simulations are presented in several formats: flow duration, peak flow, and maximum annual and partial-duration series analyses.

Analysis of Flow Durations

Table 13 shows the changes in the flow duration of the average daily flows due to TARP Phases I and II at Lockport, Marseilles, Kingston Mines, and Meredosia. In general, TARP Phase I operation had an insignificant effect on the flows at any duration. However, the results indicate that TARP Phase II operation had

Table 13. Comparison of Flow Duration Values (cfs) at Lockport, Marseilles, Kingston Mines, and Meredosia, Due to TARP Phases I and II

Probability of exceedance (%)	Lockport			Marseilles		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
99	1841	1842	1842	3373	3373	3373
98	1938	1942	1943	3603	3603	3603
97	2012	2014	2015	3725	3725	3725
96	2079	2082	2085	3846	3844	3844
95	2134	2137	2139	3977	3977	3977
94	2181	2185	2187	4082	4082	4082
93	2221	2228	2230	4205	4205	4205
92	2263	2268	2271	4297	4299	4299
91	2305	2307	2310	4374	4375	4375
90	2339	2340	2344	4443	4445	4448
85	2508	2515	2521	4818	4822	4824
80	2674	2682	2700	5153	5162	5164
75	2821	2834	2860	5506	5513	5523
70	2961	2979	3028	5838	5844	5859
65	3112	3140	3183	6195	6206	6223
60	3249	3275	3318	6566	6582	6593
55	3362	3398	3447	6984	6993	7010
50	3479	3530	3624	7485	7497	7507
45	3657	3727	3789	8126	8135	8137
40	3800	3863	3917	8805	8804	8818
35	3927	3989	4044	9609	9575	9602
30	4051	4149	4200	10587	10583	10599
25	4220	4339	4388	11804	11796	11828
20	4440	4585	4618	13356	13317	13437
15	4764	4900	4929	15671	15612	15750
10	5231	5322	5350	18494	18550	18612
9	5394	5432	5450	19198	19234	19313
8	5549	5560	5553	19971	19949	20016
7	5776	5684	5666	21097	21121	21121
6	6044	5858	5817	22185	22223	22228
5	6543	6086	5998	23783	23861	23853
4	7288	6336	6221	25629	25637	25572
3	7709	6814	6553	28182	28131	27857
2	8468	7436	6939	32316	32027	31553
1	9766	9447	7820	39696	39503	38403

Table 13. Concluded

Probability of exceedance (%)	Kingston Mines			Meredosia		
	Without TARP	With TARP I	With TARP II	Without TARP	With TARP I	With TARP II
99	4104	4104	4104	4681	4681	4681
98	4401	4401	4401	4963	4963	4963
97	4655	4655	4655	5238	5235	5235
96	4813	4813	4813	5510	5509	5509
95	4956	4955	4955	5732	5729	5729
94	5100	5099	5099	5915	5913	5913
93	5262	5262	5263	6180	6180	6180
92	5420	5420	5420	6398	6398	6396
91	5549	5549	5551	6526	6524	6522
90	5667	5666	5665	6658	6661	6659
85	6203	6205	6206	7516	7518	7514
80	6683	6684	6682	8341	8336	8336
75	7345	7344	7347	9487	9479	9475
70	8064	8060	8067	10952	10948	10951
65	8860	8865	8872	12301	12303	12329
60	9809	9808	9815	13868	13861	13879
55	10824	10831	10837	15419	15419	15420
50	11988	11986	11995	17066	17074	17089
45	13192	13191	13230	19094	19083	19112
40	14739	14740	14748	21463	21472	21471
35	16523	16492	16499	24037	24046	24051
30	18251	18262	18254	26695	26686	26688
25	20312	20279	20290	30163	30162	30178
20	23227	23249	23260	33896	33890	33905
15	26530	26541	26563	38493	38494	38514
10	31239	31239	31318	46705	46704	46742
9	32311	32296	32293	48873	48869	48951
8	33647	33674	33700	51538	51476	51461
7	35143	35143	35174	54174	54171	54202
6	37007	37021	37068	57020	57024	57033
5	39179	39220	39247	60047	59981	60007
4	41584	41586	41670	63690	63716	63692
3	45201	45262	45149	69029	69070	68988
2	49651	49709	49570	76270	76330	76297
1	58258	58317	57553	86676	86714	86604

significant effects in lowering the high flows at Lockport, Marseilles, and Kingston Mines, as well as some effect on Meredosia. For example, at Lockport, high flows corresponding to 7 percent and less duration were reduced significantly while the medium flows (between 10 and 80 percent duration) increased. Similarly, at Marseilles, flows corresponding to 4 percent or less duration were reduced, and the flows between 5 and 85 percent duration increased slightly. These effects were attenuated further downstream to Kingston Mines and Meredosia.

Analysis of Peak Flows

The impact of TARP operation on reducing the extreme flows was also investigated. For this purpose, the highest 75 daily flows that had occurred during the period of analysis (1958 - 1988) were identified and sorted in descending order for Lockport, Marseilles, Kingston Mines, and Meredosia stations. The year and the day of these flows were also identified. A procedure was developed to fiter out the secondary (or pseudo) peaks that may occur within the hydrograph by finding the maximum flow inside a time window with a variable width (say, seven days), and checking if this maximum flow is actually a peak having a rise and **a** fall. If the requirements are satisfied, the maximum flow is accepted as a peak; otherwise it is rejected, and the time window is shifted one day forward to search for another peak. By changing the window size and the minimum duration of the rise and fall period of the hydrograph, the variability in the peak data can be modified. Tables 14 - 17 show the reduction of the peak flow values for the highest 75 peak values for Lockport, Marseilles, Kingston Mines, and Meredosia, with TARP Phases I and II.

Analysis of the peaks indicates that TARP Phase II effectively reduces the flood peaks by up to 40 percent (more than 6,000 cfs) at Lockport. At Marseilles, TARP Phase II reduces the peaks by more than 4,000 cfs. Over 20 percent of the peaks at Marseilles were reduced by more than 6 percent. These reductions are attenuated as we move further downstream to Kingston Mines and Meredosia. It is common to find a reduction in peak flows greater than 1,000 cfs at Kingston Mines. These reductions were achieved by assuming that all the WRPs can operate at their maximum design capacity during the high flows.

Another remarkable phenomenon is that most of these peak reductions occur during the spring and early summer seasons, when the risk of flooding is high. Because 55 percent of the peaks identified for Lockport have occurred approximately between March and June (Water Year days 151 through 273), it is obvious that the implementation of TARP Phase II will reduce the flood hazards downstream of Lockport. Similarly, more than 70 percent of the peaks identified for Marseilles,

Table 14. Reduction in Peak Daily Flows at Lockport Due to Phases I and II of TARP

Water Year	Day	Without TARP	With TARP I			With TARP II		
		Flow	Flow	Δ	%Δ	Flow	Δ	%Δ
1985	155	16300	14402	1898	11.6	9636	6664	40.9
1975	334	16124	12780	3344	20.7	9692	6432	39.9
1976	157	16023	16023	0	0.0	9585	6438	40.2
1979	156	15394	15394	0	0.0	9294	6100	39.6
1987	331	15200	15125	75	0.5	11800	3400	22.4
1977	336	15084	11740	3344	22.2	9295	5789	38.4
1975	102	15021	11677	3344	22.3	9502	5519	36.7
1974	229	14701	14581	120	0.8	9060	5641	38.4
1976	208	14544	12080	2464	16.9	9004	5540	38.1
1975	326	14218	10874	3344	23.5	8909	5309	37.3
1968	322	14109	10817	3292	23.3	9323	4786	33.9
1987	318	14100	10809	3291	23.3	9319	4781	33.9
1966	225	13927	13920	7	0.1	8843	5084	36.5
1983	275	13692	12910	782	5.7	9319	4373	31.9
1975	201	13513	12616	897	6.6	9098	4415	32.7
1987	3	13500	13500	0	0.0	8850	4650	34.4
1983	65	13415	13415	0	0.0	8568	4847	36.1
1975	210	13393	13150	243	1.8	9048	4345	32.4
1983	184	13303	13201	102	0.8	8410	4893	36.8
1985	147	13300	13300	0	0.0	8484	4816	36.2
1978	294	13264	11801	1463	11.0	9168	4096	30.9
1965	357	13054	11423	1631	12.5	8928	4126	31.6
1976	258	13045	10993	2052	15.7	8521	4524	34.7
1976	219	12743	9560	3183	25.0	8270	4473	35.1
1974	252	12466	12349	117	0.9	8175	4291	34.4
1978	225	12462	10068	2394	19.2	8075	4387	35.2
1977	254	12441	9190	3251	26.1	8292	4149	33.3
1972	165	12155	8877	3278	27.0	8031	4124	33.9
1979	170	11971	11971	0	0.0	11215	756	6.3
1978	188	11694	8526	3168	27.1	7760	3934	33.6
1984	168	11592	9334	2258	19.5	7690	3902	33.7
1980	295	11550	8570	2980	25.8	8570	2980	25.8
1983	169	11509	8282	3227	28.0	7657	3852	33.5
1983	214	11504	11109	395	3.4	7757	3747	32.6
1983	86	11432	9976	1456	12.7	7754	3678	32.2
1977	273	11381	8248	3133	27.5	7857	3524	31.0
1970	212	11323	8202	3121	27.6	7726	3597	31.8
1980	85	11307	8138	3169	28.0	7637	3670	32.5
1979	194	11299	10300	999	8.8	8831	2468	21.8
1986	50	11200	10414	786	7.0	7705	3495	31.2
1967	183	11130	8030	3100	27.9	7646	3484	31.3
1971	278	10964	8050	2914	26.6	8050	2914	26.6
1978	275	10961	8917	2044	18.6	8223	2738	25.0
1983	178	10880	7723	3157	29.0	7398	3482	32.0
1976	75	10878	7762	3116	28.6	7486	3392	31.2
1981	257	10823	10022	801	7.4	7909	2914	26.9
1986	19	10600	8329	2271	21.4	7659	2941	27.7
1979	180	10506	8290	2216	21.1	8193	2313	22.0
1975	75	10500	8018	2482	23.6	8018	2482	23.6
1965	344	10441	7855	2586	24.8	7855	2586	24.8
1968	82	10391	7409	2982	28.7	7409	2982	28.7
1975	147	10368	9841	527	5.1	7260	3108	30.0
1966	86	10271	7702	2569	25.0	7360	2911	28.3
1970	264	10244	7587	2657	25.9	7587	2657	25.9
1975	258	10229	7273	2956	28.9	7273	2956	28.9
1966	300	10222	7745	2477	24.2	7745	2477	24.2
1983	125	10200	7173	3027	29.7	7163	3037	29.8
1972	71	10147	7345	2802	27.6	7345	2802	27.6
1980	315	10044	7752	2292	22.8	7752	2292	22.8
1984	241	9990	9198	792	7.9	7201	2789	27.9
1969	251	9941	7462	2479	24.9	7462	2479	24.9
1983	354	9935	7635	2300	23.2	7635	2300	23.2
1983	196	9913	9913	0	0.0	8355	1558	15.7
1974	185	9790	6994	2796	28.6	6994	2796	28.6
1982	312	9716	8427	1289	13.3	7804	1912	19.7
1979	272	9700	7446	2254	23.2	7446	2254	23.2
1985	179	9630	6898	2732	28.4	6898	2732	28.4
1982	295	9629	7475	2154	22.4	7475	2154	22.4
1964	299	9537	7464	2073	21.7	7464	2073	21.7
1985	93	9530	6923	2607	27.4	6923	2607	27.4
1983	321	9526	7644	1882	19.8	7644	1882	19.8
1975	232	9518	6998	2520	26.5	6998	2520	26.5
1978	352	9377	7623	1754	18.7	7623	1754	18.7
1977	312	9376	7008	2368	25.3	7008	2368	25.3
1984	361	9360	7300	2060	22.0	7300	2060	22.0

Notes: Days begin on October 1, Δ = Flow without TARP - Flow with TARP, and % Δ =Δ(+ Flow without TARP) x 100.

Table 15. Reduction in Peak Daily Flows at Marseilles Due to Phases I and II of TARP

Water Year	Day	Without TARP	With TARP I			With TARP II		
		Flow	Flow	Δ	%Δ	Flow	Δ	%Δ
1983	65	98191	97943	248	0.3	93566	4625	4.7
1970	227	78714	77848	866	1.1	76629	2085	2.6
1979	159	70371	70352	19	0.0	66879	3492	5.0
1974	234	64492	64585	-93	-0.1	61920	2572	4.0
1982	164	63519	62717	802	1.3	62156	1363	2.1
1985	148	61259	60958	301	0.5	58784	2475	4.0
1986	51	60765	60464	301	0.5	58959	1806	3.0
1976	158	59783	59764	19	0.0	55815	3968	6.6
1979	171	59214	59209	5	0.0	58551	663	1.1
1973	92	58818	57552	1266	2.2	57494	1324	2.8
1985	156	58014	57796	218	0.4	54783	3231	5.6
1981	257	57977	56540	1437	2.5	55347	2630	4.5
1982	171	57064	57058	6	0.0	55629	1435	2.5
1979	195	56623	56216	407	0.7	55603	1020	1.8
1966	225	55909	55020	889	1.6	51825	4084	7.3
1983	215	54402	54214	188	0.3	52236	2166	4.0
1973	205	54193	53567	626	1.2	52883	1310	2.4
1981	228	52152	52113	39	0.1	51703	449	0.9
1968	126	50444	49767	677	1.3	49729	715	1.4
1968	271	48336	47969	367	0.8	47969	367	0.8
1958	257	47524	47590	-66	-0.1	47590	-66	-0.1
1980	247	47415	47441	-26	-0.1	47328	87	0.2
1984	137	47327	46634	693	1.5	46634	693	1.5
1983	185	45530	45479	51	0.1	41438	4092	9.0
1982	145	45210	43847	1363	3.0	43847	1363	3.0
1975	103	44017	42719	1298	2.9	39962	4055	9.2
1967	185	43949	43283	666	1.5	41033	2916	6.6
1959	211	43358	42524	834	1.9	42524	834	1.9
1962	173	43254	43251	3	0.0	43251	3	0.0
1974	120	42954	42780	174	0.4	41670	1284	3.0
1979	182	42908	42892	16	0.0	42550	358	0.8
1987	4	42152	42090	62	0.1	39197	2955	7.0
1961	361	41215	40833	382	0.9	40163	1052	2.6
1975	210	41197	39871	1326	3.2	37417	3780	9.2
1960	183	41030	40805	225	0.5	40805	225	0.5
1966	87	40959	39899	1060	2.6	39166	1793	4.4
1975	259	40912	39666	1246	3.0	39310	1602	3.9
1984	173	40386	40308	78	0.2	39140	1246	3.1
1958	288	40106	40106	0	0.0	40106	0	0.0
1974	146	39836	38952	884	2.2	38265	1571	3.9
1983	276	39421	39106	315	0.8	35915	3506	8.9
1983	197	39091	39089	2	0.0	38361	730	1.9
1973	46	38898	38019	879	2.3	37362	1536	3.9
1974	252	38606	37691	915	2.4	34987	3619	9.4
1959	138	38332	38332	0	0.0	38332	0	0.0
1981	197	38238	37674	564	1.5	37646	592	1.5
1973	184	38215	37638	577	1.5	37638	577	1.5
1978	189	38194	36876	1318	3.5	35642	2552	6.7
1975	201	38174	36719	1455	3.8	34732	3442	9.0
1984	242	38000	37858	142	0.4	37169	831	2.2
1962	164	37976	37976	0	0.0	37976	0	0.0
1976	145	37714	37714	0	0.0	37714	0	0.0
1983	87	36320	35732	588	1.6	34052	2268	6.2
1972	332	35983	35984	-1	0.0	35984	-1	0.0
1982	200	35816	35549	267	0.7	34395	1421	4.0
1975	147	34723	34409	314	0.9	32780	1943	5.6
1965	208	34635	34077	558	1.6	34077	558	1.6
1969	123	34422	34451	-29	-0.1	34451	-29	-0.1
1979	216	34403	34221	182	0.5	33177	1226	3.6
1978	226	34008	33068	940	2.8	31331	2677	7.9
1974	267	33867	34334	-467	-1.4	33782	85	0.3
1985	180	33498	32833	665	2.0	32979	519	1.5
1976	221	33048	32994	54	0.2	32060	988	3.0
1976	209	32699	31732	967	3.0	27668	5031	15.4
1978	269	32444	32541	-97	-0.3	32541	-97	-0.3
1984	76	32153	31917	236	0.7	31415	738	2.3
1966	211	32033	31842	191	0.6	31431	602	1.9
1988	190	31367	31068	299	1.0	31068	299	1.0
1979	326	31289	31200	89	0.3	31081	208	0.7
1985	94	31182	30507	675	2.2	30383	799	2.6
1970	203	30928	30202	726	2.3	30202	726	2.3
1987	232	30293	29673	620	2.0	28697	1596	5.3
1987	331	30262	29942	320	1.1	27735	2527	8.4
1970	213	30329	29027	1202	4.0	27823	2406	8.0
1984	180	29680	30346		-2.2	30289	-609	-2.1

Notes: Days begin on October 1, = Flow without TARP - Flow with TARP, and % Δ = (+ Flow without TARP) × 100.

Table 16. Reduction in Peak Daily Flows at Kingston Mines Due to Phases I and II of TARP

Water Year	Day	Without TARP	With TARP I			With TARP II		
		Flow	Flow	Δ	%Δ	Flow	Δ	%Δ
1983	68	94770	94609	161	0.2	92354	2406	2.5
1979	176	83820	83840	-20	0.0	83531	289	0.3
1979	183	78959	78710	249	0.3	78455	504	0.6
1982	172	77997	77922	75	0.1	76895	1102	1.4
1985	158	74271	74075	196	0.3	72661	1610	2.2
1979	162	73510	73366	144	0.2	71606	1904	2.6
1979	197	73279	73031	248	0.3	72822	457	0.6
1986	54	70570	70451	119	0.2	69840	730	1.0
1970	230	70567	70327	240	0.3	69999	568	0.8
1973	207	68457	68180	277	0.4	67979	478	0.7
1974	237	67174	67177	-3	0.0	65851	1323	2.0
1962	176	64278	64319	-41	-0.1	64319	-41	-0.1
1983	198	63670	63616	54	0.1	62791	879	1.4
1976	160	61972	61862	110	0.2	60051	1921	3.1
1974	268	59174	59127	47	0.1	59057	117	0.2
1983	217	57462	57260	202	0.4	56790	672	1.2
1981	230	56013	56052	-39	-0.1	55816	197	0.4
1979	216	54586	54474	112	0.2	54271	315	0.6
1973	96	54081	53811	270	0.5	53685	396	0.7
1960	187	53729	53645	84	0.2	53645	84	0.2
1982	202	53266	53212	54	0.1	52963	303	0.6
1980	250	52814	52920	-106	-0.2	52891	-77	-0.1
1987	7	52161	52127	34	0.1	50948	1213	2.3
1973	186	51418	51223	195	0.4	51223	195	0.4
1983	89	51115	50751	364	0.7	50384	731	1.4
1966	228	50135	49909	226	0.5	49016	1119	2.2
1984	180	50113	50319	-206	-0.4	50007	106	0.2
1986	63	49774	49885	-111	-0.2	50191	-417	-0.8
1974	123	49576	49701	-125	-0.3	49280	296	0.6
1974	254	49251	48892	359	0.7	48247	1004	2.0
1981	261	48433	48368	65	0.1	47747	686	1.4
1984	244	48283	48178	105	0.2	47771	512	1.1
1985	183	47772	47562	210	0.4	47878	-106	-0.2
1986	129	47088	47072	16	0.0	47059	29	0.1
1984	143	47007	46975	32	0.1	46975	32	0.1
1973	264	46596	46594	2	0.0	46597	-1	0.0
1982	149	46499	46515	-36	0.0	46503	-4	0.0
1967	187	46369	46043	326	0.7	45276	1093	2.4
1982	187	46050	45919	131	0.3	45982	68	0.1
1973	169	44987	44975	12	0.0	44975	12	0.0
1973	192	44987	45105	-148	-0.3	45105	-148	-0.3
1975	213	44672	44556	116	0.3	43829	843	1.0
1975	216	44085	43822	263	0.6	43464	321	1.4
1969	125	43943	43948	-5	0.0	73952	-9	0.0
1958	260	43771	43796	-25	-0.1	43796	-25	-0.1
1981	270	43299	43335	-36	-0.1	43496	-197	-0.5
1970	249	43135	43209	-74	-0.2	43293	-158	-0.4
1965	194	41923	41935	-12	0.0	41935	-12	0.0
1978	191	41875	41370	505	1.2	40925	950	2.3
1960	203	41484	41465	19	0.0	41465	19	0.0
1974	164	40945	41039	-94	-0.2	41049	-104	-0.3
1970	206	40799	40639	160	0.4	40605	194	0.5
1973	49	40356	40215	141	0.3	40040	316	0.8
1968	274	40129	40141	-12	0.0	40141	-12	0.0
1974	149	39798	39664	134	0.3	39501	297	0.7
1965	211	39750	39721	-29	0.1	39721	29	0.1
1972	208	39059	39167	-108	-0.3	39170	-111	-0.3
1972	148	38827	38827	0	0.0	38827	1	0.0
1975	149	38501	38490	11	0.0	38091	410	1.1
1988	192	38207	38133	74	0.2	38133	74	0.2
1986	75	38111	38134	-23	-0.1	38199	-88	-0.2
1976	223	37920	37721	199	0.5	37319	601	1.6
1983	228	37690	37596	94	0.2	37906	-216	-0.6
1970	364	37601	37603	-2	0.0	37603	-2	0.0
1978	229	37335	37185	150	0.4	36719	616	1.6
1959	140	37219	37234	-15	0.0	37234	-15	0.0
1958	291	36614	36618	-4	0.0	36618	-4	0.0
1975	204	36511	36317	194	0.5	35746	765	2.1
1985	214	36319	36232	87	0.2	36154	165	0.5
1973	251	36237	36330	-93	-0.3	36368	-131	-0.4
1970	264	36103	35962	141	0.4	35979	124	0.3
1961	364	36064	36132	-68	-0.2	36002	62	0.2
1961	322	36042	36117	-75	-0.2	36169	-127	-0.4
1981	200	35941	35926	15	0.0	35900	41	0.1
	150	35762	35771	-9	0.0	35771	-9	0.0

Notes: Days begin on October 1, Δ = Flow without TARP - Flow with TARP, and %Δ = (Δ + Flow without TARP) × 100.

Table 17. Reduction in Peak Daily Flows at Meredosia Due to Phases I and II of TARP

Water Year	Day	Without TARP	With TARP I			With TARP II		
		Flow	Flow	Δ	%Δ	Flow	Δ	%Δ
1985	160	112707	112634	73	0.1	111750	957	0.8
1979	184	108814	108726	88	0.1	108394	420	0.4
1983	71	108751	108649	102	0.1	107557	1194	1.1
1979	176	108661	108639	22	0.0	108164	497	0.5
1973	209	106880	106773	107	0.1	106680	200	0.2
1979	201	106685	106842	-157	-0.1	106794	-109	-0.1
1974	270	104978	104971	7	0.0	105150	-172	-0.2
1982	175	102692	102666	26	0.0	102034	658	0.6
1986	57	91046	91097	-51	-0.1	90821	225	0.2
1962	178	90137	90136	1	0.0	90136	1	0.0
1983	198	88544	88483	61	0.1	87715	829	0.9
1970	231	88088	87961	127	0.1	87860	228	0.3
1986	63	86882	86966	-84	-0.1	87068	-186	-0.2
1974	245	86329	86466	-137	-0.2	86034	295	0.8
1979	210	85793	85707	86	0.1	85989	-196	-0.2
1974	124	85205	85161	44	0.1	84856	349	0.4
1974	253	83962	83884	78	0.1	83921	41	0.0
1979	216	83066	82982	84	0.1	82978	88	0.1
1973	187	81622	81565	57	0.1	81565	57	0.1
1960	188	78485	78417	68	0.1	78417	68	0.1
1983	90	77932	77856	76	0.1	77752	180	0.2
1982	203	76730	76760	-30	0.0	76672	58	0.1
1973	169	75308	75287	21	0.0	75287	21	0.0
1976	164	75222	75180	42	0.1	74241	981	1.3
1970	217	74443	74330	113	0.2	74174	269	0.4
1983	218	73446	73427	19	0.0	73288	158	0.2
1984	182	71050	71169	-119	-0.2	70953	97	0.1
1987	8	70651	70593	58	0.1	69898	753	1.1
1981	235	69794	69888	-94	-0.1	69986	-192	-0.8
1968	133	69781	69811	-30	0.0	69810	-29	0.0
1959	141	69483	69511	-28	0.0	69511	-28	0.0
1970	248	67075	67045	30	0.0	67082	-7	0.0
1983	226	66460	66428	32	0.0	66730	-270	-0.4
1984	245	66403	66348	55	0.1	66106	297	0.4
1960	204	66295	66292	3	0.0	66292	3	0.0
1973	100	66131	66082	49	0.1	66010	121	0.2
1978	195	63815	63716	99	0.2	63416	399	0.6
1974	167	63649	63697	-48	-0.1	63721	-72	-0.1
1970	364	63501	63501	0	0.0	63501	0	0.0
1980	253	62895	62934	-39	-0.1	62933	-38	-0.1
1973	271	62378	32428	-50	-0.1	62433	-55	-0.1
1969	132	62263	62269	-6	0.0	62274	-11	0.0
1981	270	62187	62223	-36	-0.1	62295	-1.08	-0.2
1985	183	62137	62008	129	0.2	62342	-205	-0.3
1966	237	61799	61891	-92	-0.1	61765	34	0.1
1978	232	61442	61510	-68	-0.1	61373	69	0.1
1970	266	61005	60938	67	0.1	60974	31	0.1
1965	199	58983	58985	-2	0.0	58985	- 2	0.0
1981	322	58784	58832	-48	-0.1	58867	-83	-0.1
1982	150	58145	58145	-3	0.0	58138	7	0.0
1981	282	57504	57535	-31	-0.1	57603	-99	-0.2
1981	314	57480	57542	-62	-0.1	57437	43	0.1
1958	263	57410	57412	-2	0.0	57412	- 2	0.0
1960	273	57375	57376	-1	0.0	57376	-1	0.0
1981	261	55187	55085	102	0.2	54702	485	0.0
1975	153	54508	54549	-41	-0.1	54359	149	0.3
1984	146	54093	54118	-25	0.0	54118	-25	0.0
1984	213	53320	53386	-66	-0.1	53437	-117	-0.2
1965	210	53199	53127	72	0.1	53127	72	0.1
1972	212	53144	53200	-56	-0.1	53206	-62	-0.1
1974	198	53110	53108	2	0.0	53150	-40	-0.1
1961	363	52709	52602	107	0.2	52554	155	0.3
1968	88	52229	52146	83	0.2	52146	88	0.2
1975	214	51783	51706	77	0.1	51307	476	0.0
1961	227	50560	50563	-3	0.0	50563	-3	0.0
1975	220	49404	49487	-83	-0.2	49420	-16	0.0
1967	189	48621	48476	145	0.3	48119	502	1.0
1969	206	48487	48468	19	0.0	48468	19	0.0
1964	212	48351	48354	-3	0.0	48354	-3	0.0
1973	253	48308	48363	-55	-0.1	48369	61	-0.1
1966	216	48003	47971	32	0.1	47844	159	0.3
1958	295	47801	47806	-5	0.0	47806	-5	0.0
1976	212	47557	47398	159	0.3	46989	568	1.2
1969	284	46690	46701	-11	0.0	46701	-11	0.0
1958	312	45695	45696	-1	0.0	45696	1	0.0

Notes: Days begin on October 1, Δ = Flow without TARP - Flow with TARP, and % Δ = (Δ +Flow without TARP) × 100.

Kingston Mines, and Meredosia also fall in that period. The negative values in tables 14 -17 indicate that those peaks were preceded by higher peaks and thus the reservoirs were being emptied at large rates at that time.

Analysis of Maximum Annual and Partial-Duration Series

Annual high flow series were developed to investigate the changes in the flood frequency and flood durations at Lockport, Marseilles, Kingston Mines, and Meredosia due to TARP operations. Generally, annual series refer to the maximum daily (or instantaneous) flow in each year. Partial duration series refer to the maximum daily flows averaged over a given duration (e.g., 7 or 15 days) in each year. While the annual series gives an indication of the intensity and probability of a single extreme event, the partial-duration series can give information about the duration of such extreme events. Partial-duration series were developed for 7-, 15-, and 31-day maximum flows (MFs). To simplify the terminology, we will also refer to the annual series as 1-day maximum flows (1-day MFs).

All these series were generated for the period of Water Years 1953 - 1988. After the series were generated, they were sorted in descending order and assigned a probability of exceedance. If there are n years of record, the probability P of the event with order m (m being 1 for the largest and n for the smallest event in n years of record) is given by

$$P = \frac{m}{n+1} \qquad (31)$$

and the expected return period of that event, in years is T = l/P.

Tables 18 - 21 summarize the results of the maximum flow series analyses. The l-, 7-, 15-, and 31-day high-flow series have been generated without TARP and with TARP Phases I and II at Lockport, Marseilles, Kingston Mines, and Meredosia. These tables show the high flows for the selected probability values (upper portion of the tables), and for the selected return periods (lower portion of the tables). In these tables the flows corresponding to more than 50 percent exceedance (i.e., high flows that are exceeded 50 percent of the time or more, or 2-yr flow) should not be considered as high flows. It is normal for flows at lower return periods than a 2-yr flow to slightly increase as a result of TARP operation because TARP is expected to reduce the flows with high return period and shift these to flows with lower return periods. Computer integer approximation of the flow values also caused some of the minor increases of these flows in these tables. Figures 17 - 20 show the flows

Table 18. Summary of High Flows at Lockport without TARP and with TARP Phases I and II for Selected Durations and Return Periods

Probability of exceedance (%)	**1 - day**			**7-day**		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
3	19202	18322	16805	11415	11178	9712
5	17060	16625	13111	11099	10748	8536
10	16074	15260	10710	10796	10393	7852
15	15409	14536	9678	10226	9826	7594
20	15200	13920	9585	9827	9670	7237
30	14018	12146	9232	7500	7344	6554
40	13054	10817	8843	7224	6991	6449
50	11436	9678	7970	6988	6837	6347
60	10964	8570	7705	6718	6444	6191
70	9661	7942	7463	6452	6213	5991
80	9090	7455	6968	6031	5962	5813
90	8194	6913	6904	5371	5255	5249
95	8025	6795	6773	5072	5067	5067
97	7897	6478	6477	4906	4906	4906
35-yr flow	19352	18441	17064	11437	11208	9794
30-yr flow	18845	18039	16190	11362	11106	9516
25-yr flow	18131	17474	14958	11257	10963	9124
10-yr flow	16074	15260	10710	10796	10393	7852
5-yr flow	15200	13920	9585	9827	9670	7237
2-yr flow	11436	9678	7970	6988	6837	6347

Probability of exceedance (%)	**15-day**			**31-day**		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
3	9676	9669	9602	9598	9593	9524
5	9023	8910	7893	8041	7961	7363
10	8465	8295	7037	6630	6615	6324
15	7771	7570	6560	6432	6365	6051
20	7487	7416	6353	6244	6177	5840
30	6643	6559	6199	5707	5674	5621
40	6221	6138	5894	5535	5457	5444
50	5914	5871	5713	5350	5312	5250
60	5702	5696	5583	5284	5274	5108
70	5608	5475	5444	5061	5041	5026
80	5326	5326	5326	4693	4684	4654
90	4805	4805	4805	4499	4498	4498
95	4587	4579	4579	4416	4416	4416
97	4466	4436	4436	4317	4317	4317
35-yr flow	9722	9722	9722	9707	9707	9675
30-yr flow	9567	9542	9317	9338	9321	9164
25-yr flow	9350	9290	8748	8819	8777	8444
10-yr flow	8465	8295	7037	6630	6615	6324
5-yr flow	7487	7416	6353	6244	6177	5840
2-yr flow	5914	5871	5713	5350	5312	5250

Table 19. Summary of High Flows at Marseilles without TARP and with TARP Phases I and II for Selected Durations and Return Periods

Probability of exceedance (%)	**1-day**			**7-day**		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
3	97753	97474	93204	66933	66691	63920
5	91498	90769	88027	64283	64140	61419
10	74542	74100	71892	54334	54029	53245
15	64250	64120	62097	49835	49762	48061
20	61259	60958	58959	47273	47258	46041
30	58398	57046	55581	41416	41210	40861
40	48644	48347	47590	38109	38106	38106
50	45672	44958	43173	35123	34948	34320
60	43254	42524	40805	30570	30212	29313
70	39612	38840	37590	27806	27878	27185
80	34422	34077	34077	24384	24457	24457
90	26626	26619	26620	22171	22227	22221
95	23256	23217	23198	19513	19583	19584
97	17208	17210	17208	14989	15003	15003
35-yr flow	98191	97943	93566	67118	66869	64094
30-yr flow	96711	96356	92341	66491	66266	63503
25-yr flow	94626	94121	90615	65608	65416	62669
10-yr flow	74542	74100	71892	54334	54029	53245
5-yr flow	61259	60958	58959	47273	47258	46041
2-yr flow	45672	44958	43173	35123	34948	34320

Probability of exceedance (%)	**15-day**			**31-day**		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
3	48843	48707	47843	40970	40897	40131
5	48695	48622	47424	38496	38429	37929
10	43379	43358	42230	31292	31289	31015
15	37576	37601	36549	29637	29594	29034
20	34281	34342	34203	27792	27785	27694
30	31520	31532	31531	25056	25083	25024
40	30428	30447	30285	22248	22254	22204
50	26429	26428	26314	21170	21170	21170
60	25649	25670	25180	20046	20046	20046
70	22044	22065	21866	18796	18797	18797
80	20810	20820	20820	15880	15884	15880
90	17820	17820	17821	14492	14492	14492
95	16369	16382	16382	12837	12837	12837
97	12763	12772	12772	10717	10717	10717
35-yr flow	48853	48713	47872	41143	41070	40285
30-yr flow	48818	48693	47773	40558	40486	39764
25-yr flow	48769	48664	47633	39733	39663	39030
10-yr flow	43379	43358	42230	31292	31289	31015
5-yr flow	34281	34342	34203	27792	27785	27694
2-yr flow	26429	26428	26314	21170	21170	21170

Table 20. Summary of High Flows at Kingston Mines without TARP and with TARP Phases I and II for Selected Durations and Return Periods

Probability of exceedance (%)	**1-day**			**7-day**		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
3	94232	94080	91930	85436	85270	83664
5	86548	86523	85732	82643	82612	81911
10	76134	75998	74778	72787	72724	71746
15	70569	70420	69959	66257	66237	65854
20	68457	68180	67979	64141	64126	63622
30	58992	58957	57934	55126	55191	54457
40	52161	52127	51565	48959	48995	49015
50	48600	48490	48038	45987	45994	45536
60	43943	43948	43829	41562	41532	41535
70	40467	40268	40048	39223	39290	39081
80	37017	36702	36163	34956	34961	33634
90	25789	25742	25748	24805	24799	24805
95	23257	23200	23202	22631	22625	22629
97	20377	20376	20376	19804	19806	19807
35-yr flow	94770	94609	92364	85631	85456	83787
30-yr flow	92951	92820	90897	84970	84827	83372
25-yr flow	90390	90301	88831	84040	83941	82787
10-yr flow	76134	75998	74778	72787	72724	71746
5-yr flow	68457	68180	67979	64141	64126	63622
2-yr flow	48600	48490	48038	45987	45994	45536

Probability of exceedance (%)	**15-day**			**31-day**		
	Without TARP	**With TARP I**	**With TARP II**	**Without TARP**	**With TARP I**	**With TARP II**
3	78669	78656	78330	72182	72157	71569
5	73365	73362	72636	61596	61586	61254
10	66684	66661	65915	55504	55514	55236
15	58706	58738	58634	50665	50671	50540
20	57526	57572	56629	48996	49031	49017
30	49025	49029	48601	42561	42555	42391
40	43765	43818	43818	37330	37371	37289
50	40080	40122	39866	34134	34126	34083
60	38138	38095	37966	32672	32678	32678
70	36103	36114	36115	30612	30613	30615
80	30552	30491	29438	24992	24996	24996
90	22627	22645	22646	19056	19057	19057
95	20812	20791	20791	16911	16906	16905
97	18654	18655	18655	15705	15706	15705
35-yr flow	79040	79026	78728	72922	72897	72291
30-yr flow	77785	77774	77381	70418	70395	69850
25-yr flow	76017	76009	75483	66889	66872	66412
10-yr flow	66684	66661	65915	55564	55514	55236
5-yr flow	57526	57572	56629	48996	49031	49017
2-yr flow	40080	40122	39866	34134	34126	34083

Table 21. Summary of High Flows at Meredosia without TARP and with TARP Phases I and II for Selected Durations and Return Periods

Probability of exceedance (%)	1 -day			7-day		
	Without TARP	With TARPI	With TARP II	Without TARP	With TARPI	With TARP II
3	112516	112442	111585	110121	110071	109260
5	109784	109700	109230	107507	107471	107015
10	107816	107711	107118	104436	104404	103882
15	104409	104397	104374	100610	100618	100645
20	91046	91097	90821	89533	89565	89321
30	76854	76798	76329	75511	75449	74989
40	70651	70593	69986	68562	68669	68716
50	66649	66614	66464	64032	64013	63878
60	61799	61891	61765	59996	60066	59876
70	55959	55984	55914	53893	53918	53861
80	48621	48509	48354	47962	47880	47588
90	38026	38026	38026	36782	36782	36782
95	33111	33116	33116	32563	32568	32568
97	26600	26620	26620	26304	26322	26323
35-yr flow	112707	112634	111750	110303	110253	109417
30-yr flow	112060	111985	111193	109685	109638	108886
25-yr flow	111150	111071	110408	108814	108771	108138
10-yr flow	107816	107711	107118	104436	104404	103882
5-yr flow	91046	91097	90821	89533	89565	89321
2-yr flow	66649	66614	66464	64032	64013	63878

Probability of exceedance (%)	15-day			31 -day		
	Without TARP	With TARP1	With TARP II	Without TARP	With TARP I	With TARP II
3	106173	106153	105743	101831	101855	101612
5	103781	103785	103200	90594	90600	90292
10	96815	96804	96464	84666	84664	84538
15	92913	92909	92632	83385	83400	83400
20	87234	87274	87181	77524	77549	77526
30	70182	70158	69803	62306	62297	62192
40	65582	65636	65641	56446	56457	56454
50	60559	60573	60419	52631	52631	52635
60	56550	56579	56579	48940	48938	48938
70	50289	50309	50285	45555	45559	45559
80	44550	44554	44554	38226	38228	38228
90	34598	34598	34598	30364	30364	30364
95	30753	30759	30759	24962	24968	24968
97	24818	24837	24838	24073	24091	24092
35-yr flow	106341	106318	105920	102618	102643	102404
30-yr flow	10575	105758	105319	99959	99980	99725
25-yr flow	104977	104969	104471	96213	96228	95952
10-yr flow	96815	96804	96464	84666	84664	84538
5-yr flow	87234	87274	87181	77524	77549	77526
2-yr flow	60559	60573	60419	52631	52631	52635

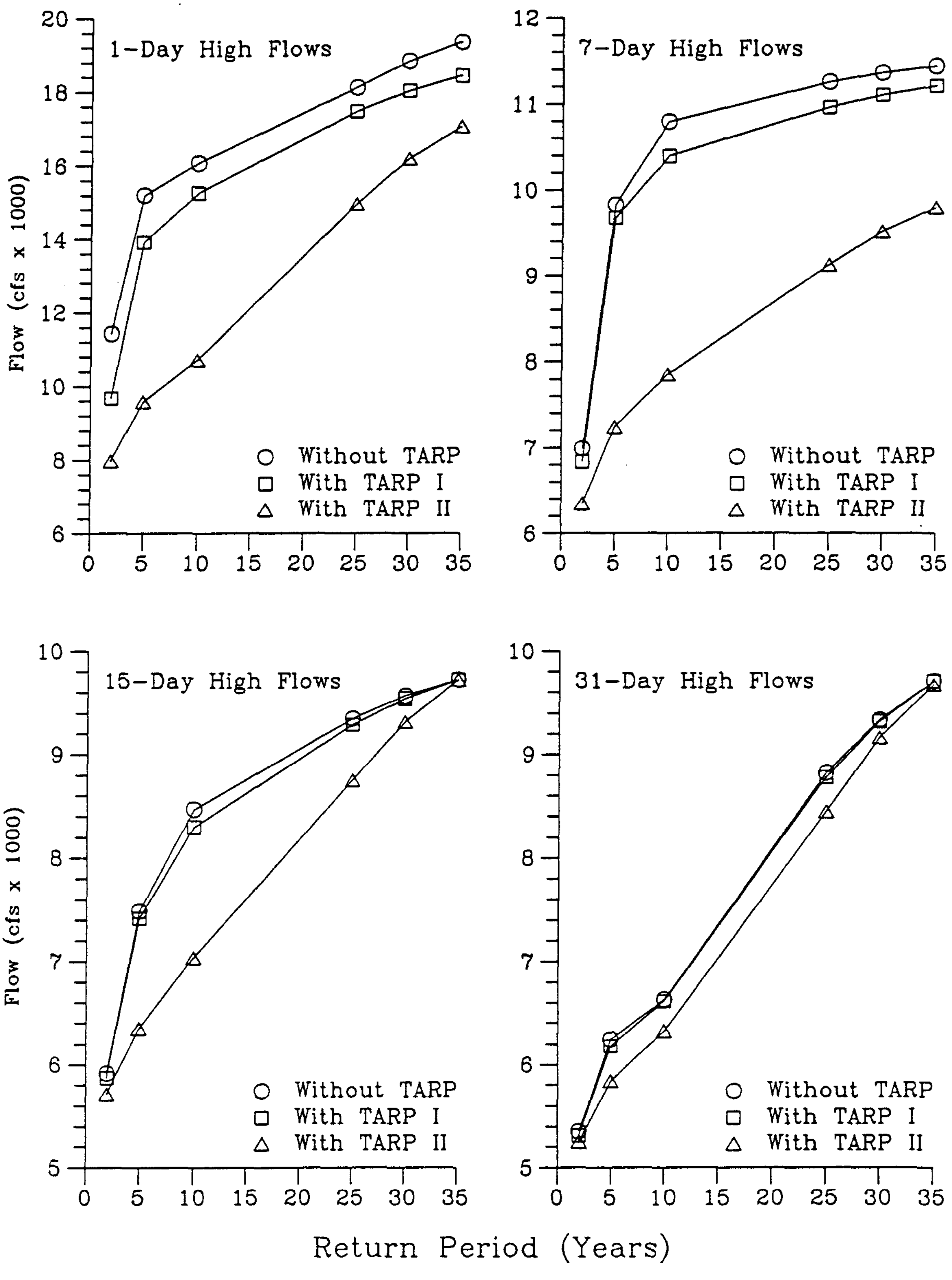


Figure 17. Reduction in 1-, 7-, 15-, and 31-day high flows for selected return periods at Lockport as a result of TARP

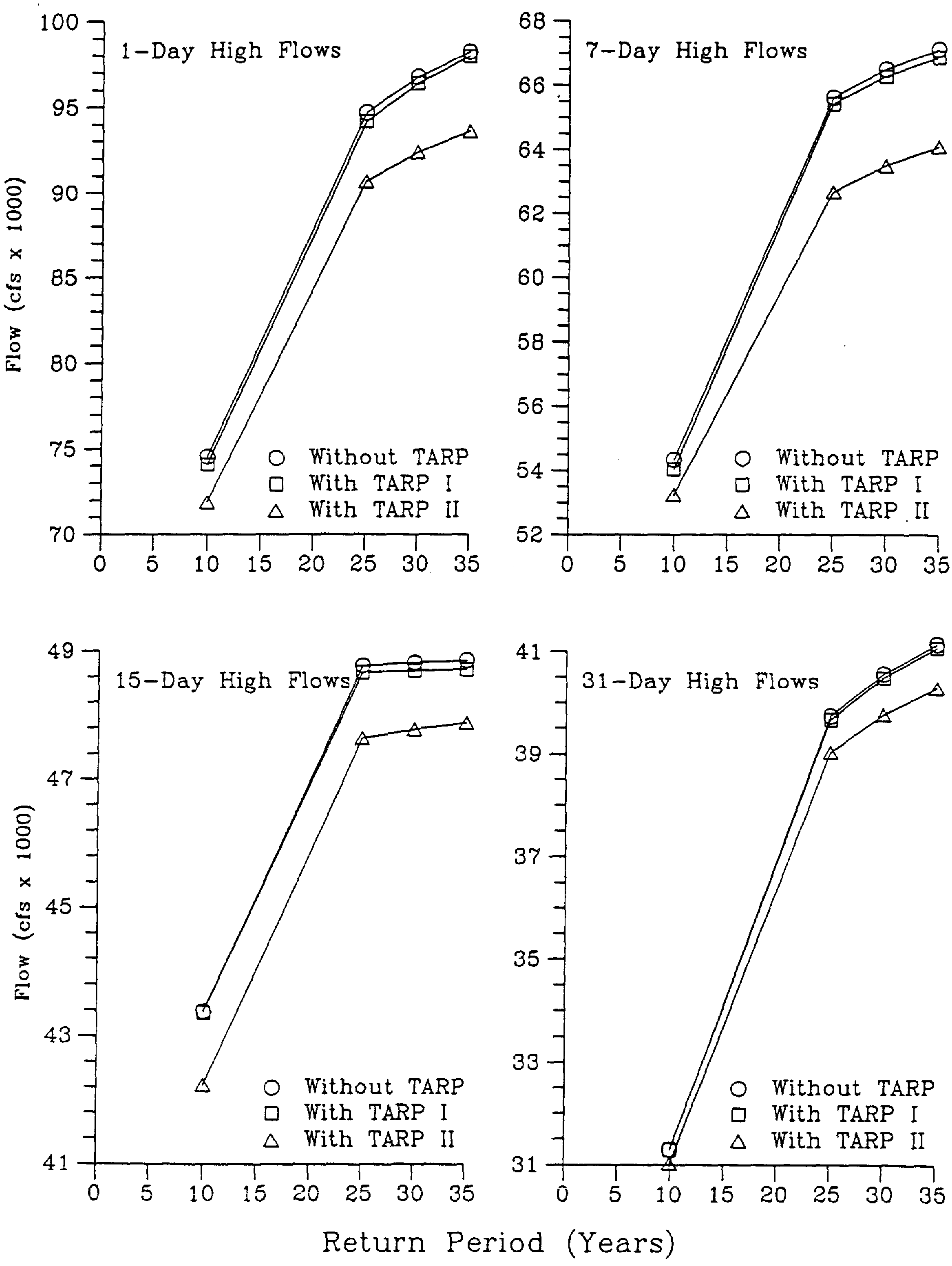


Figure 18. Reduction in 1-, 7-, 15, and 3l-day high flows for selected return periods at Marseilles as a result of TARP

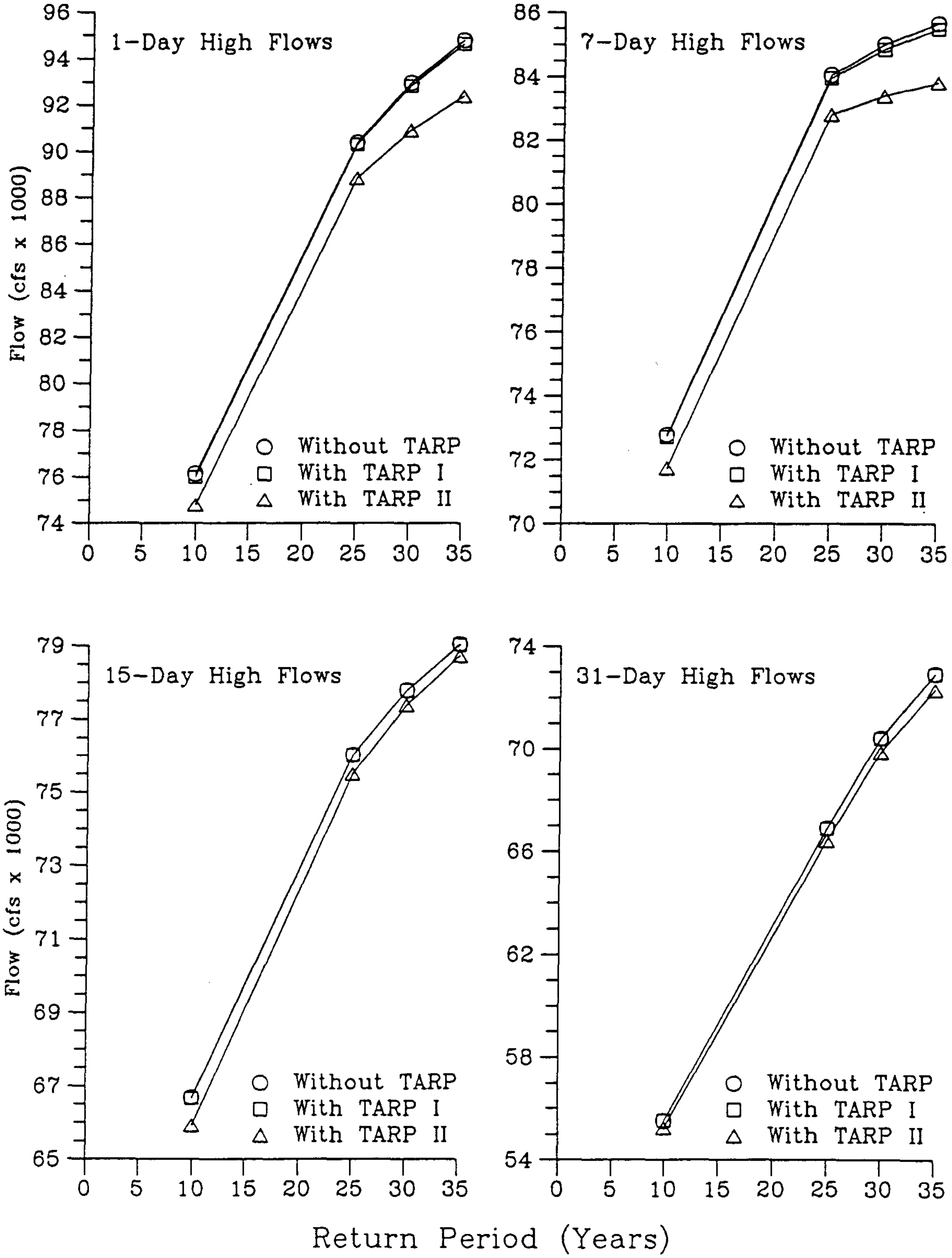


Figure 19. Reduction in 1-, 7-, 15-, and 31-day high flows for selected return periods at Kingston Mines as a result of TARP

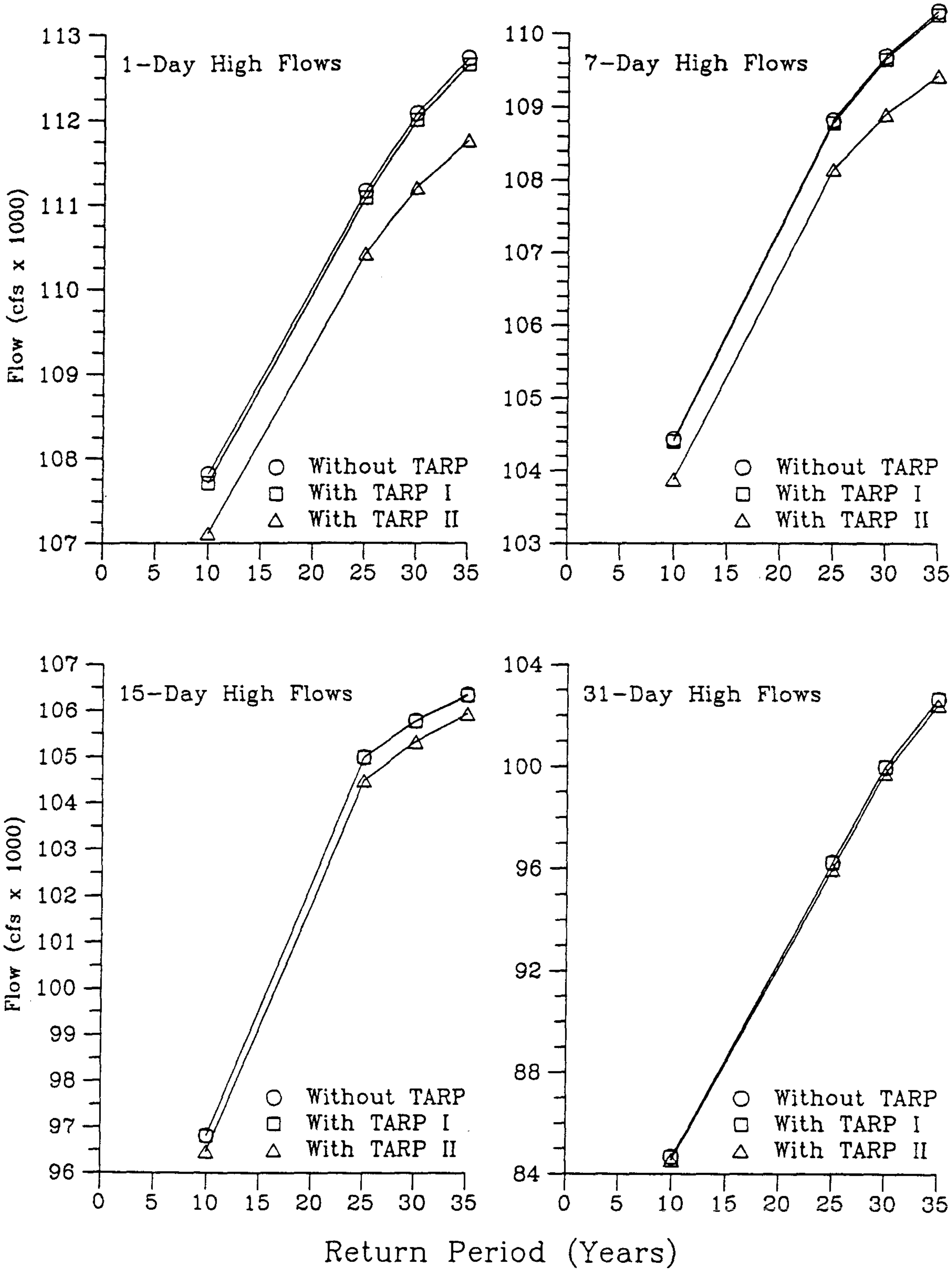


Figure 20. Reduction in 1-, 7-, 15-, and 31 -day high flows for selected return periods at Meredosia as a result of TARP

corresponding to selected return periods and durations for the four stations to facilitate the visual comparison.

It can be clearly seen from these results that there is a significant reduction in the maximum flows and their durations (at and downstream of Lockport), as a result of TARP Phase II. These effects were particularly significant down to Kingston Mines (downstream of Peoria Lake). The most pronounced high-flow reductions at Lockport are seen at 1-, 7-, and 15-day flow durations. The impacts of the higher durations (15- and 31-days) become less noticeable downstream — obviously due to increased drainage area.

Results also indicate that TARP Phase II operation will also greatly decrease the frequency of extreme flood events. For example, an overview of table 18 or figure 17 shows that a 1-day, 5-year MF that is expected at Lockport without TARP (15,200 cfs) will have about a 1-day, 25-year value (14,958 cfs). In most other cases, an average of five or more years of increase in the expected return periods can be observed for most durations at Lockport. At Marseilles, for example, the 31-day, 25-year flow without TARP (39,733 cfs) is approximately equal to a 31-day, 30-year flow with TARP Phase II (39,764 cfs). At Kingston Mines, an increase of five or more years in the return periods can be expected for low frequency events for l-, 7-, and 15-day durations, respectively. Similar but less emphasized results are also observed at Meredosia.

The information about the reduction in the expected flow values at particular return periods can also be obtained from figures 17 - 20 by drawing a vertical line at that return period value and finding the vertical difference between the points where the line intersects the curves. Similarly, the increase in the return periods corresponding to particular flow levels can be obtained by drawing a horizontal line at those flow levels and finding the horizontal difference between the points where the line intersects the curves.

SUMMARY

The flows at Lockport, one of the main inputs to the Illinois River Flow Model, are subject to change as a result of TARP operation. Significant effort has been given to establish a uniformity among the flow records that were obtained from different sources. Several regression equations were developed for the Lockport flows for this purpose and to make all Lockport flows compatible with the new AVM records. The flows obtained from these regression equations may be lower than the flows reported by MWRDGC, especially if the flows pass through the powerhouse sluice gates and the control works or both. For most other cases, the difference between the reported flows and the flows calculated from the regression equations were either very small, or the reported values were slightly lower.

The Illinois River Flow Model were developed to simulate the flows on the Illinois Waterway between Lockport and Meredosia. The basin was divided into three sub-basins, each marked with upstream and downstream gaging stations. Each sub-basin was handled as a black-box regressive model. The parameters for each sub-basin were estimated separately for different time periods to alleviate the evident nonstationarity of the flow series. The imbalances of the flows within the basins were handled by using flow correction coefficients, which were then multiplied by the flow values (or the model parameters) to provide the water balance. The parameter estimation and calibration results indicate that the Illinois River Flow Model can accurately estimate the daily flows in the Illinois Waterway.

A storage routing model was developed to simulate the effects of TARP operation on the Lockport flows. This required the WRP inflows for the two systems (Mainstream and Calumet) on a daily basis. WRP inflows were then separated into raw sewage and storm runoff components by using the minimum monthly WRP releases and the average monthly diversions. Storm runoff from the TARP service area and non-TARP area were estimated by using regional runoff coefficients and the daily Lockport flows. The estimated WRP inflows were then routed through TARP storage to estimate the daily WRP releases and spills or both. These releases, diversions, and the surface runoff from the non-TARP area were then combined to obtain the modified Lockport flows for a particular TARP operation. The results show that TARP Phase II would have a significant effect on reducing the number of spills in the TARP service area, as well as the total volume of spills. However, to eliminate all spills, based on the historical records, larger reservoir storage capacities than the COE CUP capacities would be needed even if the WRPs were assumed to be operating at their maximum design capacities.

The effects of TARP on flows downstream of Lockport were simulated by using the Illinois River Flow Model and the modified Lockport flows. Analysis of the results indicated that TARP Phase II had a significant potential in lowering the flood peaks and flood durations, and it is expected to increase the return periods of the extreme flood events. These benefits, very significant between Lockport and

Kingston Mines, diminish further downstream because of the storage effect of the Peoria Lake and increased drainage area.

In brief, with CUP reservoir storage (46,700 acre-feet), TARP Phase II operation can eliminate most but not all of the combined sewer overflows to the Chicago Waterways during the simulation period of 1958-1988, and significantly reduce flood peaks in the Illinois River downstream of Lockport, if the WRPs can operate continuously at their maximum design capacities. However, the WRPs may not operate continuously at their design maximum capacitys. The results which are summarized in table 12 show that if the WRPs can operate continuously at 90% of their maximum design capacity (condition 3) then a storage capacity of 122,200 acre-feet would eliminate all spills. This is comparable to the capacity initially proposed by the MWRDGC (125,630 acre-feet). If the WRPs can operate only at the average design capacity (which corresponds to about 80% of the maximum design capacity) for sustained periods (condition 4, table 12), then storage capacities much larger than the CUP or those proposed by the MWRDGC are needed to eliminate all spills into the waterways during the simulation period. In this study, the downstream benefits of TARP Phase II on Illinois Waterway are simulated for the CUP storage only. However, these benefits will be higher if storage capacities larger than the CUP storage are used. The associated improvements in the Illinois River water quality are significant, and are discussed in Volume 2.

REFERENCES

Abadie, J. 1970. *Integer and Nonlinear Programming.* North-Holland, Amsterdam, Holland, p. 544.

Durgunoğlu, A., and A.R. Rao. 1985. *Forecasting Daily Runoff by CLS and ARMA Models.* Purdue University Hydraulics and Systems Engineering Report No. CE-HSE-85-13, West Lafayette, Indiana, September, p. 78.

Harza Engineering Company. 1986. *Investigation of the Impact of the Acoustical Velocity Meter on Lake Michigan Diversion Accounting.* Chicago.

Metropolitan Water Reclamation District of Greater Chicago. 1987. *Facilities Planning Study, Update Supplement and Summary.* Appendix E (revised 1989, not published).

Metropolitan Water Reclamation District of Greater Chicago. 1990. *Tarp Status Report,* November 11.

Nakashima, M., and K.P. Singh. 1983. *Illinois River Flow System Model.* Illinois State Water Survey Contract Report 311, February, p. 44.

Natale, L., and E. Todini. 1974. *A Constrained Parameter Estimation Technique for Linear Models in Hydrology.* Publication No. 13, Institute of Hydraulics, University of Pavia, Italy.

Northeastern Illinois Planning Commission (NIPC). 1987. Memorandum from D. Hey, G. Schaefer, and D. Dreher to D. Injerd, Illinois Department of Water Resources, December 7.

Robison, R. 1986. The Tunnel that Cleaned Up Chicago. *Civil Engineering.* July, pp. 34-37.

U.S. Army Corps of Engineers (COE). 1986. *Chicagoland Underflow Plan Final Phase I GDM,* Supplementary Information, Volume B-1, Main Report, Hydrology and Hydraulics. Chicago District.

U.S. Army Corps of Engineers (COE). 1989. *Acoustic Velocity Meter Regression Analysis - Draft Report.* Hydrology and Hydraulics Branch, Chicago District.

Yazicigil, H., G.H. Toebes, and M.H. Houck. 1980. *Green River Basin Optimization-Simulation Model.* Technical Report 137, Purdue University Water Resources Center, West Lafayette, Indiana, p. 190.

REDUCTION IN PEAK FLOWS AND IMPROVEMENTS IN WATER QUALITY IN THE ILLINOIS WATERWAY DOWNSTREAM OF LOCKPORT DUE TO IMPLEMENTATION OF PHASES I AND II OF TARP

Volume 2: Water Quality

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CONTENTS

Page

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OBJECTIVES

The Water Quality Section of the Illinois State Water Survey (SWS) conducted in-depth water quality studies of the Illinois Waterway between Peoria and Lockport during the early 1970s (Butts et al., 1975) and during the early 1980s (Butts and Shackleford, 1987). The water quality information generated during these two studies, coupled with the sediment and sediment oxygen demand (SOD) information collected by Butts (1974), provide good databases for comparing pre- and post-TARP water quality conditions in the waterway below Lockport.

Two basic objectives were established. The first objective was to duplicate the sampling regimen of the early 1970 and early 1980 pre-TARP studies so that pre- and post-TARP water quality conditions could be compared. The second objective was to generate appropriate water quality modeling parameters and data so that the SWS dissolved oxygen/biochemical oxygen demand (DO/BOD) model could be used to predict and/or isolate the benefits attributable to both Phase I and Phase II of TARP. The second objective was to be accomplished via the use of flows generated using the flow model developed to predict the reduction in peak flows, which will result after the implementation of both phases of TARP.

Two secondary objectives were also established. One was to update the 1972 SOD rate maps developed and published by Butts (1974) for the waterway between Lockport (mile 291.0) and Chillicothe (mile 179.0). This work would include extending the maps to include the remainder of the Peoria Pool down to the Peoria Lock and Dam (mile 157.7). The second was to establish three continuous water quality measuring stations using HYDROLAB DataSonde I automatic recording field monitors. These stations were to be located immediately above the Lockport and Starved Rock Dams and at a critical location in Upper Peoria Lake. A fourth monitor was to be used as a mobile unit to gather algal productivity/respiration (P/R) data at selected locations.

METHODS AND PROCEDURES

The routine field sampling techniques used generally duplicated those used during the previous two comprehensive water quality studies conducted for the upper waterway. The SWS DO/BOD model, applied during this study, has been only slightly modified in the intervening years between this study and the previous ones. The SOD techniques and equipment are basically the same as those developed and employed during 1972 with one exception. Water within the SOD respiration chamber is now circulated internally and not externally to produce the desired one foot per second minimum velocity across the face of the DO probe.

Field Sampling

Field measurements were made for pH, water clarity (Secchi disk), temperature, and DO. Water samples were collected for laboratory analyses of nitrate-nitrogen, nitrite-nitrogen, ammonia-nitrogen, and BOD. The pH was measured at the 3-foot depth from which the nitrogen samples were collected. In addition, algae samples were collected for species identification and enumeration. DO and temperature measurements were taken in the center of the navigation channel at the surface, 3-foot depth, mid-depth, and the bottom of all stations except those located immediately above the dams. Above the dams, DO and temperature readings were taken at 2-foot intervals, starting at the surface, on a vertical in line with each open gate above the Starved Rock, Marseilles, Dresden Island, and Brandon Road Dams. Above the Peoria Dam, measurements were made at one vertical in the center of the dam.

Field pH was measured with Gallenkamp Model PHK-120-B pH sticks. A “stick” consists of a plastic-bodied, gel-filled, combination electrode and a miniaturized precision meter with a liquid crystal display (LCD). The electrode incorporates a temperature sensor, which provides automatic compensation for electrode temperature effects from 0 to 45°C. Each meter or stick was calibrated in the field at pH values of 7.0 and 10.0 just prior to sampling. Routine calibration checks were made during the course of the sampling period.

DO/temperature data were collected using YSI Model 59 digital output meters equipped with YSI Model 5795A submersible stirrers and YSI model 5739 DO probes. Calibration was done in the field, immediately prior to the sampling, using a specially constructed water-cooled, air calibration chambers. These chambers were used to check meter stability at the midpoint and at the end of the sampling periods.

The DO/temperature-stirrer/probe assembly was attached to the end of a fishing downrigger cable weighted with a 6-pound cannonball. The sampling depth positions were controlled via the use of heavy-duty downriggers fitted with depth counters. An assembled stirrer/probe was lowered to the bottom, and the total depth was recorded. DO/temperature readings were taken at the bottom, mid-depth, 3-foot, and surface positions.

Secchi disk readings were taken at selected locations in each pool using standard black and white quadrant Wildco limnological disks. The disks were attached to 3/16-inch nylon ropes, which were graduated into inches.

A 125 milliliter (ml) sample of water was retained at selected locations for nitrogen analyses. These samples were preserved by filtering using a Katadyn Pocket Filter equipped with a 0.2-micron microporous ceramic filter element. The filtrates were stored in plastic Nalgene bottles and placed on ice in the field. Upon receipt at the lab, the samples were refrigerated until analyzed.

BOD samples were collected at the mouth of five major tributaries (Des Plaines, DuPage, Kankakee, Fox, and Vermilion Rivers) and at Lockport during each routine weekly water quality sampling run. In addition, numerous additional BOD samples were collected at Lockport under a variety of temperature and flow conditions. Temperature measurements were made when BOD samples were collected. One-gallon samples were collected in plastic Nalgene bottles. These samples were not cooled in the field nor in the lab because the laboratory BOD procedure used precluded doing so. All samples that were returned to the lab at temperatures greater than 20°C were set up for incubation immediately; those less than 20°C were allowed to stand until they reached 20°C before preparation was begun.

SOD measurements were made *in situ* using the same static bell chamber sampler developed for use on the upper reaches of the waterway (Butts, 1974). However, some modification of the operating procedure has evolved since it was first employed. The contained water is now circulated entirely within the sampler using a YSI 5795A submersible stirrer held in place by a large split collar welded to the top of the sampler. The DO temperature probe is housed within the stirrer. The stirrer operates on six size D flashlight batteries. Both the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC, shortened to WRD) and SWS bell chambers were used at all locations except for station 263.1R in the Marseilles Pool. Here the SWS box chamber was used. Temperature and DO readings were recorded at one-minute intervals for the first 5 to 10 minutes of a setting and at 5-minute intervals thereafter.

Black-box water-column respiration rates were measured in concert with the SOD readings at each station. The black-box respiration chambers are designed to have approximately the same volume-to-area ratio as the box and bell SOD chambers. In fact, these chambers are basically plastic replicas of the SOD box chamber with a bottom plate attached. These chambers are filled with water from about mid depth. Oxygen usage and temperatures are measured with either a YSI Model 59 meter equipped with a submersible stirrer or with a YSI Model 56 self-recording DO/temperature meter. Running times ranged from a low of 65 minutes to a high of 98 minutes.

All 22 stations at which SOD measurements were made during 1972 were monitored. In addition, eight additional stations were visited. By pool, the number of measurements made were: Peoria (12), Starved Rock (3), Marseilles (2), Dresden Island (11), and Brandon Road (1). Readings at mile 242.0, in the Starved Rock Pool, could not be made because of the rough, rocky nature of the bottom. A SCUBA diver had to be sent down to secure the sampler at both Marseilles stations.

A sediment sample for total solids and volatile solids analysis and benthos samples were collected with a 9-inch ponar dredge in conjunction with running an SOD. Three benthos grabs were made, composited, and sieved through a 30-mesh wash tray. The benthos sample was preserved with 95 percent ethyl alcohol in plastic Nalgene bottles.

About 65 to 75 grams of homogenized sediment at each station were retained in plastic, sealed bags for laboratory analyses for moisture content and volatile solids. These samples were iced in the field and refrigerated at all other times until laboratory analyses were completed. The quality of the sediments was subjectively described at each location both at the time of collection and in the laboratory.

A 400-ml plankton sample was collected one foot below the water surface at the 28 SOD stations. The algae samples were placed in glass bottles and preserved with 10 ml of formalin.

Water Quality Sampling Regimen

The waterway between the Peoria and Lockport dams was divided into three reaches. Three 2-person sampling crews traversed these reaches once or twice a week between mid-June and mid-August during both the summers of 1989 and 1990. Sampling was started in alternate directions each time; i.e, if sampling was started upstream on a previous run, it was started downstream on the next. This systematic sampling regimen helped ensure that the DO/temperature results were not biased due to hourly differences in sampling times during the day. In effect, the average results at each station should be balanced over the course of the sampling period. Table 1 presents specific main-stem stations assigned to each crew and the parameters measured at each.

The sampling locations are the same as those monitored during 1972 and 1982 for the nitrogen, temperature, and DO. Secchi disk and pH readings were measured at the nitrogen sampling station during this study but not during the previous two studies. The division of labor among the three crews permitted complete sampling of the 134 miles of waterway to be accomplished in about 3 - 4 hours. Nitrogen, pH, and Secchi disk monitoring were done at 20 stations; DO/temperature readings were taken at 60 points on the main stem and at the mouths of the five major tributaries. These tributaries are:

- Vermilion River (mile 226.3)
- Fox River (mile 239.7)
- Kankakee River (mile 272.9)
- DuPage River (mile 277.0)
- Des Plaines - Junction with Sanitary and Ship Canal (mile 250.0)

Laboratory

Ammonia-N analyses were performed by the method developed by Harwood and Kuhn (1970). Nitrite-N analyses were done using the chromotrophic acid method; nitrate-N by the Diazonation method (American Public Health Association, 1985).

The analyses for moisture content and volatile solids were initiated by refrigerating a benthic sediment sample 24 hours to allow excess water to separate from the solids. Any excess water was decanted and the remaining material was homogenized. From 25 to 50 grams of the homogenized sample was retained and prepared for determining dried solids and volatile solids according to procedures prescribed by Standard Methods (American Public Health Association, 1985). A drying temperature of approximately 103°C and a volatilizing temperature of approximately 550°C were used. A subjective description of the physical condition of the wet sediment and the ash residual from the muffle furnace were recorded.

The preserved algae samples were prepared for microscopic examination by vacuum filtering a 50-ml aliquot of the 400-ml field sample through a Millipore Type HA 0.45 micron filter. The filter residue was washed into a vial using 10 ml of formalin. One ml was pipetted from the tube into a Sedgwick-Rafter (S-R) counting cell for microscopic examination. Identification and enumeration of cells were done using a differential- interface, contrast microscope equipped with 10× or 20× eyepieces, 20× and 100× objective lenses, and a Whipple disc. Six counting factors were used. The counting factor selection was based upon an initial subjective evaluation of cell densities. A random width was selected, and counts were made for a number of these widths at various locations on the S-R cell. Low cell densities require wider widths and more counting locations. Enumeration was done under 200×; identification was done under either 200× or 1000×.

Benthos samples were prepared by washing the 30-mesh residue through a series of five sieves including meshes of 2 ½, 5, 9, 18, and 30. The residuals from each were examined separately in white picking trays. The organisms were removed and preserved in vials containing 95-percent ethyl alcohol.

Organisms were separated and examined under a Wild M8 Zoom Stereomicroscope, which has a magnification of 6× to 50×. The microscope is fitted with a Volpi AG Intralux 150 light source. All organisms from the samples were picked and sorted; subsampling techniques were not used. Most organisms were identified to genus and species; a few were identified only to genus.

The BOD analyses were performed using a modification of the jug aeration procedure developed by Elmore (1955). The gallon samples of BOD water, collected in the field, were split equally into two portions and placed into half-gallon Nalgene aspirator bottles for aeration (or deaeration) to near- saturation levels. The samples were warmed to at least 20°C when necessary before aeration to prevent air bubbles from forming during incubation.

The nitrification process in one of the half-gallon bottles was inhibited by adding at least 1.2 grams of Hach 2533 nitrification inhibitor chemical. The chemical was reintroduced every five days during the incubation period. The inhibitor was injected into the bottle prior to aeration to accord thorough mixing. Aeration/mixing was maintained for a minimum of 10 minutes. Three standard 300-ml Wheaton BOD bottles were filled from each uninhibited and inhibited aeration bottle. These BOD-bottle samples and the sample remaining in both aeration bottles were incubated at 20°C ± l.0°C. Daily DO/temperature readings were made over 18- to 20-

day periods using YSI Model 59 DO/temperature meters equipped with YSI Model 5739 BOD stirrer/probes. Whenever, the DO concentration approached 2.0 mg/l in **a** BOD bottle, the three samples were poured back into the appropriate aeration jug and reaerated.

Six DO/temperature meters were used, and care was taken to avoid interchanging the stirrer and probes for the inhibited and uninhibited samples. Also, care was taken to use the same meters to take readings on the same samples throughout the test period. All six meters were air-calibrated in a communal air-calibration chamber at the same time to insure uniform- stable calibration conditions.

Data Reduction and Analyses

The data reduction and analyses involved five major components: (1) BOD-curve formulations, (2) SOD rate computations, (3) time-of-travel (TOT) computations, (4) BOD/DO water quality model parametric input development, and (5) individual water quality parameter prediction equation development.

Biochemical Oxygen Demand (BOD) Data

Generally, the long-term BOD or DO usage in a stream is modeled as a first-order exponential reaction, i.e., the rate of biological oxidation of organic matter is directly proportional to the remaining concentration of unoxidized material. The integrated mathematical expression representing this reaction is:

$$L = L_a\left[1 - e^{-K_1 t}\right] \qquad (1)$$

where

L = oxygen demand exerted up to time t

L_a = ultimate oxygen demand

K_1 = reaction rate per day

t = incubation time, days

e = base of natural logarithm, 2.7183

When a delay occurs in oxygen uptake at the onset of a BOD test, a lag time factor, t_0 is included and the equation becomes:

$$L = L_a\left[1 - e^{-K_1(t - t_0)}\right] \qquad (2)$$

However, at times, neither equation 1 or 2 provides a good model for observed BOD progression curves generated for samples collected in the Brandon Road and Lockport Pools. The BOD in waters from these pools often consists primarily of high-profile second-stage or nitrogenous BOD (NBOD), and the onset of the exertion of this NBOD is often delayed one or two days. The delayed NBOD curve and the total BOD (TBOD) curve, dominated by the NBOD fraction, often exhibit an S-shaped configuration. The general mathematical model used to simulate the S-shaped curve is:

$$L = L_a\left[1 - e^{-K_1(t-t_0)^x}\right] \tag{3}$$

where x is a power factor, and the other terms are the same as previously defined.

Statistical procedures were used by Butts et al. (1975) to show that a power factor of 2.0 in equation 3 best represents S-shaped BOD curves generated in the Lockport and Brandon Road area of the waterway. Substituting x = 2 in equation 3 yields:

$$L = L_a\left[1 - e^{-K_1(t-t_0)^2}\right] \tag{4}$$

Three types of BOD were developed: total, carbonaceous, and nitrogenous. TBOD (uninhibited) and CBOD (inhibited) were measured directly while NBOD was computed by subtracting CBOD values from TBOD values for given time elements.

All the BOD curves generated during this study were fitted to equations 1, 2, and 4. The observed data were fitted to these equations using a statistical process known as the method of steepest descent (or slope). It is an interactive process that can best be applied using computer techniques. Accurate estimates can be made of L_a, K_1, and t_0, using these computer solutions.

Sediment Oxygen Demand (SOD) Data

SOD curves were plotted showing the accumulated DO used (Y-axis) versus elapsed time (X-axis). These curves are analogous to BOD curves in concept but not in analyses. These curves generally do not represent first-order biological oxidation reactions. For the most part, SOD is caused by bacteria reacting to an “unlimited” food supply. Consequently, the oxidation rates are linear in nature.

The SOD rates, as taken from the curves, are in linear units of milligrams per liter per minute (mg/l/min) and are converted into grams per square meter per day

($g/m^2/day$) for practical applications. The general conversion formula is:

$$SOD = \frac{1440\ SV}{10^3 A} \tag{5}$$

where

SOD = sediment oxygen demand, $g/m^2/day$

S = slope of stabilized portion of the curves, mg/l/min

V = volume of sampler, liters

A = bottom area of sampler, m^2

The above formula can be reduced to the general form:

$$SOD = KS \tag{6}$$

where K is a constant specific to a respiration chamber design.

The K-values for the SWS bell, the WRD bell, and SWS box chambers used during this study are 187.38, 189.58, and 207.79, respectively. Equations 5 and 6 also apply to the black-box, water-column, oxygen-demand (WCOD) chamber. The K-value for the WCOD chamber is 213.91.

Each SOD curve was examined, and linear rates were computed for each portion of the curve that exhibited a significant and lengthy change in slope. The true benthic SOD rate was computed by subtracting the WCOD rate from the gross bottom chamber rate.

Areal SOD maps were developed showing estimated SOD rates along various reaches and segments of the Illinois Waterway from Peoria to the waterway's three-point termination at Lake Michigan. SOD rates were identified in gross terms of 0-l, 1-2, 2-3, and greater than 4 $g/m^2/day$.

SWSBOD/DOModel

The basic model used by the SWS 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:

$$DO_n = DO_a - DO_u + DO_r + DO_x \tag{7}$$

where

DO_n = net DO at the end of a reach

DO_a = initial DO at the beginning of a reach

DO_u = the DO used biologically

DO_r = the DO addition due to aeration

DO_x = 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 7 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 SOD. The ratio of algal productivity to respiration is assumed to be unity, although the model can handle values greater or less than one when derived on a diurnal basis. Both forms of BOD are programmed to follow first-order biochemical oxidation reactions as expressed by equation 2.

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

$$G' = \frac{3.28\,G\,t}{H} \tag{8}$$

where

G' = oxygen usage per reach, mg/l

G = the SOD rate, $g/m^2/day$

t = the detention time per reach, days

H = the average reach water depth, feet

All biological rates, including BOD and SOD, were corrected for temperature using the basic Arrhenius model:

$$R_T = R_A(\Theta^{T-A}) \tag{9}$$

where

R_T = biological oxygen usage rate at any temperature, T°C

R_A = biological oxygen usage rate at ambient or standard temperature, A°C

Θ = proportionality constant set equal to 1.047 for this study

The aeration factor DO_r is computed using the theoretical concepts advocated by Velz (1947, 1970). Refer 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.

DO, 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:

$$\frac{C_S - C_A}{C_S - C_B} = 1 + 0.38\ a\ b\ h\ (1\text{-}0.11h)\ (1\text{+}0.046T) \qquad (10)$$

where

C_s = DO saturation concentration at a given temperature
C_A = the DO concentrations above the dam flow release structure
C_B = the DO concentrations below the dam flow release structure
a = the water quality factor
b = the weir aeration coefficient
h = the static head loss at the dam in meters
T = the water temperature in °C.

The State 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), Butts and Adkins (1987), Butts et al. (1989a), and Butts et al. (1989b).

DO saturation (DO_S) is computed using the American Society of Civil Engineers (1960) formula:

$$DO_s = 14.652 - 0.41022\ T + 0.007991\ T^2 - 0.000077774\ T^3 \qquad (11)$$

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.

Hydraulic/Hydrologic Model and Information

River time of travel (TOT) and stream geometry characteristics were computed using a volume displacement model represented by the simple equation:

$$t = \frac{V}{Q} \times \frac{1}{86400} \qquad (12)$$

where

t = stream reach time of travel, days
V = stream reach volume, ft^3
Q = average flow in reach, ft^3/sec

Central to the use and accuracy of this basic formulation is the need for good, reliable stream cross-sectional information. The SWS has on file over 1,650 cross sections between Lockport and Grafton for the Illinois River. This information has been gleaned from U.S. Army Corps of Engineers (COE) maps and files over the past 10-15 years. This massive amount of information is retained in a computer file, which was reviewed, updated, and corrected as needed for this study.

An important fact was uncovered during the original transcription of the COE data into the SWS computer file. The COE 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 SWS, are presented and compared to the COE designations in Appendix A. Differences occur for a number of reasons. Besides differences attributable to accuracy errors, which obviously can be a factor, the COE distances deviate from those measured by the SWS for two major reasons: 1) the COE retains original mileage designations even when channel shortening and straightening has occurred, and 2) the COE 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 two, however, appear to balance each other in the end as can be noted from the upstream net results at Lockport (COE River Mile 291.0) in Appendix A; only 0.04 of a mile separates the COE designation from that actually measured by the SWS.

Nevertheless, differences do become obvious in specific pools or reaches. For example, because of channel shortening in the Starved Rock pool (COE River Mile 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 COE mileage for convenience, but all computations have been done using SWS lengths.

A copy of a computer printout showing the input and the subsequent output data for a flow simulation is presented in Appendix B. Included in the output is the SWS 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 cross-sectional information obtained for the upper and lower Peoria Lake reaches was modified to minimize the effects of the extreme width and shallow nature of this area. Much of the lake area is 1 to 2 miles wide and less than 5 feet deep. The main channel is only 500 to 900 feet wide and 10 to 20 feet deep, and most of the flow passes in the navigation channel. Consequently, allowances were made to limit cross-sectional areas in association with certain flow rates. For flow rates at Marseilles of 5,000 cfs or less (low flow) the average channel cross-sectional area in upper Peoria Lake was limited to 6500 sq ft; for flows 5,000 cfs to 10,500 cfs (medium flow), the cross-sectional area was limited to 10,500 sq ft; and for flows greater than 10,500 cfs, the flow was allowed to pass through the entire lake. For lower Peoria Lake, the area limits for low and medium flows were set at 9,300 ft^{2}2 and 11,800 ft^{2}2, respectively.

Water Quality Regression Equations

Prediction equations were developed using statistical regression techniques so that comparisons could be made between pre- and post-TARP river water quality. conditions. The general form of the predictive equation used was:

$$Y = a + bT + c(\log Q) \tag{13}$$

where

Y = predictive parametric result, mg/l
T = stream water temperature, °C
log Q = stream flow, cfs ($\log_{10}$)
a, b, c = regression constants (coefficients)

Sets of pre- and post-TARP equations were developed for DO, ultimate CBOD (L_{ac}), ultimate NBOD (L_{an}), the carbonaceous usage rate constant (K_c), and the nitrogenous usage rate constant (K_n). These relationships were developed for the Chicago Sanitary and Ship Canal (CS&SC at Lockport and for the mouths of the Des Plaines (junction with CS&SC), DuPage, Kankakee, Fox, and Vermilion Rivers. Point source loads were gleaned from the work of Butts et al. (1983).

From the data generated using the TARP-imposed changes in flow, six time periods were selected to evaluate anticipated changes in water quality due to changes in TARP-related downstream flow patterns and TARP-related waste load reductions in the Chicago area. Two significantly different approaches were used. One consisted simply of imposing pre- and post-TARP waste loadings, as predicted from the appropriate version of equation 13, and pre- and post-TARP SOD rates, on ambient flow conditions for each period. By doing this, the effects of waste load reductions, after the implementation of TARP, could be viewed independently from any water quality changes that may have been caused by changes in flow.

The second approach consisted of evaluating the combined effects of waste load and flow regime changes due to TARP on water quality. A baseline set of water quality conditions were established at a flow rate of 5,000 cfs at Lockport. A perusal of the flow and hydrologic information cataloged into the computer indicated that 5,000 cfs approximated the “breakpoint” at which combined sewers began to overflow in the Chicago area. Waste loads, DO-usage rates, and DO boundary conditions were set using this flow in conjunction with the appropriate predictive equation developed for the post TARP time frame. Next, using the flows generated from the flow model for each time period, pre-TARP loads and boundary conditions were established. Water quality model runs were then performed for various degrees of “overflow” waste load reductions, namely 20, 40, 60, and 80 percent for both TARP I and II, and an additional 97 percent for TARP II.

Because the predictive DO-usage rate factors K_C and K_n vary with flow, as do L_{ac} and L_{an}, certain situations develop whereby a low waste load may be “married” to a high K-value or a high waste load may be “married” to a low K-rate. Both may produce similar DO profiles for a limited time interval. Consequently, the waste loads are not directly additive at a given point in time unless they are adjusted to a common base. Because of the exponential nature of a first-order biological reaction, a finite common base cannot be derived. However, an approximation can be achieved by computing L in equation 1 for a large value of t (say, 20 days, which would yield L_{20}) for a given combination of L_a and K for which L_a needs to be adjusted to some “base” K-value. The computed L_{20} is then used in equation 1 in conjunction with the “base” K-value and t = 20 to compute an adjusted L_a. For example, for the 5,000 cfs-base conditions, the post-TARP regression equations for a June 1976 flow and temperature condition produced an L_{an} = 232,623 pounds per day (lb/day) loading at Lockport in conjunction with a K_n = 0.095 l/days. However, significant overflows occurred during this period producing a predicted L_{an} of 1,470,229 lb/day at a K-rate of 0.068 1/day. Since the 1,470,229 lb/day load is associated with a usage rate considerably less than the base usage rate, it cannot be directly compared to the base load without some adjustment. The adjustment computations are done using t = 20 in equation 1:

$$L_{20} = 1{,}470{,}229 \left[1 - e^{-(0.068 \times 20)}\right]$$

$$L_{20} = 1{,}091{,}657 \text{ lb/day}$$

Converting to base (5,000 cfs) conditions

$$1{,}092{,}920 = L_{an}\left[1 - e^{-(0.095 \times 20)}\right]$$

$$L_{an} = 1{,}285{,}087 \text{ lb/day}$$

The L_{an} of 1,285,087 lb/day is associated with a K-value of 0.095 l/days, the same as the base condition, thereby, permitting computational interchanges to be performed within an acceptable degree of accuracy. The load associated with a reduction in overflow contamination would be computed thusly:

$$L_{aa} = L_{ab} + \left[\left(1 - \frac{P}{100}\right)\left(L_{aI,II} - L_{ab}\right)\right] \tag{14}$$

where

L_{aa} = adjusted ultimate BOD load, lb/day

L_{ab} = the base ultimate BOD load, lb/day

P = percent reduction in overflow load

$L_{aI,II}$ = predicted stream load, for either TARP I or TARP II conditions, lb/day

For the above example for an 80-percent load reduction, the results would be:

$$L_{aan} = 232{,}623 + \left[\left(1 - \frac{80}{100}\right)\left(1{,}285{,}087 - 232{,}623\right)\right] \tag{15a}$$

and

$$L_{aan} = 443{,}116 \text{ lb/day} \tag{15b}$$

This ultimate load at Lockport, with an associated K-value of 0.095 1/days, would be used in the water quality model to develop DO-sag curves for an 80-percent reduction in overflow oxygen-consuming waste load.

RESULTS

Overall, the results of this study were good to excellent. The only goal not accomplished was the establishment of a DataSonde continuous monitoring station in upper Lake Peoria. After investigating the possibility of locating a station in this area, a decision was made not to do so. Such a station would pose a hazard to navigation, especially to pleasure boats, and the risk of losing an instrument here would be too great.

Water Quality Data

The results of the water quality parameters measured during this study will be presented in tabular and graphical form when appropriate. Also, historical tabulations and plots of DO, temperature, ammonia, nitrite, and nitrate will be presented for comparative purposes.

Ten river sampling runs were conducted during both 1989 and 1990. These dates are presented in table 2, along with flows for each sampling date for main-stem U.S. Geological Survey gages at Lockport (LP), Marseilles (Mar), Henry (Hen), and Kingston Mines (KM). Also presented in the table are tributary flows for the Des Plaines (Des) above its junction with the CS&SC, DuPage (DuP), Kankakee (Kan), Fox, and Vermilion (Ver) Rivers. Runs were not completed on July 2, 1990 and July 16, 1990 because of boat failures. On July 2, 1990, the Starved Rock Pool was not sampled, and on July 16, 1990 the upper end of the Peoria pool from mile 217.1 to 230.8 was not completed.

The daily, average, and medium flow values given in table 2 for the 1989/90 sampling period indicate that medium to high flows persisted during this study. However, similar flow characteristics persisted throughout during the 1982 sampling period. In addition, equally high or higher flows occurred above Marseilles during the 1971/72 sampling period. During 1971/72, flows below Marseilles were high, but not quite as high as those experienced in this reach of the river during this study. In certain respects, the relatively high 1989/90 summer flows provided ideal conditions for conducting this study since, prior to the implementation of TARP I, they would have been sufficient to cause frequent significant combined sewer overflows (CSOs) in the Chicago area. Also, good, direct comparisons of water quality conditions could be made relative to the two pre-TARP studies since similarly high summer flows persisted during both of those studies.

Dissolved Oxygen/Temperature

The individual DO results for 1989 and 1990 are listed by date, station, and depth in Appendix C. The temperature results are listed similarly in Appendix D. The average, maximum, and minimum DO values are summarized by station in table 3. A similar summary of temperature results is given in table 4. Similar summaries are presented in each table for the 1971/72 and 1982 studies. Of particular significance is the fact that the DO levels at Lockport displayed marked improvement since 1982. During 1989/90, the minimum observed DO concentration was a lofty 1.71 mg/l when compared to the historical zero levels that persisted here. The 1989/90 maximum value was 7.40 mg/l — over 200 percent greater than the 1982 maximum value and almost 250 percent greater than the 1971/72 maximum value. The 1989/90 average value was over 300 percent greater than either the two previous studies' values.

The average DO values were higher at all stations during this study than the previous two pre-TARP studies with two exceptions. These two exceptions occurred at miles 170.9 and 167.0 in upper Peoria Lake. Figure 1 graphically illustrates the significant, if not somewhat dramatic, increase in DO levels throughout the upper waterway over the past 20 years. Marked improvement even occurred over the past ten years especially above Starved Rock. The tendency for the 1982 values to be slightly higher in the lower Peoria Pool could be the result of greater photosynthetic oxygen production and/or lower temperature (see figure 2). Flows were lower in this area of the river during 1982 (see Hen, table 2), thereby providing a better environment for algal growth. The 1982 average DO at station 167.0 of 8.12 mg/l is 98.6 percent of saturation for an average temperature of 23.8°C (table 4); the 1989/90 average DO value at this station of 7.69 represents a saturation level of 96.0 percent for an average temperature of 25.2°C (table 4).

An interesting phenomenon has occurred over the past 20 years relative to the effects of flow release control on reaeration at the Marseilles Dam. Until the late 1970s, a power plant operated at this site. During low summer flows, most of the river flow was diverted into a raceway around the dam to the power plant. This resulted in an almost total lack of aeration at the dam since little aeration is achieved in water used for power generation. This accounts for the continuous DO-sag across the Marseilles Dam as evidenced by the 1971/72 curve shown on figure 1. After the power plant ceased to operate, aeration at the dam occurred, resulting in some aeration at the site as shown by the 1982 curve on figure 1. However, as DO levels in the Marseilles Pool improved to near-saturation level, little "room" was left for oxygen uptake to occur at the dam as shown by the 1989/90 curve on figure 1.

The average temperatures in the river seem to have varied considerably over the past 20 years (figure 2 and table 4). The widely divergent nature of the curves and data for the three sampling periods are explainable to a great degree. During the early 1970s, the temperatures in the upper waterway were significantly influenced by cooling water discharges, many of which no longer exist. This accounts for the large decrease in average summer temperature in the waterway above Starved Rock between 1972 and 1982. The 1982 temperature profile is lower than the 1989/90 profile principally because sampling was conducted in May and October during 1982, whereas sampling commenced in June and was terminated at the end of August during 1989/90.

Ammonia, Nitrites, and Nitrates

The ammonia, nitrite, and nitrate results are presented in Appendix E and are summarized in tables 5, 6, and 7, respectively. Summaries of these parameters for the 1971/72 and 1982 sampling periods are also presented in these tables. Ammonia profiles for the three sampling periods are shown on figure 3. Examination of this figure and the data contained in table 5 reveals that the reduction in ammonia discharges in the Chicago area has been spectacular over the past 20 years; moreover, much of this reduction has occurred since 1982. During the 1970s ammonia was being biologically oxidized at a high rate as far downstream as Peoria (figure.3). During 1982, the oxidation was still highly significant as far downstream as Starved Rock but became drastically reduced in the Peoria Pool. During 1989/90, the oxidation rate was barely significant anywhere, even in the Brandon Road and Dresden Island Pools. Ammonia levels entering the Peoria Pool during 1989/90 were too low to sustain significant nitrification as evidenced by the stable, low concentration ammonia curve shown for that pool on figure 3, and the elevated but slightly progressive downstream reduction in nitrates as shown on figure 5. The nitrate levels increased downstream during the previous two studies which indicates that nitrification was active during those periods and contributing to the nitrate levels throughout the upper waterway.

The sharp increase in nitrite levels in the Peoria Pool, as depicted by the 1972 plot shown on figure 4, illustrates the magnitude of nitrification that was occurring in the pool at that time. Nitrite production is an intermediate step in nitrification and is biologically unstable. Nitrite instability precludes a permanent buildup of the compound, unlike nitrate, which increases commensurately with decreases in ammonia (figures 3 and 5). Consequently, levels along the waterway have decreased and remain at very low levels. The temporary “blip” in concentration at station 162.8 (figure 4, table 6), which is on the downstream end of lower Peoria Lake, is unexplainable. The slight upturn in ammonia concentration at the end of the Peoria Pool (figure 3, table 5) is caused by the effluent from the Greater Peoria Sanitary District treatment plant.

Table 8 lists average nitrogen loads at sampling stations located close to the three main-stem USGS gaging stations. The average Lockport ammonia load decreased 91.6 percent from those observed during 1971/72, while the average concentration decreased slightly less, 88.6 percent. Interestingly, the load at Marseilles appeared to remain relatively stable between 1982 and 1989/91, although the load at Lockport decreased by over 44,000 lb/day between this period.

Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) samples were collected on 40 dates at Lockport throughout all months of the year during both 1989 and 1990. Tributary BOD samples were collected on 31 dates throughout both years. DO and pH readings were taken in the field on most dates, and samples were collected for laboratory analyses of ammonia, nitrite, and nitrate.

Tables 9 and 10 show typical printouts of computer files in which the long-term (20-day) BOD data is stored. These detailed data are available upon request but will not be made available in hard copy as part of this report. Also available upon request are graphical plots of the BOD progression curves as typified by figures 6, 7, and 8. These plots correspond to the data given in tables 9 and 10.

These three particular sets of data were chosen to illustrate several unique characteristics and considerations. Figure 6 demonstrates that S-shaped NBOD and TBOD curves still exist at Lockport that fit the mathematical model represented by equation 3. This curve is similar to the Lockport cold-weather curve published by Butts et al. (1975). These curves usually occur at Lockport in cold weather (note the l/16/90 date) but not always.

Figure 7 shows typical Lockport warm-weather progression curves. Note the extreme difference between the warm- and cold-weather curves. The January $NBOD_{20}$ represents 75.3 percent of the $TBOD_{20}$, whereas the September $NBOD_{20}$ represents only 56.6 percent of the $TBOD_{20}$. Furthermore, the September $TBOD_{20}$ is only 23.3 percent as great as the January $TBOD_{20}$ (see table 9).

Figure 8 illustrates most tributary BOD characteristics. The tributary warm-weather $TBOD_{20}$ values often approach those observed at Lockport (7.03 mg/l versus 8.92 mg/l), but the fraction due to $NBOD_{20}$ is much less. Only 16.9 percent of the Kankakee $TBOD_{20}$ consisted of $NBOD_{20}$. However, the $TBOD_{20}$ loads coming from the tributaries are usually much less than that originating from Lockport since the tributary flows are normally much lower. Nevertheless, the example, the flow in the Kankakee was 3,010 cfs on August 13, 1990, whereas it was only 2,947 cfs at Lockport. The respective Kankakee and Lockport loads were 114,083 and 141,724 lb/day, an unusually close match in loadings.

Secchi Disk and pH

Secchi disk reading and pH measurements were recorded at the stations noted in table 1. These parametric results are not central to meeting the objective of this study. Such readings are normally taken by SWS personnel during any data-gathering run along the waterway irrespective of the type of study being undertaken. The results are presented in Appendix F.

Some discussion, however, appears in order concerning these results, as the variability of these parameters can reflect upon cause and effect relationships relative to the DO balance along the waterway. For example, note from the Secchi disk results (an indicator of water clarity) that light penetration, as measured by the disk, can be six or seven times greater at Lockport than at Peoria. Even with the relatively low depth of light penetration in the Peoria Pool, photosynthetic oxygen production often dictates DO levels in this area of the waterway. For example, on June 27, 1989 at station 166.1 the surface DO concentration was 15.85 mg/l, whereas the bottom concentration was only 7.75 mg/l (see Appendix C1). Twenty years ago such algal influence did not exist. With the significant improvement in water quality in recent years and the good water clarity sustained in Chicago-area waterways, primary production could become a major influence on the DO balance in the extreme upper reaches of the waterway in the near future. The inclusion of primary production as a factor in the modeling evaluation of the effect of TARP on downstream DO levels is beyond the scope of this study.

The pH variability, as displayed by the results presented in Appendix F, is reflective of algal influences on present water quality in the lower half of the study area. The increase in a downstream pH levels also could reflect on future releases of ammonia from ammonia sinks along the lower portion of the study area waterway (Kaufmann, 1991).

Statistical summaries of all the water quality results are presented in Appendix G.

SOD and Sediments

SOD measurements were made at 30 locations between Peoria and Lockport during the last two weeks of August 1990. Twenty-two of the stations were at approximately the same locations at which SOD measurements were made during 1972. The finite input used to derive the SOD rates and the final rates are presented in Appendix H1. The areal rates estimated for all waterway reaches between the Peoria Dam and Lake Michigan are presented as maps in Appendix H2. Sediment descriptions at each SOD measurement station are given in Appendix H3. Plots of the SOD curves (DO usage versus time in minutes) are available upon request.

The tabulated computed values (Appendix H1) reflect incremental changes dictated by major inflection points on the curve and overall average values for the total curve (or for a realistic overall time interval). For example, the values at station 164.4R (R means right bank looking downstream) $\Sigma t = 59$ minutes represents the SOD rate for a 10-minute interval of the SOD curve between 49 and 59 minutes of elapsed time. The best overall average was computed exclusive of the first 14 minutes. Various incremental and overall rates have been computed to provide alternatives in selecting the portion of the curve that appears to be most representative. In most cases, the substrates below Brandon Road are of such a nature that high initial rates due to the bottom disturbances of placing the sampler do not materialize. In fact, at many of the locations such as at 179.0 and 198.9 river miles, the rates over the initial 15 - 20 minutes are significantly lower than the rates over the final 40 - 60 minutes.

A comparison between the 1972 SOD rates and those measured during this study is given in table 11. A cursory comparison between the current results and the earlier ones indicates that little change has occurred in the “gross” SOD rates of the sediments below Dresden Island Dam. However, the 1990 rates in the Dresden Island Pool appear to be significantly lower than the 1972 rates in this pool. The 1990 rates, in fact, are so much lower that they are not realistic for some locations. A significant reduction in SOD rates can, in part, be attributed to a wide disappearance of fine-textured benthic sediments in and around the navigation channel. For example, Butts (1974) describes 1972 sediments at station 282.3L as “oily smell, oily gritty watery muck,” whereas the 1990 description indicates that only a thin layer of silt exists on top of packed-clay, gravel, rocks, and shell fragments (Appendix H3).

Somewhat aberrantly low rates in some locations may have been due to the fact that difficulty was encountered in keeping the respiration chamber sealed due to the gravel, rock, and shell nature of much of the substrate encountered, coupled with the relatively high flow rates that existed during the settings. Also, the 1972 measurements were done using external pumping through the chamber, thereby causing constant bottom disturbances and possibly producing misleadingly high rates. In any event, **a** follow-up check needs to be-conducted in Dresden Island Pool. However, the areal rates presented in Appendix H2 for this Pool are deemed realistic.

Benthos and algal samples are routinely collected by SWS investigators when performing SOD measurements for supportive and interpretive reasons. The process of picking, sorting, identifying, and enumerating these organisms is costly and time-consuming. These tasks have been only partially completed, but they will be completed and made available upon request. Benthos/algal information is not central to the outcome of this study, and its absence will not affect any computations, results, or conclusions.

DataSonde Monitoring

The Starved Rock DataSonde monitoring station was established during 1989 at a distance of 400 feet above the dam. Continuous daily water data was available between May 31 and November 20 during 1989 and between June 28 and August 30 during 1990. The Lockport monitoring station was also established during 1989 on the outside of the dam fender wall on the west side at mile 291.2. Continuous daily data was available between May 26 and November 11 during 1989 and between June 27 and August 30 during 1990. Parameters routinely measured were temperature (°C), pH, conductivity (ms/cm), and DO (mg/l). At times, oxidation-reduction potential was included depending on the DataSonde unit utilized. A given unit was left in place for 7 days before being replaced with a newly calibrated unit. Consequently, most unit data print-outs were retrieved and summarized on a 7-day basis. An example of daily and summarized data for a 7-day period is included (Appendix I). A statistical summary was included after each date and an overall 7-day summary was printed out at the end of the last date. The statistical summaries included the number of readings (maximum, minimum, and mean values), maximum change, and standard deviation. An hourly sampling interval set on the hour was used. The DataSonde recorded at a depth of about 30 inches.

Printouts for all dates, as exemplified by those presented in Appendix I, are available upon request. During the course of the study, much of the information recorded has already been sent to various District personnel to meet special, immediate needs. The tabular data is massive — in many instances, daily or weekly summaries may suffice to meet future needs.

The ability to record hourly parametric water quality measurements at two more stream locations literally adds a third dimension to the visualization, both temporally and spatially, of water quality changes and variations in a flowing body of water. Plots of hourly changes in water quality data (figures 9 - 13) demonstrate this. Presented are 1989 and 1990 Starved Rock and Lockport DO plots for two 72-hour periods and a pH plot for two 1990 72-hour periods at Starved Rock. From just these selected presentations, deductions can be made about the water quality characteristics of much of the upper waterway. Figures 9 and 10 show that diurnal fluctuations in DO at Starved Rock can be great or small for certain periods and that these patterns are repeated from year to year. Minimum standard concentrations of 5.0 mg/l at Starved Rock are seldom violated.

Lockport DO patterns (figures 11 and 12) greatly contrast to those at Starved Rock. Diurnal fluctuations are minimal and are quite predictable throughout long time periods. The minimum standard of 3.0 mg/l imposed at Lockport is violated at times.

The July 21-23 pH curve (figure 13) indicates that temporal variations in pH at Starved Rock can be highly significant during the onset of prolific algal activity as shown by the corresponding July 21-23 DO curve (figure 10). Over the 7-day period, which includes the July 21-23, 1990 dates, the pH ranged from a low of 7.88 to a high of 9.09. This net difference (1.21 pH units), was significantly greater than the average spatial difference between Lockport and Peoria (0.94 pH units) for the 20 sampling dates presented in Appendix F. Much of the downstream spatial increase, in turn, can be attributed to progressively increasing phytoplanktonic activity downstream.

Regression Modeling of Water Quality Parameters

The regression constants or coefficients derived from various water quality parameters to fit equation 13 are presented in table 12. Given in the table are pre- and post- TARP I values. Note that the multiple coefficient of correlation values (R) relating the various water quality parameters to water temperature and streamflow range from poor (0.05: Kankakee, pre-TARP, L_{ac}) to excellent (0.92: Kankakee, post-TARP, K_c). However, with a few exceptions, all are statistically significant. Even for those not statistically significant the predictive results are not affected. It merely means that over a wide range of temperatures and flows, the input or predicted values will remain relatively constant or unchanged.

Most importantly, the relationships developed for the Lockport parameters exhibit fair to very good correlations. Furthermore, the pre- and post-TARP equations predict distinctively different results with post-TARP results being indicative of major improvements in water quality. This fact was demonstrated by applying the predicted pre- and post-TARP inputs to the water quality model from widely divergent flow regimes for six time periods: 6/13-19/76, 9/03/76, 7/21-27/80, 7/01/85, 8/14-2l/87, and 8/22/88. Also, pre-TARP SODs (Butts et al., 1983) were loaded to the pre-TARP model run while post-TARP SODs were derived from the SOD maps (Appendix H2) and loaded to the post-TARP model run. A pre-TARP nitrification lag time (t_o) of two days was used; t_o was reduced to one day for the post-TARP model run. The results of these water quality model simulations are depicted in figures 14 - 19.

All six simulations show that post-TARP waste load inputs, coupled with lower SOD rates and higher boundary DO levels, predict higher overall DO concentrations when compared to pre-TARP conditions. This is like stating the obvious — but not quite. The degree of improvement and the reach or pool location is highly dictated by flow. Also, by reducing the post-TARP lag time to one day from the two days used for pre-TARP, post-TARP nitrification is initiated farther upstream. Consequently, depending upon the overall flow regime, this phenomenon can put more stress on the DO resources in the pools above Starved Rock. This extra strain on upper pool DO levels was clearly evident for the 6/13-19/76 simulation (figure 14). The actual post-TARP DO profile fell slightly below pre-TARP values. However, the differences were small, and both the predicted pre- and post-TARP DO concentrations remained well above the minimum standard instituted below Brandon Road, was maintained through the rest of the study area for post-TARP conditions, but pre-TARP input allowed the simulation to violate the standard in the lower end of the Peoria Pool.

When relatively low-flow conditions persist throughout the study area, the most marked improvement in DO levels appears in the Brandon Road and Dresden Island Pools (figure 19); the remainder of the waterway exhibits only modest improvements. When very high flows originate at Lockport, such as those during the

7/21-27/90 period (figure 16), pre-TARP simulations indicate that serious violations of stream standards would probably have occurred throughout much of the Peoria pool. This results from the fact that high flows reduce upstream waste residence time, thereby pushing the initiation of nitrification into the lower end of the Starved Rock pool or the upper end of the Peoria pool. Numerical summaries of the maximum and minimum simulated DO concentrations per pool by date are given in table 13,

DISCUSSION

The results of this study clearly indicate that significant water quality improvements have been manifested in waters of the upper Illinois Waterway since the inception of TARP I. The summary of field results (figures 1 - 5), and the summary of water quality model runs (figures 14 - 19) attest to this. However, the improvements, as depicted by these figures, represent gross improvements. Differentiation between the improvements resulting from the reduction of combined sewer overflows and those resulting from wastewater treatment plant improvements needs to be addressed.

A methodology for doing this was developed using equation 14. Overflow waste load reduction of 20,40,60, and 80 percent were used for both TARP I and TARP II, and an additional reduction of 97 percent was used in conjunction with TARP II. Equation 15a was used to develop input to the water quality model which uses equation 14. To evaluate TARP's possible effects for improving water quality below Lockport, three historical flow periods were chosen for applying this methodology. All three flow periods represent medium to high Lockport and downstream flows during which significant combined sewer overflows (CSOs) occurred or would have occurred had TARP not been in effect.

Two pre-TARP periods, 6/13-19/76 and 7/21-27/80, and one post-TARP period, 8/14-21/87, were selected. These three periods were chosen to represent three distinct scenarios: (1) a high Lockport discharge with significant increases in downstream flow (6/13-19/76), (2) a very high Lockport discharge with little significant downstream increase in flow (7/21- 27/80), and (3) an extremely high Lockport discharge with significant increases in downstream flow (8/14-21/87). The results of the TARP I water quality model simulations are presented as figures 20 - 22, and the results for TARP II simulations are presented as figures 23 - 25. Note that the original flows (0), TARP I (TI) flows, and TARP II (TII) flows are presented on the right margin of each figure. Numerical summaries of the maximum and minimum simulated DO concentrations per pool for each scenario are presented in table 14.

The simulated results reveal some interesting and informative insights on the possible effects that implementation of TARP I and II could have on downstream water quality as represented by DO levels. Some resultant aspects are not only informative but also somewhat unexpected.

TARP I

Probably the most noteworthy positive aspect is that TARP I significantly improves the overall waterway DO concentrations under all flow regime scenarios as exemplified by figures 20 - 22. The high streamflows that occur in concert with large Chicago-area CSOs rapidly convey the raw overflow waste loads downstream where biodegradation intensifies. Much of the load is nitrogenous in nature, and bio-oxidation of ammonia does not proceed at a maximum rate until high nitrifying bacteria numbers are built up. The time of travel below Lockport needed to buildup nitrifying bacteria populations sufficient to use the ammonia content of raw waste, such as contained in CSOs, is about two days. This figure was derived from fitting pre-TARP Lockport NBOD curves to equations 2 and/or 3 (Butts et al., 1975) and plotting ammonia concentrations versus travel time below Lockport (figure 3). NBOD lag times appear to average one-day travel time below Lockport. This figure was derived by fitting the 40 Lockport NBOD curves derived during this study to equation 2 and/or 3. The lag times used for the various P- values were proportioned between one- and two-day lag times; i.e., lag times of 1.8, 1.6, 1.4, 1.2, and 1.03 days for P-values of 20, 40, 60, 80, and 97 percent, respectively.

The DO levels were significantly raised in the Brandon Road Pool commensurate with CSO reductions for all flow regimes. However, commensurate raises were not always evident in the Dresden Island, Marseilles, and Starved Rock Pools. For scenario 1 (figure 20), commensurate improvements were still somewhat evident in the Dresden Island Pool but less so in the Marseilles and Starved Rock Pools. Distinct improvements appeared in the Peoria Pool. In effect, scenario 1 - type flow regimes produced by TARP I appear to produce marked improvement in DO levels in the Brandon Road and Peoria Pools, but only slightly noticeable changes appear in the intermediate three pools. This results from the reduced lag times introduced with reduced waste loadings and the creation of greater times of travel with the introduction of TARP. While the waste load is reduced, the travel time or incubation time is increased in some pools due to TARP storage. During the 6/13-19/76 period, TARP reduced Lockport and Marseilles flows 17 and 12 percent, respectively.

Scenario 2 - type flow regimes in conjunction with TARP (figure 21) exhibit the same overall characteristics as scenario 1. However, even less improvements are evident in the middle three pools. In fact, the implementation of TARP probably produces slightly lower DOs in the Starved Rock Pool than expected during pre-TARP conditions The predicted minimum pre-TARP DO is 7.27 mg/l, whereas the post-TARP, 80 percent, minimum value is 6.57 mg/l (table 14). This difference is mostly academic since 6.57 mg/l is well above the minimum acceptable standard of 5.0 mg/l. The effect of TARP I on the DO resources of the Peoria Pool for scenario 1 is not academic - the effect is positive and significant as evidenced by figure 21. Note from table 14 that the minimum DO is raised from a 2.01 mg/l pre-TARP value to a 3.90 mg/l post-TARP, 80-percent value, albeit a value that still violates the minimum standard.

Scenario 3 - type flow regimes in conjunction with TARP (figure 22) produce predicted DO profiles roughly similar to scenarios 1 and 2 upstream of Starved Rock. The Peoria Pool profile, however, is distinctly different. The 2.78 mg/l predicted pre-TARP minimum is raised to a predicted 3.99 mg/l for an 80-percent reduction level. However, the overall Peoria Pool conditions appear much better for scenario 3 than for scenario 2. The scenario 3 profile is concave throughout the upper half of the pool, whereas the scenario 2 profile is convex.

TARP II

The number of days per year with spills or CSOs for the years 1958 - 1988 are given in figure 13 (page 38, Hydraulics and Hydrology volume) for three conditions: without TARP, with TARP I, and with completion of TARP II. For the "without TARP" condition, the spill days per year varied from 10 to 60 for all years. With TARP I, six years have no spills, the remaining 25 years have spills ranging from 5 to 40 days per year. However, with the completion of TARP II with the recommended Chicago Underflow Plan (CUP) storage, only one year shows spills for about 20 days, four years with spills for 3 days, and no spills for the remaining 26 years. Thus, the average reduction in waste loads with TARP I may be 60 to 80 percent over the entire period of 31 years, but during years with high spills, this reduction may be only 20 percent or less during the high CSO events. On the other hand, maximum reduction is achieved for 30 of the 31 years with TARP II completion. The recommended CUP storage used in the TARP II simulation is 46,700 acre-feet (32,100 acre-feet for McCook, and 14,600 acre-feet for Thornton reservoirs), and another 2,342 acre-feet is provided by TARP II relief tunnels. However, it is possible that the relief tunnels may not be constructed until the full TARP II reservoirs are built. TARP I provided 6,602 acre-feet of storage in the tunnels (excluding the O’Hare System). Provision of reservoir storage as preferred by the Metropolitan Water Reclamation District of Greater Chicago (MWRDGC) would eliminate any overflows or spills in the 31 years of record simulated.

For low and medium CSOs that can be partially or wholly stored in the TARP I tunnels and then routed through the treatment plants to the waterway, the wasteload reductions of 80 to 97 percent can be achieved, raising minimum DO levels in Brandon Road, Dresden Island and Peoria Pools (table 14) up to 2 to 3 mg/l. However for many CSO events, especially those associated with high storm runoff, the tunnels in TARP I may be able to achieve only 20 percent or less reduction in wasteload because of their limited storage capacity resulting in DO increases of only about 0.5 mg/l or less. The excess overflows in such events can be stored in the TARP II reservoirs, thus effecting a waste load reduction of up to 97 percent and an associated increase in minimum DO of up to 3 mg/l. Under high CSO conditions, TARP II will improve the water quality (in terms of DO) to the same level as with TARP I for low and medium CSO conditions when overflows can be fully managed by the tunnels. In other words, TARP II ensures maximum waste load reduction irrespective of the magnitude of CSOs.

The interrelationships between the three flow regime scenarios for TARP II implementation are relatively similar to those summarized for TARP I. A close examination of figures 23 - 25 verifies this. However, relative to the pure “mechanics” of organic waste assimilation in a stream, for a given percentage of waste load reduction, minimum DOs predicted for the implementation of TARP I and TARP II are essentially equal. In fact, the minimum predicted DOs for scenarios 1 and 2 for TARP II are essentially equal to or less than the corresponding results for TARP I (table 14). For example, an 80-percent reduction produces predicted minimum DO concentrations of 5.50 mg/l and 5.37 mg/l for TARP I and II, respectively, for the 6/13- 19/76 simulation in the Peoria Pool (table 14). The reason for this is that TARP II reduces flow rates, which in turn results in commensurate increases in time of travel throughout the upper reaches of the waterway (table 15a). Note that

TARP II adds about half a day of travel time to the Peoria Dam over that of TARP I for the 6/13-19/76 and 8/14-21/87 periods. TARP II adds a full day of travel time over the original flow for the 6/13-19/76 period. A value of 0.109 was used for K_c in equation 2 during the model runs. Table 15b gives the relative amounts of CBOD used at various points for each simulation. Note that for the 6/13-19/76 period, 3 percent more CBOD was used down to the Peoria Dam for the TARP II simulation than during the TARP I simulation. Similarly, over 9 percent more SOD-related oxygen usage was realized. However, this phenomenon is somewhat academic in that, as just pointed out above, TARP II would actually ensure maximum waste load reductions under almost any circumstances.

The validity of these results and analyses cannot be directly verified or proven. Empirically, however, they can be justified somewhat and even proven to some degree. Historically, the SWS has made biweekly DO measurements at Peoria at mile 161.6, and some of these measurements were made during high flow periods. Also, Butts (1974) has published some DO values taken at high-flows in the Peoria Pool.

Table 16 lists high-flow dates on which relatively low DO concentrations appeared in the Peoria Pool. An attempt was made to match simulated flows to observed flows at Marseilles and Kingston Mines. But agreements occurred in only a few cases between the observed flows and the flows used for the three simulations. Nevertheless, on 7/21/69 the 3.94 mg/l simulated DO at mile 161.6 compared favorably to the 3.75 mg/l observed value. In some cases, like on 6/23/69, the simulated DO was significantly lower (2.25 mg/l) than the observed value (4.40 mg/l). In other cases, the simulated DO was much higher, like on 7/20/72 at mile 179.0, when it was 4.32 mg/l compared to the 1.50 mg/l observed value. The observed “low” DO values are dramatically influenced by the time of sampling on the flow hydrograph. The 1.5 mg/l DO concentration was taken early on the up side of the hydrograph, whereas the 6/23/69 DO reading was taken on the down side of the hydrograph after a prolonged period of high flow.

During 1987, water quality samples and measurements were taken throughout the Peoria Pool twice per week (Butts and Shackleford, in press). DO measurements were taken on August 19 and August 21, 1987, two dates included within the 8/14-21/87 TARP I simulation period (figure 22). This afforded an opportunity to compare a simulated profile with actual instream observations. Table 17 shows the results. The 8/19, 21/87 DO values represent the average DO measured near the bottom. Significant photosynthetic oxygen production appears to have been occurring during this period in spite of the high flows. For example on August 21, 1987 at station 159.4 the DO concentrations ranged from 6.17 mg/l near the surface to 4.49 mg/l near the bottom. Since algal productivity was not included in the simulation and the near-bottom DO levels essentially represent an absence of photosynthetic oxygen production, these observed values appeared to be more suitable for making omparisons.

The overall agreement between the 80-percent reduction simulated values and the observed ones is fair to good at best. The simulations are slightly high at the head of the pool and slightly low at the tail. Amazingly, the overall pool average for the 80-percent reduction curve is equal to that of the observed curve. The data in table 17 strongly indicates that the implementation of TARP I has been instrumental in improving Illinois River water quality as far below Lockport as Peoria. In this case, the minimum Peoria Pool DO level appeared to have been raised 1.67 mg/l, while the average pool DO was raised 0.42 mg/l.

These figures take on added significance with the realization that a 14,100 cfs pre-TARP flow is indicative of tremendous potential CSO activity in the Chicago area.

CONCLUSIONS

General conclusions reached as a result of this field study and computer model analyses are summarized as follows:

1. <u>Dramatic improvements occurred in upper Illinois Waterway water quality between 1972 and 1990</u>. A significant proportion of these improvements have been manifested since the inception of TARP during the early 1980s. Minimum DO concentrations observed at Lockport for 1971/72, 1982, and 1989/90 were 0.00 mg/l, 0.00 mg/l, and 1.71 mg/l respectively; minimum DO values at Chillicothe for these respective periods were 2.30 mg/l, 5.10 mg/l, and 5.68 mg/l. Similarly, minimum Lockport ammonia values for the respective periods were 2.45 mg/l, 1.49 mg/l, and 0.14 mg/l. The maximum observed 1971/72 Lockport ammonia concentration was 6.12 mg/l, whereas during 1989/90 it was only 1.44 mg/l. The reduction in nitrogenous BOD loading at Lockport has been commensurate with the reduction in ammonia. The overall carbonaceous BOD loading has remained relatively steady at a low level for the past 20 years. Benthic sediments in the Brandon Road and Dresden Island Pools exhibit remarkably lower SOD rates now than 20 years ago. The

implementation of TARP I has, undoubtedly, been instrumental in producing this remarkable improvement.

2. The establishment of computerized continuous water quality monitors, like HYDROLAB DataSondes, at just a few selected locations in the waterway produce a wealth of useful information that hitherto has been unobtainable. The establishment of DataSonde stations at Lockport and Starved Rock produced unexpected temporal and spatial relationships for such standard water quality parameters as DO and pH. The daily variance in pH at Starved Rock, at times, was found to be as great as the variance between Lockport and Starved Rock. Extremely wide diurnal variances in DO were recorded at Starved Rock — some daily values fell to 6.0 mg/l after reaching highs in excess of 20.0 mg/l. Presently, only moderate diurnal DO fluctuations persist at Lockport, however, the continuous monitoring data reveals that over a long period it may become more pronounced.

3. Empirical equations were developed relating both pre- and post-TARP I carbonaceous (L_{ac}) and nitrogenous (L_n) BOD loads (lb/day), carbonaceous (K_C) and nitrogenous (K_n) BOD usage rates (1/day), and stream DO concentrations (mg/l) to river flow (cfs) and temperature (°C) - post TARP relationships predict lower L_{an} loads and higher DO levels at Lockport compared to the pre-TARP relationships. Pre- and post-TARP L_{ac} prediction equations produce similar outputs for a given set of conditions; i.e., a statistically significant overall reduction in CBOD does not appear to have occurred with the inception of TARP. This is not surprising since the overall average pre-TARP CBOD load was in itself small. The predictive equations were used to generate parametric input to the SWS BOD/DO model to help delineate the effects of TARP I on water quality between the Lockport and Peoria Dams.

4. Results of the BOD/DO water quality modeling endeavor indicate that the implementation of TARP I has produced measurable and meaningful improvements in DO in the Illinois Waterway between Lockport and Peoria. Simulation results, which could be directly compared to actual field observations, suggest that minimum DO levels in the Peoria Pool may have been raised at least by 1.50 mg/l during a very high CSO condition, which happened to occur in concert with high waterway flows. The implementation of TARP I appears to have raised DO levels most dramatically in the Brandon Road and Peoria Pools. Additionally, Dresden Island Pool improvements have been significant whereas those in the Marseilles and Starved Rock Pools have not. However, the Marseilles and Starved Rock Pools

have, traditionally exhibited high DO concentrations leaving little room for improvement even during the pre-TARP era.

5. TARP II would ensure maximum waste load reduction irrespective of the magnitude of the CSOs. TARP I, due to its limited size, captures only a fraction of the overflow volume during a high storm runoff event, although, due to the "first flush" effect, actual wasteload reduction is substantially greater. Since TARP II is designed as a flood control retention system, essentially all the overflow is retained and stored for treatment no matter how great the storm event. This will result in persistent wasteload reductions of 90 percent or greater. However, these persistently high TARP II reductions do not necessarily provide commensurate increases in instream DO levels. Retention of all the overflows over a period of days can reduce downstream flows such that significant increases in time of travel can occur. Because of this fact, a TARP II scenario producing a 97-percent waste load reduction may only provide downstream DO levels equivalent to a TARP I scenario producing an 80-percent reduction.

REFERENCES

American Public Health Association, American Water Works Association, and Water Pollution Control Federation. 1985. *Standard methods for the examination of water and wastewater (16th edition).* American Public Health Association, Inc., 1740 Broadway, New York, NY, 1268 p.

American Society of Civil Engineering Committee on Sanitary Engineering Research. 1960. *Solubility of atmospheric oxygen in water.* Journal of Sanitary Engineering Division v. 86(7): 41-53.

Butts, T.A. 1974. *Measurements of sediment oxygen demand characteristics in the upper Illinois Waterway.* Illinois State Water Survey Report of Investigation 76, 32 p.

Butts, T.A. and H.R. Adkins. 1987. *Aeration characteristics of Starved Rock Dam Tainter gate flow controls.* Illinois State Water Survey Contract Report 423, 120 p.

Butts, T.A., H.R. Adkins, and D.H. Schnepper. 1989a. *The effects of hydropower development at Brandon Road Dam on downstream dissolved oxygen resources.* Illinois State Water Survey Contract Report 466, 106 p.

Butts, T.A., H.R. Adkins, and D.H. Schnepper. 1989b. *The effects of hydropower development at the Dresden Island Dam on downstream dissolved oxygen resources.* Illinois State Water Survey Contract Report 467, 108 p.

Butts, T.A. and R.L. Evans. 1980. *Aeration characteristics of flow release controls on Illinois Waterway dams.* Illinois State Water Survey Circular 145, 69 p.

Butts, T.A., R.L. Evans, and S. Lin. 1975. *Water quality features of the upper Illinois Waterway.* Illinois State Water Survey Report of Investigation 79, 60 p.

Butts, T.A., R.L. Evans, and J.B. Stall. 1974. *A waste allocation study of selected streams in Illinois.* Illinois State Water Survey Contract Report prepared for Illinois EPA, 215 p.

Butts, T.A., D. Roseboom, T. Hill, S. Lin, D. Beuscher, R. Twait, and R.L. Evans. 1981. *Water quality assessment and waste assimilative analysis of the LaGrange Pool, Illinois River.* Illinois State Water Survey Contract Report 260, 116 p.

Butts, T.A. and D.B. Shackleford (in press). *Impacts of commercial navigation on Illinois River channel water quality.* Illinois State Water Survey Contract Report, 150 p.

Butts, T.A. and D.B. Shackleford. 1987. *Upper Illinois Waterway water quality - a 1982 study related to increased Lake Michigan diversion.* Draft report prepared by the WQS of the SWS for DWR-IDOT and the U.S. Army Corps of Engineers, 129 p.

Butts, T.A., D.H. Schnepper, and R.L. Evans. *1970. Dissolved oxygen resources and waste assimilative capacity of the LaGrange Pool, Illinois River.* Illinois State Water Survey Report of Investigation 64, 28 p.

Butts, T.A., D.H. Schnepper, and K.P. Singh. 1983. *The effects of Lake Michigan discretionary diversion strategies on Illinois Waterway dissolved oxygen resources.* Illinois State Water Survey Contract Report 324.

Butts, T.A., V. Kothandaraman, and R.L. Evans. 1973. *Practical considerations for assessing waste assimilative capacity of Illinois streams.* Illinois State Water Survey Circular 110,49 pages.

Elmore, H.L. 1955. *Determinations of BOD by a reaeration technique.* Sewage and Industrial Wastes v. 27(9): 993-1002.

Harwood, J.E., and A.L. Kuhn. 1970. *A calorimetric method for ammonia in natural waters.* Water Research v. 4: 805-811.

Illinois Environmental Protection Agency. 1977. *Illinois Pollution Control Board rules and regulations, Chapter 3: Water Pollution.* Springfield, IL, 54 p.

Kaufmann, R.S. 1991. *Fate of ammonia-N from Chicago metropolitan area along the Illinois River: Nitrogen chemistry and nitrogen isotope distribution: January - June 1990.* Personal communication - letter February 20, 1991.

Velz, C.J. *1947. Factors influencing self-purification and their relation to pollution abatement.* Sewage Works Journal v. 19(7): 629-644.

Velz, C.J. *1970. Applied stream sanitation.* John Wiley & Sons, Inc., New York, NY, p. 168.

Tables

Table 1. Routine Sampling Stations

Crew	Pool	Station	Parameter				
			pH	Secchi disk	Nitrogen	Temperature	DO
3	Brandon Road	291.1	X	X	X	X	X
		290.2				X	X
		289.8				X	X
		287.9				X	X
		286.2				X	X
		285.4	X	X	X	X	X
	Dresden Island	284.0				X	X
		281.0				X	X
		278.0	X	X	X	X	X
		276.1				X	X
		273.5	X	X	X	X	X
		272.4				X	X
		271.6				X	X
2	Marseilles	271.2	X	X	X	X	X
		270.6				X	X
		267.2				X	X
		265.0	X	X	X	X	X
		263.7				X	X
		261.6	X	X	X	X	X
		258.0				X	X
		256.0				X	X
		253.0	X	X	X	X	X
		250.0				X	X
		247.0	X	X	X	X	X
	Starved Rock	246.0				X	X
		243.7	X	X	X	X	X
		242.9				X	X
		240.0				X	X
		239.0				X	X
		236.8	X	X	X	X	X
		234.5				X	X
		231.0				X	X

Table 1. Concluded

			Parameter				
Crew	Pool	Station	pH	Secchi disk	Nitrogen	Temperature	DO
1	Peoria	230.8	X	X	X	X	X
		229.6				X	X
		226.9	X	X	X	X	X
		224.7				X	X
		222.6	X	X	X	X	X
		219.8				X	X
		217.1				X	X
		213.4	X	X	X	X	X
		209.4				X	X
		205.4				X	X
		200.4				X	X
		196.9	X	X	X	X	X
		190.0				X	X
		188.0				X	X
		183.0				X	X
		179.0	X	X	X	X	X
		177.4				X	X
		174.9				X	X
		170.9				X	X
		167.0				X	X
		166.1	X	X	X	X	X
		165.3				X	X
		164.4				X	X
		162.8	X	X	X	X	X
		161.6				X	X
		160.7	X	X	X	X	X
		159.4				X	X
		158.0				X	X

Table 2. River & Tributary Flows During Sample Dates

	Flow (cfs) at Station								
	Main Stem				Tributaries				
Date	LP	Mar	Hen	KM	Des	DuP	Kan	Fox	Ver
6/15/89	2,630	10,100	15,000	18,100	314	238	6,836	1,010	187
6/27	3,820	-6,350	7,900	7,010	261	158	4,160	621	104
7/18	5,310	5,800	7,990	5,100	334	95	2,540	335	25
7/20	6,400	16,100	21,600	6,400	2,110	724	5,660	1,250	26
7/25	4,080	9,140	12,000	12,000	334	185	5,220	804	342
8/01	4,430	8,000	12,000	8,200	695	339	2,940	2,130	55
8/03	4,300	6,050	11,000	9,000	364	168	2,750	1,590	53
8/08	4,030	8,890	11,300	8,700	1,490	320	2,020	3,050	21
8/10	5,490	7,470	10,600	9,200	696	221	1,900	2,200	15
8/16	3,870	5,770	8,200	7,200	373	175	1,830	1,140	15
6/11/90	2,994	10,500	18,500	24,000	394	303	6,660	1,390	958
6/18	2,621	7,730	19,100	22,100	481	325	3,910	2,450	915
6/25	3,026	10,100	22,400	13,900	594	331	4,390	2,740	1,770
7/02	3,547	14,000	29,400	20,900	823	475	6,070	3,340	3,770
7/09	3,522	6,850	25,300	24,900	336	169	2,480	1,660	870
7/16	3,151	9,710	24,300	21,800	480	249	4,890	1,460	2,090
7/23	4,608	20,600	25,200	36,900	630	681	12,600	3,190	4,340
7/30	3,217	11,000	21,700	36,700	553	243	6,970	1,620	891
8/06	3,329	7,690	15,600	19,200	283	192	4,110	1,110	689
8/13	3,709	8,440	14,000	24,800	1,400	295	3,010	979	288
Average									
1989/90	3,904	9,515	16,655	16,806	647	294	4,547	1,703	871
1982	3,628	8,524	10,992	15,625	459	266	3,877	2,262	743
1971/72	5,274	8,724	11,277	10,620	-	-	1,890	519	-
Medium									
1989/90	3,765	9,015	17,050	12,950					
1982	3,595	8,080	10,550	16,400	375	235	3,730	2,130	638
1971/72	5,871	8,919	-	9,190	-	-	1,175	429	-
7-day, 10-yr Low Flow	2,320	3,240	3,409	3,000	29	46	635	208	8

Notes: LP = Lockport, Mar = Marseilles, Hen = Henry, KM = Kingston Mines, Des = DesPlaines, DuP = DuPage, Kan = Kankakee, Fox = Fox, and Ver = Vermilion Rivers

Table 3. Summary Comparison of 1971-72, 1982, and 1989-90 Dissolved Oxygen Concentrations (mg/L)

Pool	Mpt.	Number of Samples			Average			Maximum			Minimum		
		1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
BR	291.0	27	19	20	1.19	1.05	3.79	3.00	3.55	7.40	0.00	0.00	1.71
	290.9	27	19	-	4.55	1.45	-	6.30	3.85	-	1.10	0.00	-
	290.2	-	-	20	-	-	3.85	-	-	7.40	-	-	2.05
	289.8	-	-	20	-	-	4.12	-	-	6.00	-	-	2.01
	288.7	27	19	-	3.66	2.53	-	5.80	4.40	-	0.70	0.40	-
	287.9	-	-	20	-	-	4.27	-	-	6.90	-	-	2.31
	287.3	27	19	-	3.45	2.27	-	5.90	4.05	-	0.60	0.60	-
	286.2	-	18	-	-	2.63	-	-	5.75	-	-	0.40	-
DI	286.1	23	19	-	6.47	6.95	-	7.90	8.90	-	5.50	4.20	-
	285.4	-	19	20	-	6.78	7.72	-	7.90	8.64	-	5.90	6.77
	284.0	26	19	20	6.17	6.42	7.26	8.20	8.25	9.80	4.90	5.20	5.64
	281.0	26	19	20	5.05	5.80	6.73	7.15	6.90	8.90	3.10	4.60	5.00
	278.0	26	19	20	4.33	5.65	6.68	6.50	9.40	8.20	2.60	3.70	5.47
	276.1	25	19	20	3.89	5.52	6.90	6.10	8.00	8.20	2.10	4.30	5.97
	273.5	25	19	20	3.79	5.60	6.93	5.25	7.20	8.00	2.70	4.40	6.20
	272.4	25	19	20	3.93	6.12	7.26	5.30	8.20	9.08	2.80	4.15	6.19
	271.6	25	19	-	5.16	6.78	-	7.30	10.30	-	3.30	5.60	-
MR	271.2	-	-	20	-	-	8.29	-	-	10.35	-	-	7.68
	270.6	25	19	20	6.77	7.87	8.24	8.10	8.60	8.97	5.60	7.40	6.79
	267.2	25	19	20	6.24	7.65	8.18	7.60	8.50	9.48	5.20	6.60	6.82
	265.0	25	19	20	6.12	7.55	8.01	7.50	8.30	9.83	5.00	6.40	6.47
	263.7	25	19	20	5.95	7.44	8.00	7.25	8.50	9.75	4.90	6.60	6.61
	261.6	25	19	20	5.61	7.34	7.87	6.90	8.80	9.56	4.60	6.30	6.41
	258.0	25	19	20	5.32	7.07	7.83	6.35	8.30	8.90	4.20	6.00	6.15
	256.0	25	19	20	5.16	7.07	7.74	6.20	8.10	9.19	4.00	6.10	6.16
	253.0	25	19	20	5.04	7.08	7.73	6.10	8.60	9.26	4.00	5.85	5.90
	250.0	25	19	20	4.87	6.98	7.80	6.50	8.40	9.39	3.90	5.80	5.57
	247.0	25	19	20	4.72	7.03	7.79	6.20	9.40	9.72	3.70	5.50	5.46
SR	246.9	-	19	-	-	7.49	-	-	8.90	-	-	5.50	-
	246.0	26	19	18	4.77	7.43	7.88	7.05	9.05	9.71	2.90	6.70	6.04
	243.7	26	19	19	4.76	7.28	7.85	6.10	9.80	9.58	3.60	6.30	5.84
	242.9	21	19	19	4.56	7.21	7.92	6.30	9.40	9.05	3.45	6.00	5.86
	240.0	25	19	19	4.58	7.03	7.89	6.00	9.50	9.23	3.40	6.20	5.64
	239.0	25	19	19	4.69	7.27	8.03	6.20	9.50	8.96	3.55	6.10	6.15
	236.8	25	19	19	4.76	7.38	8.00	6.70	9.90	9.27	3.70	6.20	5.99
	234.5	24	10	18	4.83	7.43	8.31	6.90	9.90	10.10	3.85	6.20	5.65
	231.0	24	19	19	4.97	7.73	8.51	6.10	12.20	9.74	3.60	6.20	7.41

Table 3. Concluded.

Pool	Mpt.	Number of Samples			Average			Maximum			Minimum		
		1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
Peo	229.6	24	19	19	6.40	8.33	8.62	7.60	10.20	10.10	5.30	7.10	7.27
	226.9	24	19	19	6.40	8.35	8.62	7.40	10.40	10.75	5.25	7.00	7.02
	224.7	24	19	19	6.59	8.26	8.43	7.40	10.40	10.25	5.10	6.90	7.10
	222.6	24	19	19	5.93	8.02	8.21	7.50	10.30	9.65	4.90	6.75	6.75
	219.8	23	19	19	5.73	8.01	8.12	6.90	10.30	9.96	4.80	6.70	6.56
	217.1	24	19	19	5.72	7.93	8.22	7.30	10.20	9.80	4.80	6.45	6.57
	213.4	24	19	20	5.65	7.83	8.08	7.10	10.00	10.50	4.55	6.10	6.71
	209.4	24	19	20	5.31	7.65	8.02	7.00	9.90	10.95	4.40	5.90	6.67
	205.4	-	-	20	-	-	7.90	-	-	10.80	-	-	6.38
	205.0	24	19	-	5.11	7.51	-	6.90	9.80	-	3.60	5.70	-
	200.4	24	19	20	4.81	7.45	7.67	6.80	10.10	10.80	3.15	5.20	6.26
	196.9	24	19	20	4.43	7.37	7.69	6.50	9.90	12.00	3.15	5.20	5.92
	190.0	24	19	20	4.19	7.20	7.38	5.90	10.20	11.20	2.70	5.60	5.87
	188.0	24	19	20	3.81	7.11	7.24	5.60	9.80	10.80	2.40	5.40	5.80
	183.0	24	19	20	3.83	6.77	7.04	5.60	9.80	10.60	2.30	5.10	5.68
	179.0	24	19	20	3.54	6.75	6.93	5.90	9.30	10.85	2.70	5.20	5.12
	177.4	-	19	20	-	6.81	7.03	-	9.70	10.90	-	5.10	4.69
	174.9	-	19	20	-	6.82	7.05	-	9.90	10.80	-	5.10	4.74
	170.9	-	19	20	-	7.27	7.06	-	11.70	11.47	-	4.80	5.06
	167.0	-	19	20	-	8.12	7.69	-	12.60	12.00	-	5.30	5.75
	166.1	-	-	20	-	-	7.54	-	-	10.80	-	-	5.82
	165.3	-	-	20	-	-	7.46	-	-	10.80	-	-	5.51
	164.4	-	-	20	-	-	7.17	-	-	9.40	-	-	5.41
	162.8	-	-	20	-	-	7.94	-	-	11.50	-	-	5.76
	161.6	-	-	20	-	-	7.75	-	-	12.00	-	-	6.06
	160.7	-	-	20	-	-	7.86	-	-	11.50	-	-	6.07
	159.4	-	-	20	-	-	7.77	-	-	11.40	-	-	6.19
	158.0	-	-	-	-	-	-	-	-	-	-	-	-
Tribs.	Des	27	19	20	9.49	8.45	8.91	16.00	15.55	16.68	2.10	3.90	4.63
	DuP	26	19	15	7.51	7.08	8.26	14.10	11.30	13.42	1.30	3.20	6.93
	Kan	27	20	20	7.75	8.25	8.12	10.20	12.20	10.52	5.30	6.50	6.97
	Fox	24	20	19	8.88	9.72	10.87	18.10	13.70	16.58	4.10	7.20	6.25
	Ver	12	20	19	8.92	8.74	8.61	13.90	11.40	9.39	4.80	6.80	4.06

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria, Des = DesPlaines, DuP = DuPage, Kan = Kankakee, Fox = Fox, Ver = Vermilion Rivers

Table 4. Summary Comparison of 1971-72, 1982, and 1989-90 Temperatures (°C)

Pool	Mpt.	Number of Samples			Average			Maximum			Minimum		
		1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
BR	291.0	27	19	20	25.1	23.6	23.9	28.0	27.0	25.6	22.1	18.0	19.7
	290.9	27	19	-	24.6	23.7	-	28.0	27.5	-	20.8	18.0	-
	290.2	-	-	20	-	-	23.8	-	-	25.8	-	-	19.7
	289.8	-	-	20	-	-	23.9	-	-	26.0	-	-	19.6
	288.7	27	19	-	24.7	23.4	-	28.0	27.0	-	21.2	19.0	-
	287.9	-	-	20	-	-	23.8	-	-	25.9	-	-	19.5
	287.3	27	19	-	24.4	23.5	-	27.5	28.0	-	21.5	18.5	-
	286:2	-	18	-	-	23.6	-	-	28.0	-	-	18.0	-
DI	286.1	23	19	-	24.4	23.5		-	26.9	28.0	-	21.7	18.5
	285.4	-	19	20	-	23.2	23.8	-	28.0	28.9	-	17.5	19.8
	284.0	26	19	20	28.4	25.2	25.3	32.0	30.0	28.3	23.5	20.5	20.4
	281.0	26	19	20	27.3	24.4	24.3	30.0	28.0	27.2	23.5	19.5	20.3
	278.0	26	19	20	27.2	24.3	24.8	29.5	28.5	29.0	24.0	20.0	20.5
	276.1	25	19	20	27.0	24.2	24.7	29.5	28.5	28.3	24.0	19.0	20.7
	273.5	25	19	20	26.9	24.3	24.5	29.5	28.5	27.0	24.0	19.5	21.0
	272.4	25	19	20	26.8	23.9	25.0	29.8	28.0	29.2	23.5	19.0	20.9
	271.6	25	19	-	27.7	24.7	-	31.2	29.5	-	24.9	18.5	-
MR	271.2	-	-	20	-	-	25.6	-	-	28.9	-	-	21.2
	270.6	25	19	20	27.1	25.2	25.7	30.0	31.5	28.9	24.0	19.5	21.0
	267.2	25	19	20	27.1	24.7	25.6	30.0	30.0	28.7	24.0	19.0	20.3
	265.0	25	19	20	27.0	24.6	25.7	29.8	30.0	28.6	23.8	19.0	20.5
	263.7	25	19	20	27.0	24.7	25.6	29.6	30.0	28.6	23.2	19.0	20.7
	261.6	25	19	20	26.9	24.5	25.6	29.4	30.0	28.5	23.0	19.0	20.8
	258.0	25	19	20	26.7	24.5	25.5	29.2	30.5	28.7	23.1	19.0	20.7
	256.0	25	19	20	26.6	24.4	25.4	29.1	30.0	28.7	23.2	19.0	20.7
	253.0	25	19	20	26.7	24.5	25.4	29.2	30.0	28.5	23.1	19.0	20.7
	250.0	25	19	20	26.7	24.5	25.4	29.2	30.5	28.2	23.0	19.0	20.7
	247.0	25	19	20	26.7	24.6	25.5	29.0	30.5	28.2	22.9	19.5	20.7
SR	246.9	-	19	-	-	24.9	-	-	29.5	-	-	20.0	-
	246.0	26	19	18	26.8	23.9	26.0	29.2	28.5	28.3	23.0	18.5	20.7
	243.7	26	19	19	26.8	23.8	25.6	29.1	28.5	28.2	23.0	18.0	20.8
	242.9	21	19	19	26.7	23.8	25.6	29.1	28.5	28.1	23.0	18.0	20.7
	240.0	25	19	19	26.6	23.7	25.5	29.0	28.5	27.8	22.9	18.0	20.8
	239.0	25	19	19	26.3	23.3	25.2	29.0	27.5	27.7	22.8	18.0	20.9
	236.8	25	19	19	26.4	23.4	25.2	28.5	28.0	27.8	22.8	18.0	20.8
	234.5	24	10	18	26.2	23.5	25.1	29.0	28.0	28.0	22.6	18.0	20.8
	231.0	24	19	19	26.0	23.6	25.3	29.1	28.0	27.7	22.1	18.0	20.6

Table 4. Concluded.

Pool	Mpt.	Number of Samples			Average			Maximum			Minimum		
		1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
Peo	229.6	24	19	19	25.6	23.4	25.3	29.0	28.0	28.3	21.4	18.0	20.4
	226.9	24	19	19	25.4	23.3	25.3	29.0	28.0	28.0	21.0	18.0	20.5
	224.7	24	19	19	25.6	23.2	25.1	29.0	28.0	27.9	20.9	18.0	20.0
	222.6	24	19	19	25.7	23.2	25.3	29.0	27.5	28.1	20.9	18.0	20.8
	219.8	23	19	19	25.6	23.2	25.4	29.0	28.0	28.2	21.0	18.0	20.9
	217.1	24	19	19	25.7	23.3	25.5	29.0	28.0	28.1	21.0	18.5	21.0
	213.4	24	19	20	25.6	23.4	25.4	29.0	28.0	28.0	20.1	18.5	21.1
	209.4	24	19	20	25.7	23.5	25.4	29.0	27.5	28.3	21.5	19.0	21.2
	205.4	-	-	20	-	-	25.3	-	-	28.2	-	-	21.0
	205.0	24	19	-	25.8	23.4	-	29.0	27.5	-	21.5	18.5	-
	200.4	24	19	20	25.8	23.5	25.4	28.8	28.5	28.7	21.5	19.0	21.1
	196.9	24	19	20	25.4	23.7	25.4	29.0	28.5	28.6	21.4	18.5	21.0
	190.0	24	19	20	25.5	23.5	25.4	29.0	28.0	28.4	21.5	18.5	21.2
	188.0	24	19	20	25.5	23.5	25.3	29.0	28.0	28.2	21.4	18.5	21.2
	183.0	24	19	20	25.3	23.4	25.4	29.0	28.0	28.7	20.8	18.5	21.3
	179.0	24	19	20	25.2	23.3	25.3	29.0	28.0	28.2	20.4	18.5	21.6
	177.4	-	19	20	-	23.6	25.5	-	28.0	28.4	-	19.0	21.6
	174.9	-	19	20	-	23.8	25.4	-	28.5	28.0	-	19.0	21.7
	170.9	-	19	20	-	23.6	24.7	-	28.5	27.7	-	18.0	21.0
	167.0	-	19	20	-	23.8	25.2	-	29.0	29.4	-	18.0	20.6
	166.1	-	-	20	-	-	25.0	-	-	28.4	-	-	20.7
	165.3	-	-	20	-	-	25.0	-	-	28.5	-	-	20.7
	164.4	-	-	20	-	-	25.2	-	-	28.5	-	-	21.0
	162.8	-	-	20	-	-	25.3	-	-	28.8	-	-	21.2
	161.6	-	-	20	-	-	25.3	-	-	28.7	-	-	21.7
	160.7	-	-	20	-	-	25.3	-	-	29.5	-	-	21.5
	159.4	-	-	20	-	-	25.2	-	-	28.8	-	-	21.6
Tribs.	DsP	26	18	20	24.6	22.9	24.6	28.3	27.5	29.4	16.7	16.0	19.0
	DuP	25	18	15	22.6	22.1	24.0	26.1	27.0	30.0	15.6	15.5	17.7
	Kan	26	16	20	23.0	23.5	24.4	27.4	28.0	27.6	17.5	18.0	19.4
	Fox	23	16	19	25.1	22.0	24.4	28.0	26.0	27.8	16.0	16.5	20.2
	Ver	11	19	19	24.2	23.3	24.3	26.5	29.5	27.8	18.1	17.0	20.5

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria, Des = DesPlaines, DuP = DuPage, Kan = Kankakee, Fox = Fox, Ver = Vermilion Rivers

Table 5. Summary Comparison of 197-72,1982, and 1989-90 Ammonia-N Concentrations (mg/L)

		Number of Samples			Average			Maximum			Minimum		
Pool	Mpt.	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
BR	291.0	11	19	18	4.03	2.65	0.46	6.12	4.80	1.44	2.45	1.49	0.14
	288.7	11	19	-	3.88	2.44	-	6.25	5.25	-	2.32	0.81	-
DI	285.4	11	19	19	3.76	2.27	0.52	5.83	4.64	1.10	2.75	0.64	0.15
	278.0	11	19	19	3.74	2.19	0.46	6.01	4.18	1.05	2.25	0.83	0.11
	273.5	10	19	19	3.76	1.86	0.46	6.12	4.24	0.78	2.54	0.80	0.05
	271.6	10	19	-	2.79	1.08	-	4.79	3.84	-	1.52	0.42	-
MR	271.2	-	-	19	-	-	0.35	-	-	1.52	-	-	0.03
	270.6	11	19	-	2.79	1.07	-	4.65	2.68	-	1.83	0.45	-
	265.0	11	19	19	2.75	0.95	0.25	4.76	1.73	0.52	1.78	0.39	0.05
	261.6	11	19	19	2.65	0.91	0.23	4.55	7.94	0.50	1.25	0.38	0.06
	253.0	11	19	19	2.48	0.80	0.23	4.48	7.43	0.53	1.47	0.36	0.09
	247.0	11	19	19	2.40	0.74	0.21	3.65	7.25	0.49	1.44	0.29	0.06
SR	243.7	10	19	18	2.19	0.60	0.12	3.33	1.20	0.54	1.18	0.21	0.04
	236.8	9	19	18	1.67	0.40	0.17	2.94	0.84	0.52	1.06	0.03	0.04
	231.0	10	19	18	1.75	0.32	0.12	3.20	0.81	0.53	0.64	0.04	0.01
Peo	226.9	10	19	18	1.63	0.32	0.09	2.59	0.90	0.26	0.70	0.05	0.01
	222.6	10	19	18	1.55	0.28	0.08	2.30	0.84	0.17	0.52	0.07	0.01
	213.4	10	19	19	1.42	0.23	0.09	2.24	0.72	0.18	0.35	0.08	0.02
	196.9	10	19	19	1.05	0.18	0.08	1.46	0.66	0.19	0.12	0.11	0.02
	179.0	10	19	18	0.62	0.15	0.10	0.86	0.65	0.33	0.18	0.07	0.02
	167.0	-	19	-		0.09	-		0.31	-		0.05	-
	166.1	-	-	19	-	-	0.09	-	-	0.22	-	-	0.03
	162.8	-	-	19	-	-	0.11	-	-	0.26	-	-	0.02
	160.7	-	-	19			0.15	-	-	0.52	-	-	0.02
	158.0	-	-	19	-	-	0.27	-	-	1.35	-	-	0.01
Tribs	DsP	-	19	18	-	0.22	0.63	-	0.84	1.45	-	0.03	0.24
	DuP	-	19	18	-	0.27	0.63	-	1.40	1.02	-	0.08	0.21
	Kan	-	19	18	-	0.340	0.22	-	1.67	0.52	-	0.03	0.07
	Fox	-	19	15	-	0.04	0.22	-	0.17	0.58	-	0.01	0.05
	Ver	-	19	16		0.14	0.08	-	0.26	0.20	-	0.03	0.01

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria, Des = DesPlaines, DuP = DuPage, Kan = Kankakee, Fox = Fox, Ver = Vermilion Rivers

Table 6. Summary Comparison of 1971-72, 1982, and 1989-90 Nitrite-N Concentrations (mg/L)

		Number of Samples			Average			Maximum			Minimum		
Pool	Mpt.	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
BR	291.0	4	19	18	0.28	0.17	0.17	0.42	0.34	0.28	0.20	0.08	0.06
	288.7	4	19	-	0.22	0.16	-	0.32	0.36	-	0.20	0.07	-
D I	285.4	4	19	19	0.25	0.22	0.25	0.39	0.33	0.66	0.16	0.14	0.09
	278.0	4	19	19	0.25	0.28	0.20	0.27	038	0.35	0.22	0.18	0.11
	273.5	4	19	19	0.25	0.28	0.16	0.30	0.39	0.78	0.21	0.20	0.07
	271.6	4	19	-	0.16	0.19	-	0.28	0.32	-	0.06	0.08	-
MR	271.2	-	-	19	-	-	0.22	-	-	0.38	-	-	0.06
	270.6	4	19	-	0.20	0.20	- -	0.38	0.33	-	0.06	0.01	-
	265.0	4	19	19	0.22	0.21	0.13	0.40	0.37	0.57	0.05	0.12	0.07
	261.6	4	19	19	0.21	0.21	0.13	0.38	0.38	0.23	0.04	0.11	0.06
	253.0	4	19	19	0.24	0.23	0.13	0.45	0.40	0.21	0.04	0.12	0.06
	247.0	4	19	19	0.29	0.24	0.13	0.61	0.43	0.23	0.05	0.13	0.06
SR	243.7	4	19	18	0.30	0.24	0.11	0.60	0.39	0.21	0.06	0.14	0.05
	236.8	4	19	18	0.28	0.20	0.13	0.62	035	0.19	0.02	0.10	0.06
	231.0	4	19	18	0.35	0.22	0.10	0.65	034	0.40	0.08	0.11	0.05
Peo	226.9	4	19	18	0.37	0.23	0.09	0.61	0.34	0.15	0.12	0.13	0.04
	222.6	4	19	18	0.44	0.23	0.11	0.65	0.37	0.15	0.28	0.12	0.05
	213.4	4	19	19	0.44	0.23	0.11	1.25	0.36	0.14	0.59	0.12	0.05
	196.9	4	19	19	1.10	0.24	0.11	1.60	0.51	0.16	0.65	0.11	0.05
	179.0	4	19	18	1.21	0.24	0.12	1.88	0.61	0.20	0.52	0.10	0.05
	167.0	-	19	-	-	0.19	-	-	0.40	-	-	0.08	0.05
	166.1	-	-	19	-	-	0.11	-	-	0.20	-	-	0.01
	162.8	-	-	19	-	-	0.53	-	-	0.21	-	-	0.01
	160.7	-	-	19	-	-	0.10	-	-	0.21	-	-	0.05
	158.0	-	-	19	-	-	0.15	-	-	0.20	-	-	0.01
Tribs	DsP	-	19	18	-	0.22	0.09	-	0.19	0.48	-	0.01	0.02
	DuP	-	19	18	-	0.27	0.12	-	0.17	0.28	-	0.02	0.06
	Kan	-	19	18	-	0.34	0.10	-	0.09	0.37	-	0.01	0.02
	Fox	-	19	15	-	0.04	0.07	-	0.04	0.10	-	0.01	0.04
	Ver	-	19	16	-	0.14	0.08	-	0.11	0.12	-	0.01	0.04

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria, Des = DesPlaines, DuP = DuPage, Kan = Kankakee, Fox = Fox, Ver = Vermilion Rivers

Table 7. Summary Comparison of 1971-72, 1982, and 1989-90 Nitrate-N Concentrations (mg/L)

		Number of Samples			Average			Maximum			Minimum		
Pool	Mpt.	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90	1971-72	1982	1989-90
BR	291.0	8	19	18	0.38	2.32	3.55	1.03	4.68	6.39	0.18	0.64	2.54
	288.7	8	19	-	0.50	2.36	-	1.24	5.48	-	0.10	0.89	-
DI	285.4	8	19	19	0.60	2.34	3.62	1.26	4.06	5.26	0.10	1.34	2.26
	278.0	8	19	19	0.73	2.51	3.94	1.31	4.20	5.92	0.32	1.24	2.54
	273.5	8	19	19	0.89	2.62	4.40	1.59	4.10	6.63	0.35	1.78	2.54
	271.6	8	19	-	1.50	3.17	-	2.94	6.77	-	0.45	1.67	-
MR	271.2	-	-	19	-	-	4.41	-	-	7.40	-	-	2.33
	270.6	8	19	-	1.37	3.20	-	2.81	7.89	-	0.48	1.90	-
	265.0	8	19	19	1.62	3.34	4.54	3.15	7.98	8.13	0.58	1.84	2.30
	261.6	8	19	19	1.57	3.30	4.84	3.22	7.80	8.64	0.52	1.78	2.26
	253.0	8	19	19	1.75	3.65	4.89	3.55	8.11	9.00	0.56	2.03	2.32
	247.0	8	19	19	1.83	3.68	4.98	3.58	8.16	9.22	0.54	1.99	2.35
SR	243.7	8	19	18	2.20	3.70	4.94	3.65	7.92	10.20	0.62	1.99	2.44
	236.8	7	19	18	2.35	3.62	4.98	3.65	6.59	9.87	0.75	1.90	1.60
	231.0	7	19	18	2.35	3.57	5.11	3.63	6.55	8.80	0.66	2.12	2.19
Peo	226.9	7	19	18	2.49	3.67	7.15	3.75	6.92	14.60	0.76	2.09	2.29
	222.6	7	19	18	2.75	4.06	6.13	4.22	8.04	18.00	0.89	1.98	1.70
	213.4	7	19	19	2.99	4.09	5.76	5.60	8.28	15.50	1.01	2.00	2.27
	196.9	7	19	19	3.07	3.99	5.83	4.63	7.74	16.40	1.05	1.82	2.20
	179.0	7	19	18	3.24	4.22	5.66	4.83	7.74	15.30	1.42	1.91	2.02
	167.0	-	19	-	-	3.94	-	-	7.72	-	-	1.68	-
	166.1	-	-	19	-	-	5.32	-	-	14.40	-	-	1.75
	162.8	-	-	19	-	-	5.24	-	-	14.30	-	-	1.64
	160.7	-	-	19	-	-	5.41	-	-	14.20	-	-	1.75
	158.0	-	-	19	-	-	5.16	-	-	13.90	-	-	1.71
Tribs	DsP	-	19	18	-	3.59	3.54	-	6.16	5.34	-	1.91	2.04
	DuP	-	19	18	-	4.27	4.59	-	7.05	7.73	-	2.78	2.62
	Kan	-	19	18	-	3.38	4.92	-	9.04	9.74	-	0.43	0.67
	Fox	-	19	15	-	2.69	4.49	-	6.06	10.50	-	0.45	1.39
	Ver	-	19	16	-	7.75	9.17	-	15.27	30.60	-	0.05	1.62

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria, Des = DesPlaines, DuP = DuPage, Kan = Kankakee, Fox = Fox, Ver = Vermilion Rivers

Table 8. Average Ammonia-N, Nitrite-N, and Nitrate-N Loads Near Mainstem Gaging Stations

	Station								
	Lockport			Marseilles			Henry		
River Mile	291.0			270.6			196.9		
Date	1971/72	1982	1989/90	1971/72	1982	1989/90	1971/72	1982	1989/90
Average Flow (cfs)	5,274	3,628	3,904	8,724	8,524	9.515	11,277	10,992	16,655
Ave. Ammonia Cond.									
Concen. (mg/L)	4.03	2.65	0.46	2.79	1.07	0.35	1.05	0.18	0.08
Load (lbs/day)	114,589	53.879	9,682	50.327	16,085	17,955	63,837	4,741	7,183
Ave. Nitrite Cond.									
Concen. (mg/L)	0.28	0.17	0.17	0.20	0.20	0.22	1.10	0.24	0.11
Load (lbs/day)	7,962	3,448	3,578	9,407	10,110	11,286	66,878	6,519	9,877
Ave. Nitrate Cond.									
Concen. (mg/L)	0.38	2.32	3.55	1.37	3.20	4.41	3.07	3.99	5.83
Load (lbs/day)	10,805	47,279	74,720	64,437	202,666	226,228	186,651	345,496	523,540

Table 9. Biochemical Oxygen Demand (BOD) at 20°C
Illinois State Water Survey

Sample: Kankakee 11
Date: 08/13/90
pH: 8.39
Temp: 23.7O°C

Incremental Value

Time (days)	TBOD (mg/L)	CBOD (mg/L)	NBOD (mg/L)
0.78	0.81	0.44	0.37
2.79	1.76	1.13	0.63
3.52	2.20	1.26	0.93
6.03	2.42	1.62	0.79
6.77	2.83	1.94	0.89
7.77	3.20	2.22	0.98
8.76	3.54	2.49	1.06
9.49	3.83	2.81	1.02
10.76	4.19	3.09	1.10
13.01	4.85	3.76	1.10
13.43	5.08	3.94	1.14
14.75	5.24	4.02	1.22
15.48	5.57	4.42	1.15
17.73	6.46	5.30	1.17
19.96	7.03	5.85	1.19

Table 10. Biochemical Oxygen Demand (BOD) at 20°C
Illinois State Water Survey

Sample: Lockport 18 Date: 01/16/90 pH: 7.03 Temp: 16.05°C				Sample: Lockport 36 Date: 09/26/90 pH: 6.98 Temp: 19.10°C			
Incremental Value				Incremental Value			
Time (days)	TBOD (mg/L)	CBOD (mg/L)	NBOD (mg/L)	Time (days)	TBOD (mg/L)	CBOD (mg/L)	NBOD (mg/L)
0.89	1.09	0.98	0.11	0.72	0.19	0.18	0.01
1.88	1.99	1.73	0.25	1.69	0.66	0.18	0.48
2.87	2.74	2.06	0.68	2.65	0.99	0.92	0.07
3.87	3.39	2.25	1.14	3.65	1.38	1.25	0.13
4.87	4.60	3.08	1.52	4.72	1.81	1.25	0.56
5.62	5.48	3.45	2.04	5.80	2.74	1.62	1.12
6.58	7.41	4.17	3.24	6.75	3.51	2.09	1.43
7.62	9.87	4.83	5.04	7.79	4.17	2.53	1.64
8.57	12.62	5.28	7.34	8.67	4.65	2.92	1.74
9.62	16.45	6.15	10.30	9.73	5.59	2.92	2.67
10.94	21.55	6.62	14.94	10.69	6.22	3.08	3.14
11.73	25.21	6.96	18.25	11.74	6.95	3.08	3.88
12.58	29.66	7.26	22.40	12.66	7.28	3.12	4.16
13.62	34.19	7.90	26.29	13.69	7.79	3.56	4.23
14.67	35.68	8.14	27.55	14.66	7.79	3.56	4.23
15.67	36.43	8.38	28.05	15.65	8.36	3.56	4.80
16.58	37.08	8.75	28.33	16.64	8.56	3.57	4.99
17.81	37.45	8.92	28.53	17.76	8.80	3.82	4.99
18.80	37.64	9.16	28.47	18.67	8.80	3.82	4.98
19.90	38.19	9.39	28.79	19.66	8.92	3.87	5.05
20.60	38.56	9.55	29.01				

Table 11. Summary Comparison of 1972 and 1990 SOD Rates Between Peoria and Brandon Road

Pool	Station[1]	SOD Rate (g/m^2/day) at 25ºC	
		1972	1990
Peoria	179.0R	1.20	0.32
	179.0L	0.87	0.35
	183.0L	2.80	1.61
	187.5R	1.27	1.51
	193.0R	0.49	0.92
	198.8R	2.46	0.73
	204.6R	1.44	0.69
	208.2R	0.98	2.23
Starved Rock	231.7L	1.63	1.36
	234.2L	1.67	2.65
Dresden Island	271.7C	1.60	0.76
	275.5R	4.68	0.92
	276.9L	8.46	0.74
	277.4R	6.78	0.11
	278.0R	2.57	0.83
	278.9L	1.87	0.59
	280.6R	2.34	0.65
	281.4L	4.34	0.89
	282.3L	2.50	0.12
	282.3C	2.07	0.12
	282.8L	4.56	1.37
	283.6L	5.00	0.58

[1] Corps river mile looking downstream: L and R indicate left and right bank looking downstream, and C indicates center of channel.

Table 12. Regression Coefficients for Equation 13

		Pre-TARP I				Post-TARP I			
		Coefficients				Coefficients			
Station	Parameter	a	b	c	R[1]	a	b	c	R[1]
Lockport	L_{ac}	19.020	0.133	-5.038	0.87	16.820	-0.009	-2.453	0.64
	K_c	0.064	0.012	-0.052	0.59	0.067	0.001	0.008	0.78
	DO	-14.071	-0.575	8.008	0.73	-1.856	-0.210	2.966	0.64
	L_{an}	-34.748	-3.690	38.518	0.54	30.280	-0.334	-3.930	0.86
	K_n	0.157	-0.004	-0.001	0.51	0.409	0.000	-0.085	0.66
Des Plaines R.	L_{ac}	30.922	0.211	-10.614	0.48	-10.008	0.041	5.114	0.60
	K_c	-0.059	0.012	-0.026	0.49	0.244	0.001	0.051	0.64
	DO	26.619	0.342	-9.820	0.55	19.777	0.099	-4.822	0.54
	L_{an}	13.055	0.011	-2.424	0.88	2.100	0.042	0.181	0.83
	K_n	0.187	-0.005	0.005	0.74	0.280	-0.002	0.032	0.84
DuPage R.	L_{ac}	9.285	-0.279	1.296	0.46	0.432	0.143	2.004	0.70
	K_c	0.081	0.007	-0.028	0.34	-0.383	-0.004	-0.230	0.76
	DO	13.680	0.724	-9.267	0.37	15.348	0.005	-3.014	0.41
	L_{an}	7.505	-0.537	4.682	0.31	-11.563	0.080	4.991	0.92
	K_n	0.042	-0.004	0.056	0.48	0.620	0.004	-0.143	0.70
Kankakee R.	L_{ac}	32.507	-0.245	-6.734	0.05	-9.029	0.086	4.041	0.70
	K_c	0.527	-0.011	-0.035	0.60	0.030	-0.001	0.027	0.92
	DO	23.878	-0.192	-3.334	0.44	24.017	-0.171	-3.279	0.31
	L_{an}	44.985	-0.250	-10.263	0.92	2.650	0.025	-0.454	0.69
	K_n	0.119	-0.001	-0.012	0.35	0.219	-0.003	0.023	0.55
Fox R.	L_{ac}	34.393	0.279	-9.689	0.38	1.770	0.558	1.303	0.62
	K_c	0.378	-0.095	0.564	0.81	0.307	0.000	-0.069	0.53
	DO	22.933	0.135	-5.227	0.37	18.585	-0.045	-2.114	0.48
	L_{an}	10.047	0.517	-3.992	0.55	17.499	0.112	-4.509	0.76
	K_n	0.057	-0.002	0.015	0.39	-0.094	0.000	0.066	0.83
Vermilion R.	L_{ac}	15.818	-0.111	-3.377	0.36	1.040	0.341	0.303	0.66
	K_c	0.032	0.008	-0.009	0.37	0.207	-0.003	-0.021	0.79
	DO	11.699	-0.094	-0.367	0.23	12.446	-0.201	0.355	0.51
	L_{an}	14.164	-0.093	-3.198	0.38	8.968	0.060	-2.757	0.67
	K_n	-0.001	0.002	0.011	0.39	0.067	-0.005	0.075	0.66

[1] Multiple Correlation Coefficient

Table 13. Minimum and Maximum Dissolved Oxygen Levels by Pool for Pre-TARP and Post-TARP Conditions

Date	Pool	Dissolved Oxygen (mg/L)			
		Minimum		Maximum	
		Pre-	Post-	Pre-	Post-
9/3/76	BR	0.00	3.13	0.39	3.61
	DI	3.03	3.61	6.67	7.34
	MR	4.20	5.84	7.62	7.82
	SR	4.16	6.34	5.24	7.61
	Peo	4.12	5.05	6.59	7.49
7/1/85	BR	0.89	3.67	1.43	4.05
	DI	4.51	4.95	6.79	7.35
	MR	4.68	5.53	7.76	7.89
	SR	4.14	6.30	5.47	7.70
	Peo	3.85	4.35	6.95	7.77
8/22/88	BR	0.00	3.21	0.61	3.64
	DI	3.83	4.47	6.39	7.02
	MR	3.98	4.65	7.28	7.37
	SR	5.58	6.07	6.73	7.01
	Peo	3.69	4.15	7.09	7.28
6/13-19/76	BR	4.70	5.14	4.93	5.33
	DI	6.90	7.11	7.81	7.90
	MR	7.69	7.25	8.36	8.43
	SR	7.59	7.80	8.31	8.19
	Peo	4.07	5.30	8.27	8.35
7/21-27/80	BR	4.43	5.05	4.60	5.17
	DI	6.46	6.87	7.39	7.52
	MR	6.65	6.58	7.86	7.94
	SR	7.11	6.70	7.65	7.63
	Peo	2.09	3.30	7.76	7.60
8/14-21/87	BR	4.30	4.91	4.54	5.18
	DI	6.33	6.80	7.25	7.37
	MR	7.05	7.15	7.70	7.80
	SR	7.18	7.43	7.67	7.80
	Peo	2.54	3.14	7.82	7.89

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria

Table 14. Minimum and Maximum Dissolved Oxygen Levels (mg/L) by Pool for Various Wasteload Reductions

Pool	Reduction (%)	June/13-19/76				July/21-27/80				August/14-21/87			
		TARP I		TARP II		TARP I		TARP II		TARP I		TARP II	
		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
BR	original	4.70	4.91	4.70	4.91	4.45	4.48	4.45	4.68	4.44	4.55	4.44	4.55
	20	5.46	5.67	5.46	5.67	5.16	5.28	5.16	5.28	4.95	5.20	4.92	5.20
	40	6.21	6.38	6.21	6.39	5.71	5.89	5.71	5.89	5.42	5.86	5.36	5.86
	60	6.95	7.09	6.95	7.10	6.24	6.60	6.24	6.60	5.89	6.52	5.80	6.52
	80	7.63	7.80	7.64	7.81	6.76	7.30	6.76	7.30	6.36	7.18	6.26	7.18
	97	-	-	8.23	8.41	-	-	7.23	7.90	-	-	6.64	7.74
DI	original	6.94	7.81	6.94	7.81	6.62	7.42	6.62	7.42	6.65	7.28	6.65	7.28
	20	7.42	7.99	7.36	7.99	6.89	7.55	6.89	7.55	6.91	7.38	6.86	7.37
	40	7.55	8.14	7.48	8.14	6.97	7.66	6.97	7.66	7.01	7.48	6.92	7.46
	60	7.67	8.29	7.60	8.29	7.05	7.77	7.05	7.77	7.08	7.57	6.99	7.55
	80	7.78	8.44	7.73	8.44	7.14	7.88	7.14	7.88	7.18	7.67	7.07	7.65
	97	-	-	7.83	8.57	-	-	7.23	7.98	-	-	7.13	7.72
MR	original	7.67	8.41	7.67	8.41	6.85	7.90	6.85	7.90	7.22	7.77	7.22	7.77
	20	7.25	8.49	7.02	8.48	6.86	7.96	6.86	7.96	7.35	7.82	7.27	7.81
	40	7.39	8.51	6.43	8.50	6.24	7.97	6.24	7.97	7.37	7.84	7.28	7.82
	60	7.02	8.52	6.76	8.51	6.39	7.98	6.36	7.98	7.37	7.85	7.29	7.83
	80	7.10	8.54	6.87	8.53	6.53	8.00	6.53	8.00	7.39	7.87	7.31	7.85
	97	-	-	7.27	8.53	-	-	6.39	8.01	-	-	7.32	7.86
SR	original	7.55	8.37	7.55	8.37	7.27	7.72	7.27	7.72	7.47	7.83	7.47	7.83
	20	7.10	8.15	6.82	8.07	7.58	7.72	5.84	7.72	7.57	7.92	7.50	7.90
	40	7.31	8.20	7.07	7.86	6.09	7.51	6.09	7.51	7.58	7.93	7.50	7.90
	60	7.52	8.07	7.34	7.98	6.34	7.56	6.34	7.56	7.58	7.93	7.51	7.90
	80	7.71	8.15	7.58	8.08	6.57	7.61	6.57	7.61	7.59	7.94	7.52	7.91
	97	-	-	7.83	8.25	-	-	6.84	7.56	-	-	7.49	7.88
Peo	original	3.80	8.25	3.80	8.25	2.01	7.82	2.01	7.82	2.78	7.92	2.78	7.92
	20	4.03	8.06	3.76	7.92	2.80	7.26	2.83	7.30	3.39	7.94	3.36	7.94
	40	4.43	8.14	4.56	8.02	3.35	7.36	3.37	7.39	3.55	7.95	3.50	7.94
	60	5.08	8.22	4.92	8.13	3.65	7.45	3.65	7.49	3.81	7.95	3.70	7.94
	80	5.50	8.29	5.37	8.22	3.90	7.55	3.91	7.57	3.99	7.95	3.90	7.92
	97	-	-	5.63	8.32	-	-	4.28	7.68	-	-	4.05	7.92

Notes: BR = Brandon Road, DI = Dresden Island, MR = Marseilles, SR = Starved Rock, Peo = Peoria

Table 15. Comparison of Time of Travel and Percentage of Carbonaceous Biochemical Oxygen Demand (CBOD) Used Between Lockport (COE mile 291.0) and Other Dams Using $K_c = 0.1091$ 1/day

a. Time of Travel (in days) below Lockport

Dam	River Mile		June/13- 19/76			July/21 -27/80			August/14-21/87		
	COE	SWS	0	I	II	0	I	II	0	I	II
Brandon Road	286.0	286.25	0.226	0.268	0.271	0.139	0.174	0.174	0.099	0.120	0.135
Dresddn Island	271.5	271.52	1.018	1.216	1.270	0.696	0.872	0.872	0.454	0.524	0.569
Marseilles	247.0	246.78	1.871	2.202	2.346	1.622	1.983	1.983	0.947	1.042	1.128
Starved Rock	231.0	231.02	2.317	2.713	2.911	2.174	2.619	2.619	1.188	1.285	1.394
Peoria	157.7	158.06	5.638	6.087	6.648	6.743	7.552	7.552	5.827	5.991	6.479

b. CBOD Used (in percentage) below Lockport

Dam	River Mile		June/13-19/76			July/21-27180			August/14-21/87		
	COE	SWS	0	I	II	0	I	II	0	I	II
Brandon Road	286.0	286.25	2.4	2.9	2.9	1.5	1.9	1.9	1.1	1.3	1.5
Dresden Island	271.5	271.52	10.5	12.4	12.9	7.3	9.1	9.1	4.8	5.6	6.0
Marseilles	247.0	246.78	18.4	21.3	22.6	16.2	19.4	19.4	9.8	10.7	11.6
Starved Rock	231.0	231.02	22.3	25.6	27.2	21.1	24.8	24.8	12.1	13.1	14.1
Peoria	157.7	158.06	45.9	48.5	51.5	52.0	56.1	56.1	47.0	48.0	50.7

Notes: COE = Corps of Engineers and SWS = State Water Survey;
0, I, and II denote conditions without TARP, with TARP I, and with TARP II, respectively.

Table 16. Historical High-Flow/Dissolved Oxygen (DO) Comparisons

	Flow (cfs)		Observed DO		Comparable Simulated DO	
Date	Marseilles	Kingston Mines	River Mile	Conc. (mg/L)	Period	Conc.(mg/L)
7/22/63	12,300	11,800	161.6	3.60	7/21-27/80	2.25
7/23/63	7,660	12,700	"	3.90	none	-
7118168	9,110	17,200	"	4.95	none	-
6.23.69	9,500	10,700	"	4.40	7/21-27/80	2.25
6/26/69	12200	8,300	"	4.90	none	-
7/07/69	10,600	18,000	"	4.60	6/13-19/76(?)	3.94
7/10/69	16.900	19,100	"	4.94	6/13-19/76	3.94
7/21/69	13,400	21,100	"	3.75	6/13-19/76	3.94
7/28/69	24,600	19,900	"	4.50	8/14-21/87	
7/31/69	14,100	22,300	"	3.20	6/13-19/76	3.94
8/04/69	9,700	20,100	"	4.05	6/13-19/76(?)	3.94
6/18/70	17,600	40,300	"	4.80	none	-
8/O3/70	8,490	14,700	"	3.50	none	-
7/20/72*	21200	23,800	179.0	1.50	8/14-21/87	4.32
7/21/72*	17,100	25.700	183.0	2.60	8/14-21/87	4.73
7/24/72*	15,300	25,200	187.5	4.20	8/14-2187	5.50
7/31/72*	8330	20500	193.0	5.40	6/13-21/87(?)	5.43
8/01/72*	7,850	19,400	198.8	4.50	6/13-21/87(?)	5.58
8/04/72*	8,120	11,300	204.6	4.50	6l13-21/87(?)	5.75
8/23/79	23,700	11,400	161.6	4.30	8/14-21/87(?)	3.00
7/21/80	11,000	27,700	"	4.93	none	-
8/11/80	9,710	9.390	"	4.35	7/21-27/80(?)	2.25
9/02/80	19,200	19,700	"	5.09	none	-
9/04/80	11,400	22,700	"	4.17	none	-
9/11/83	25,700	23,800	"	3.83	8/14-21/87	3.00
7/05/83	18.900	27,400	"	4.70	none	-
7/07/83	13,400	27,400	"	5.12	none	-

* Reference: Butts (1974).

(?) indicates marginal comparison conditions.

Table 17. Observed Peoria Pool Dissolved Oxygen Profile
Compared to TARP I Simulations; August 19-21, 1987

Station (mile)	Dissolved Oxygen Concentration (mg/l)					
	Simulated TARP I % Reduction					August 19-21, 1987 Observed Averages
	0	20	40	60	80	
158.0	2.90	3.40	3.55	3.81	3.99	4.57
159.4	2.94	3.44	3.58	3.85	4.04	4.55
160.7	2.98	3.46	3.61	3.88	4.07	5.30
161.6	3.00	3.49	3.64	3.90	4.09	5.21
162.8	3.02	3.50	3.65	3.91	4.10	5.19
164.4	3.09	3.54	3.69	3.95	4.16	5.34
165.3	3.13	3.57	3.71	3.99	4.19	5.31
166.1	3.15	3.59	3.74	4.02	4.23	5.51
167.0	3.00	3.44	3.75	4.04	4.25	5.25
170.9	3.00	3.73	4.00	4.22	4.47	5.47
183.0	4.70	5.21	5.30	5.42	5.62	4.97
188.0	5.50	5.62	5.63	5.70	5.86	4.85
190.0	5.74	5.74	5.79	5.82	5.96	5.02
196.9	6.62	6.27	6.14	6.15	6.28	5.12
200.4	6.95	6.55	6.40	6.35	6.45	5.08
205.4	7.07	6.89	6.64	6.56	6.63	5.83
209.4	7.20	7.21	6.89	6.77	6.82	6.02
213.4	7.35	7.36	7.22	7.05	7.07	6.09
217.4	7.47	7.53	7.50	7.29	7.28	6.21
219.8	7.55	7.61	7.62	7.45	7.43	6.33
222.6	7.64	7.72	7.73	7.62	7.57	6.38
224.7	7.72	7.78	7.79	7.72	7.69	6.51
226.9	7.79	7.83	7.84	7.85	7.78	6.55
229.6	7.88	7.91	7.92	7.92	7.89	6.88
231.0	7.92	7.94	7.95	7.95	7.95	7.32
Pool Average	5.41	5.61	5.65	5.73	5.80	5.82

Figures

Figure 1

Comparison of May–Oct. Avg. DO Profiles (3–ft. depth)

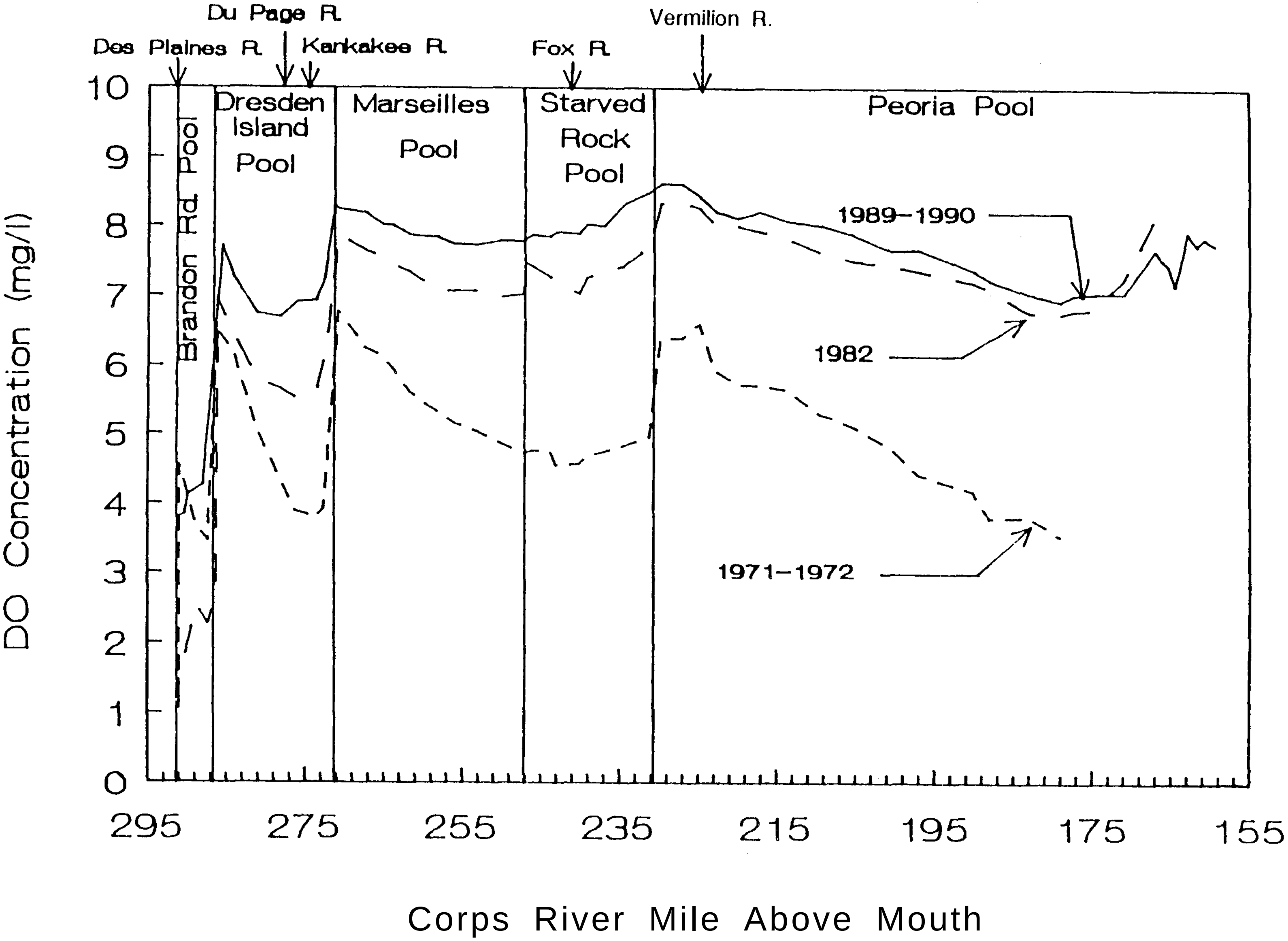


Figure 2

May–October Average Temperature Profiles

(3–ft. depth)

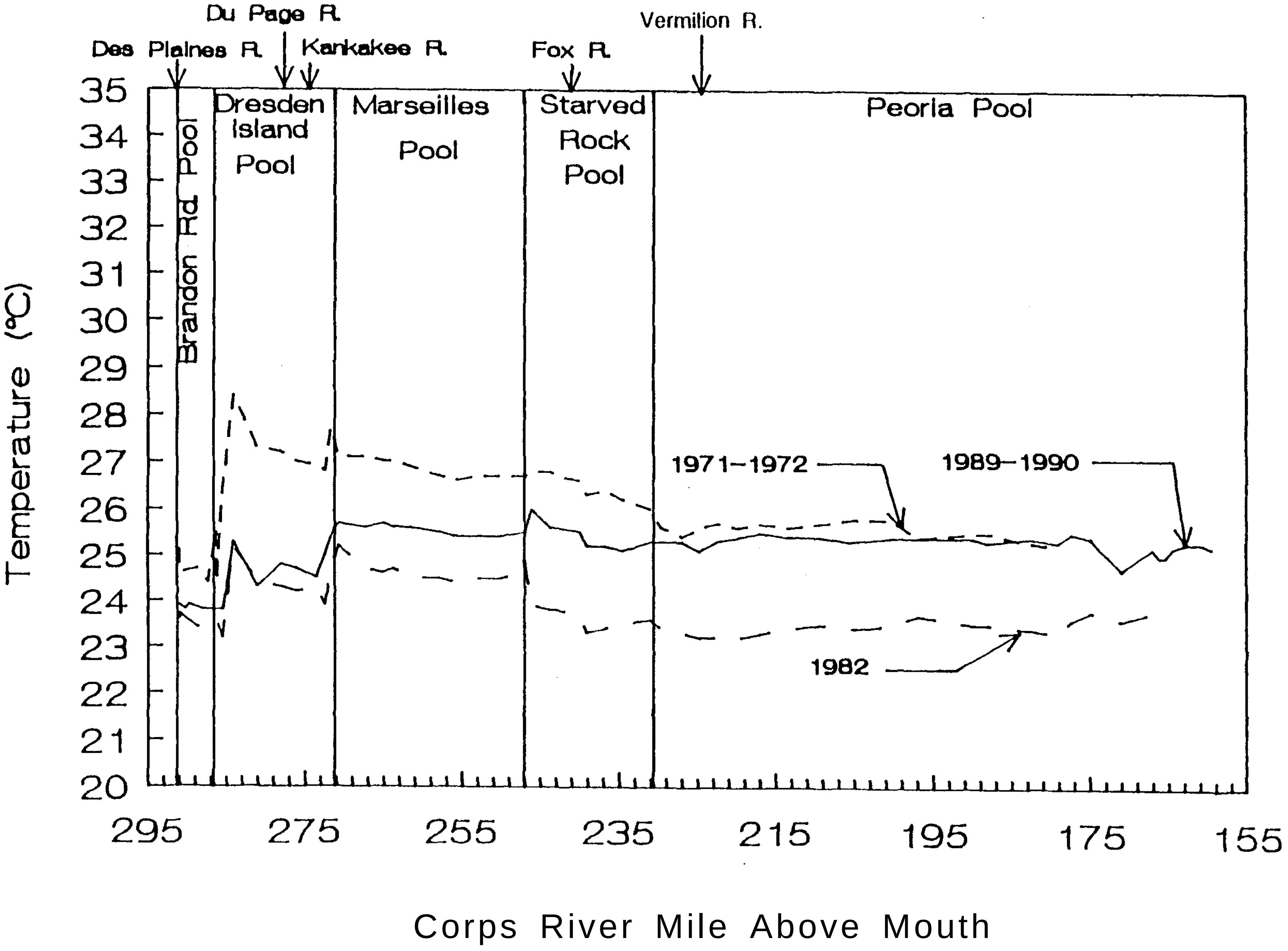


Figure 3

May–October Average Ammonia–N Profiles (3–ft. depth)

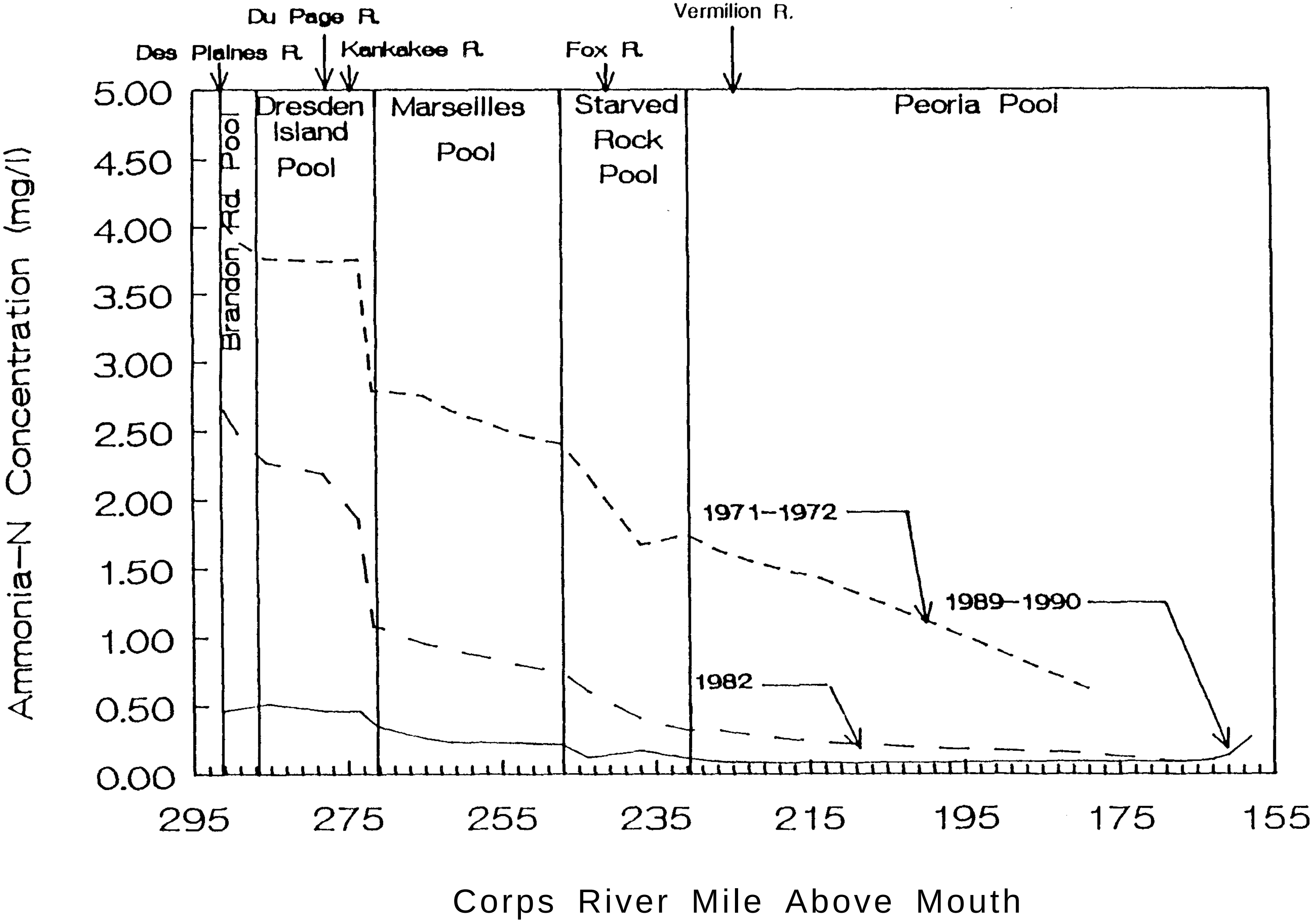


Figure 4

May–October Average Nitrite–N Profiles
(3–ft. depth)

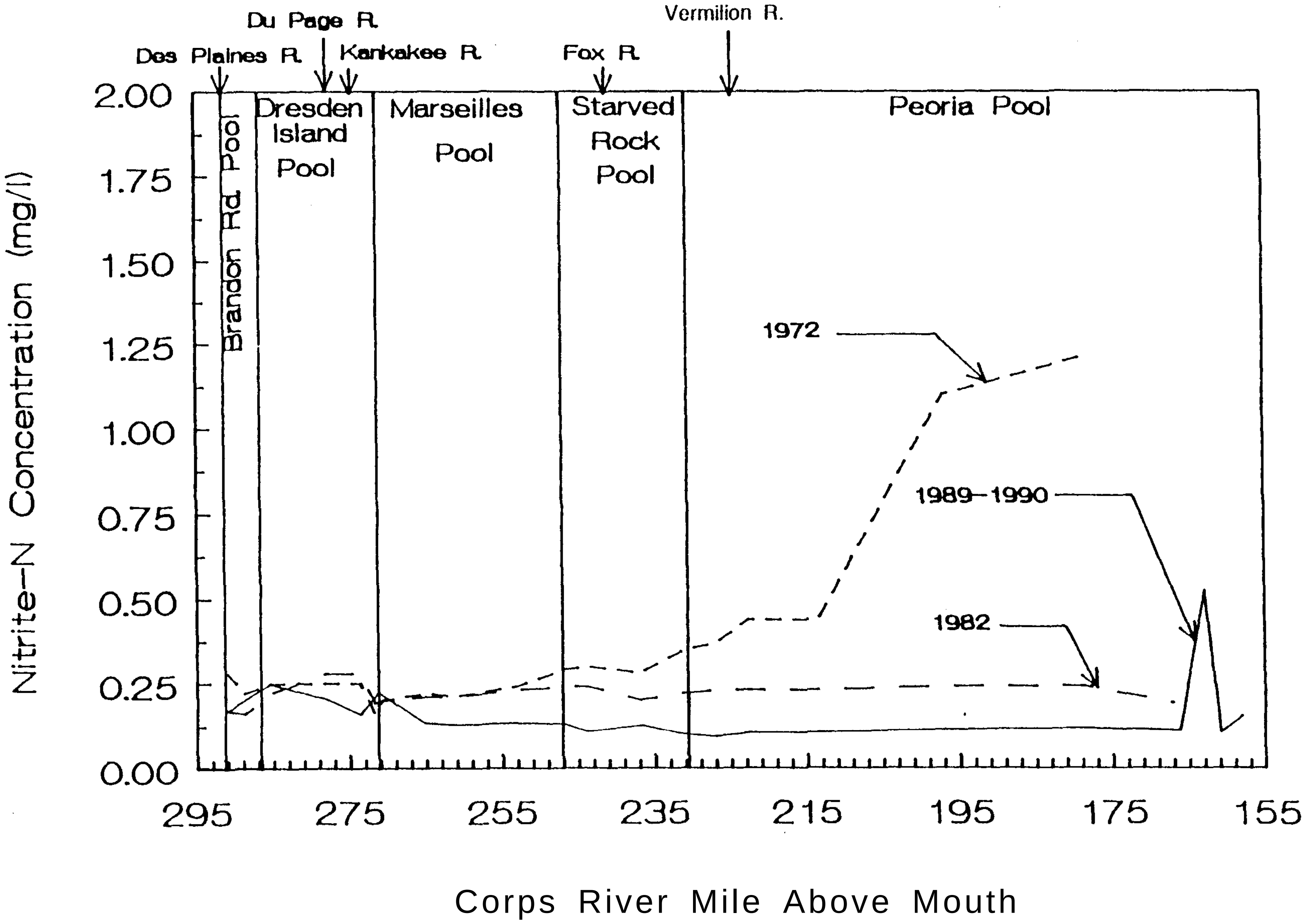


Figure 5

May–October Average Nitrate–N Profiles
(3–ft. depth)

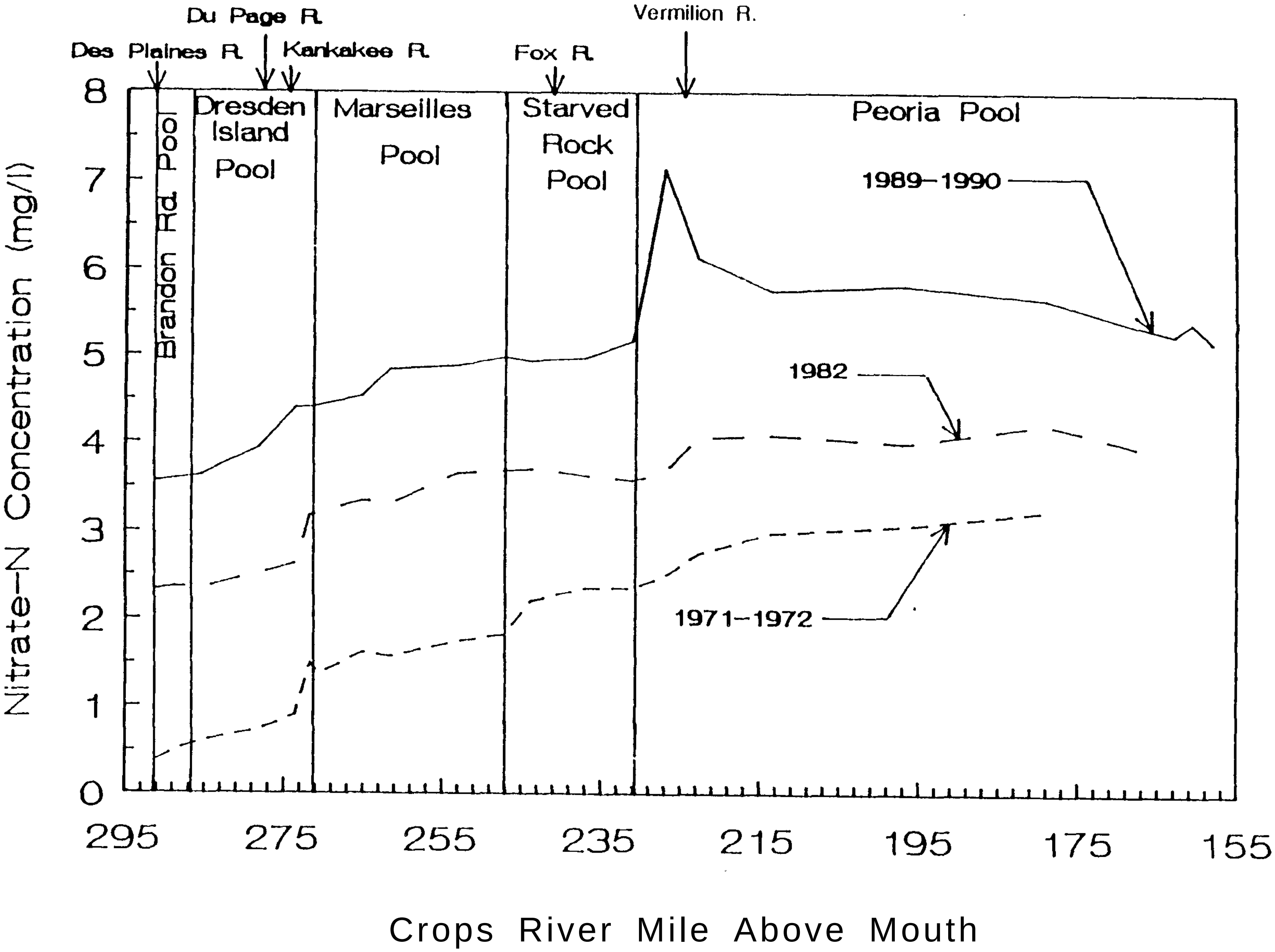


Figure 6

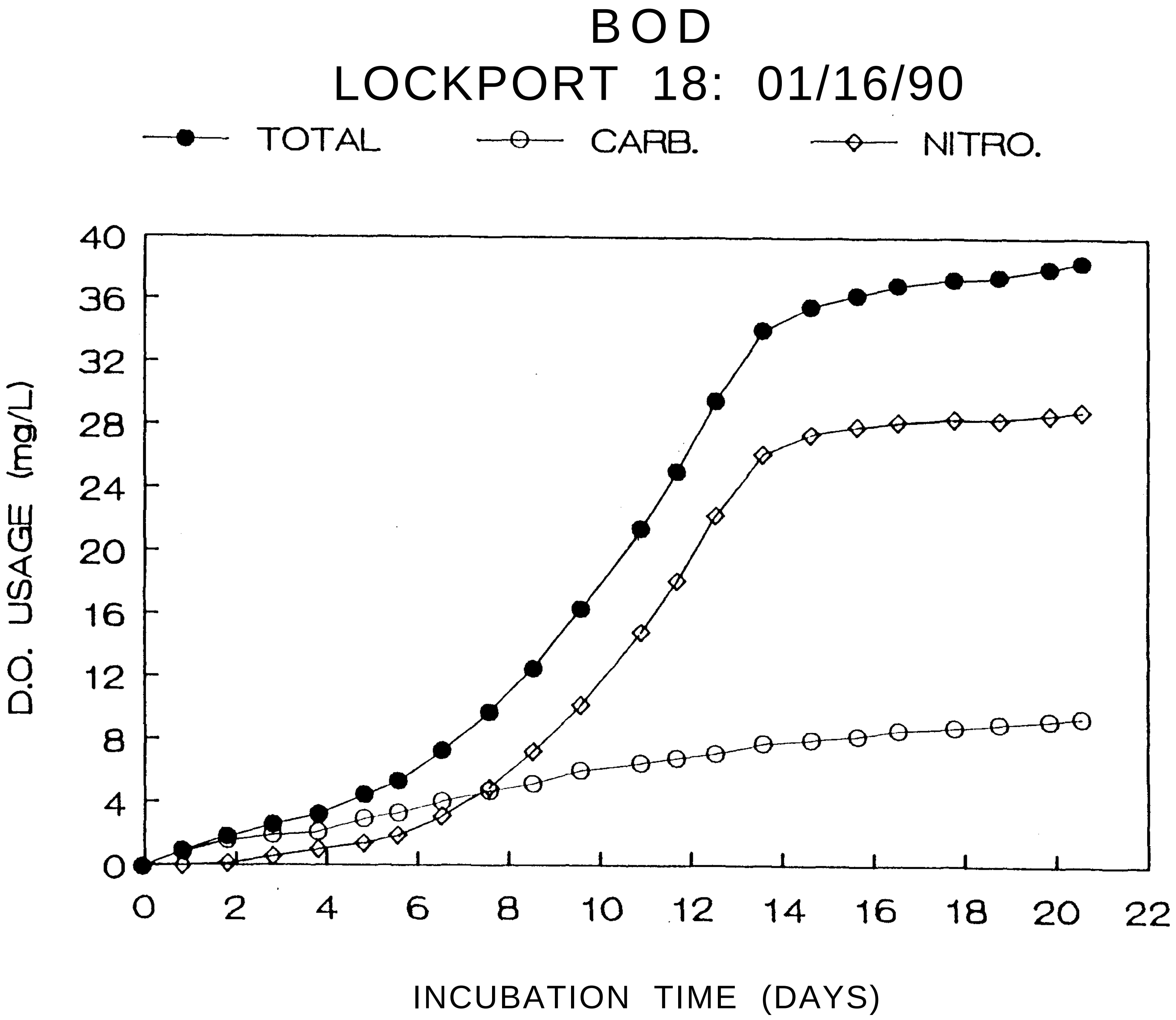

BOD
LOCKPORT 18: 01/16/90
TOTAL
CARB.
NITRO.
D.O. USAGE (mg/L)
0
4
8
12
16
20
24
28
32
36
40
INCUBATION TIME (DAYS)
0
2
4
6
8
10
12
14
16
18
20
22

Figure 7

BOD
LOCKPORT 36: 09/26/90

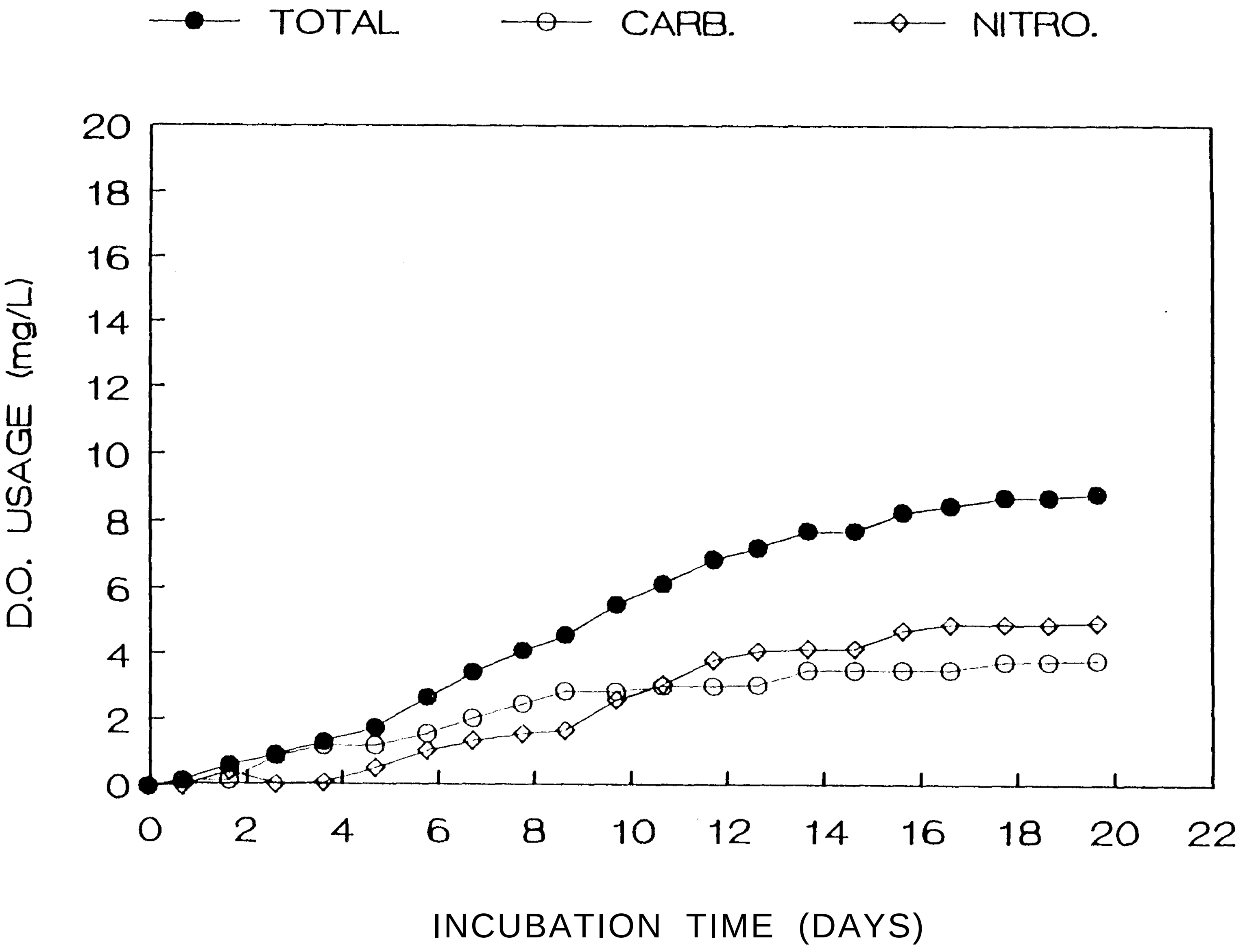


Figure 8

BOD
KANKAKEE 11: 08/13/90

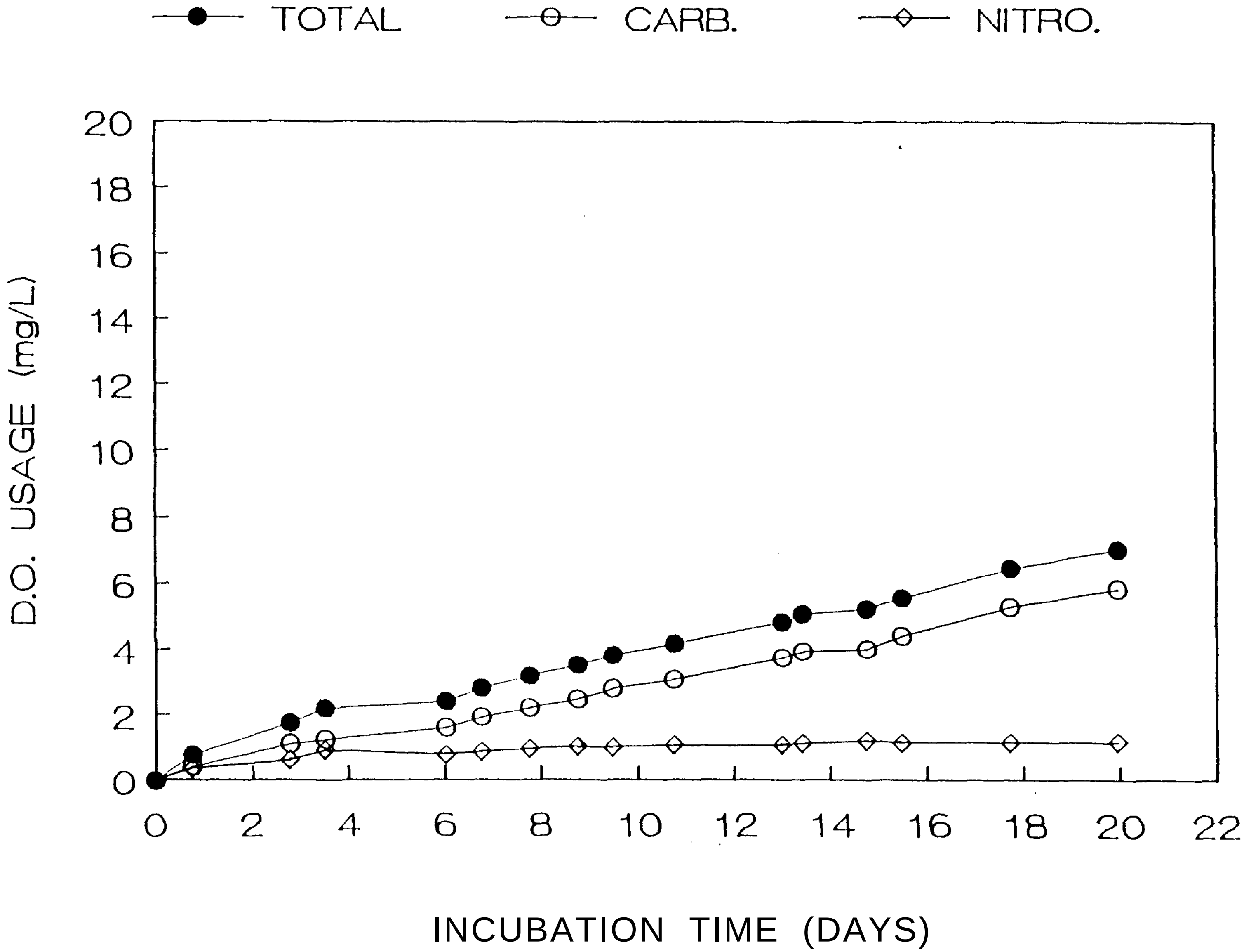


Figure 9

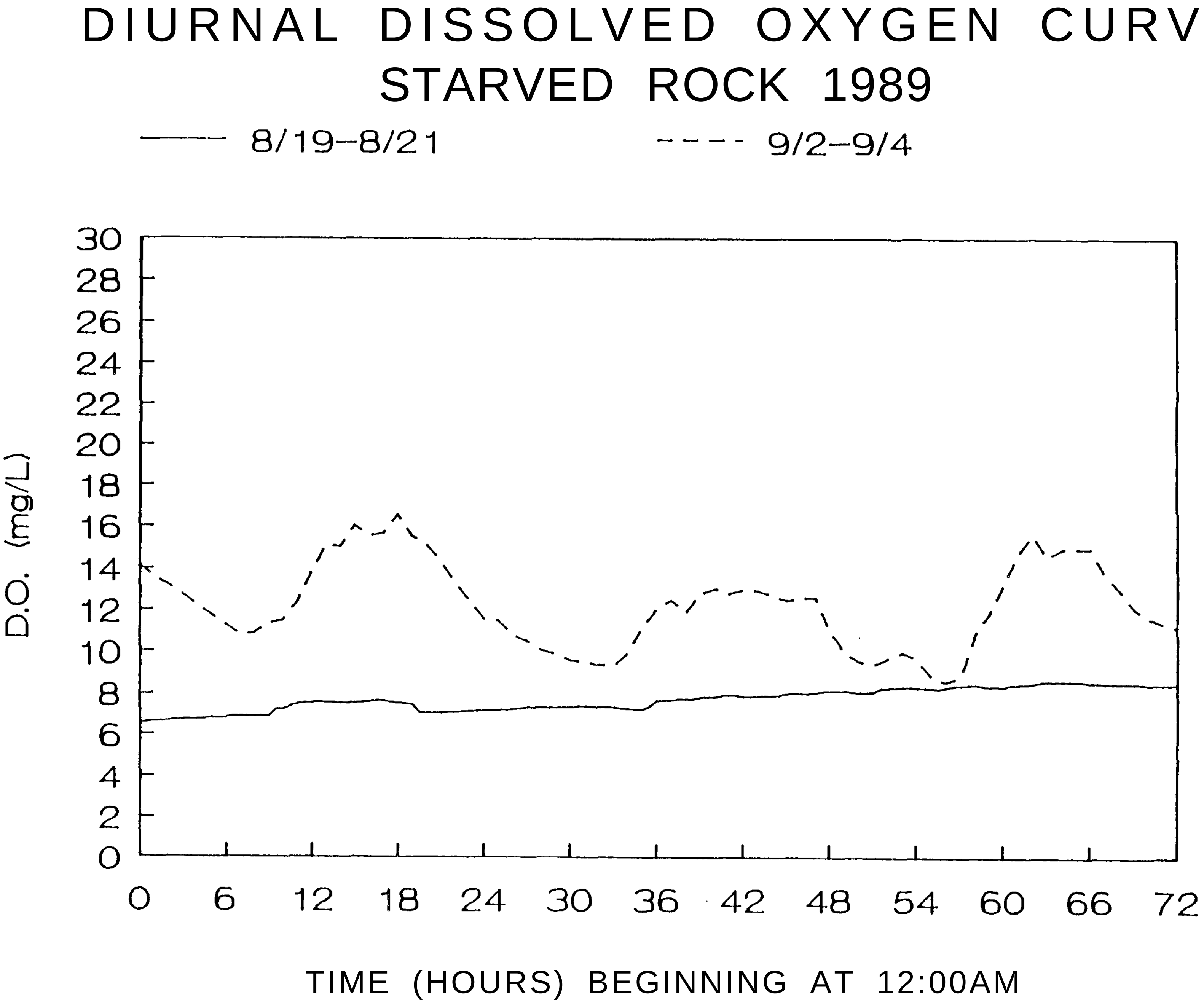

DIURNAL DISSOLVED OXYGEN CURVE
STARVED ROCK 1989
8/19–8/21
9/2–9/4
D.O. (mg/L)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
0
6
12
18
24
30
36
42
48
54
60
66
72
TIME (HOURS) BEGINNING AT 12:00AM

Figure 10

DIURNAL DISSOLVED OXYGEN CURVE
STARVED ROCK 1990

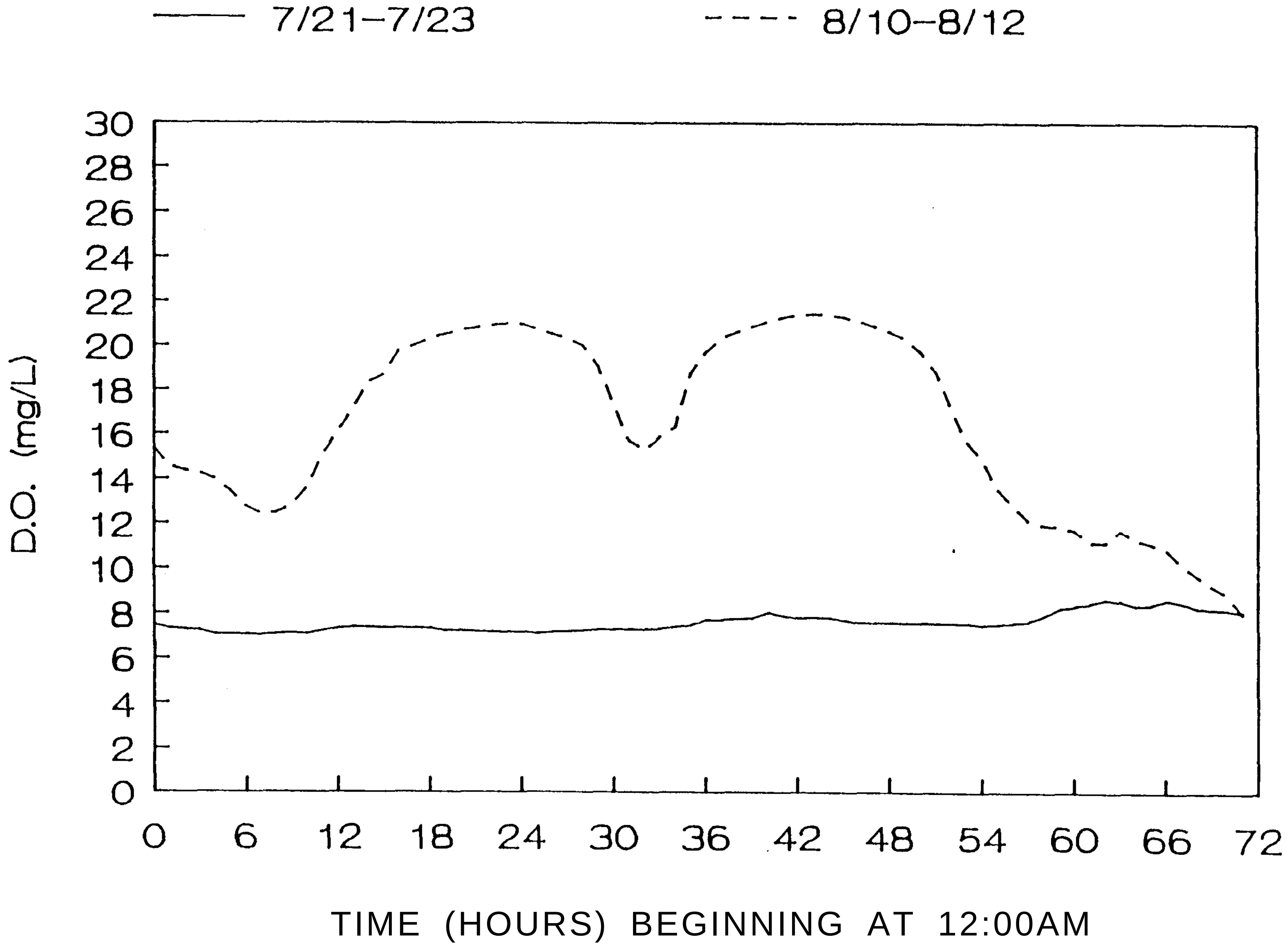


Figure 11

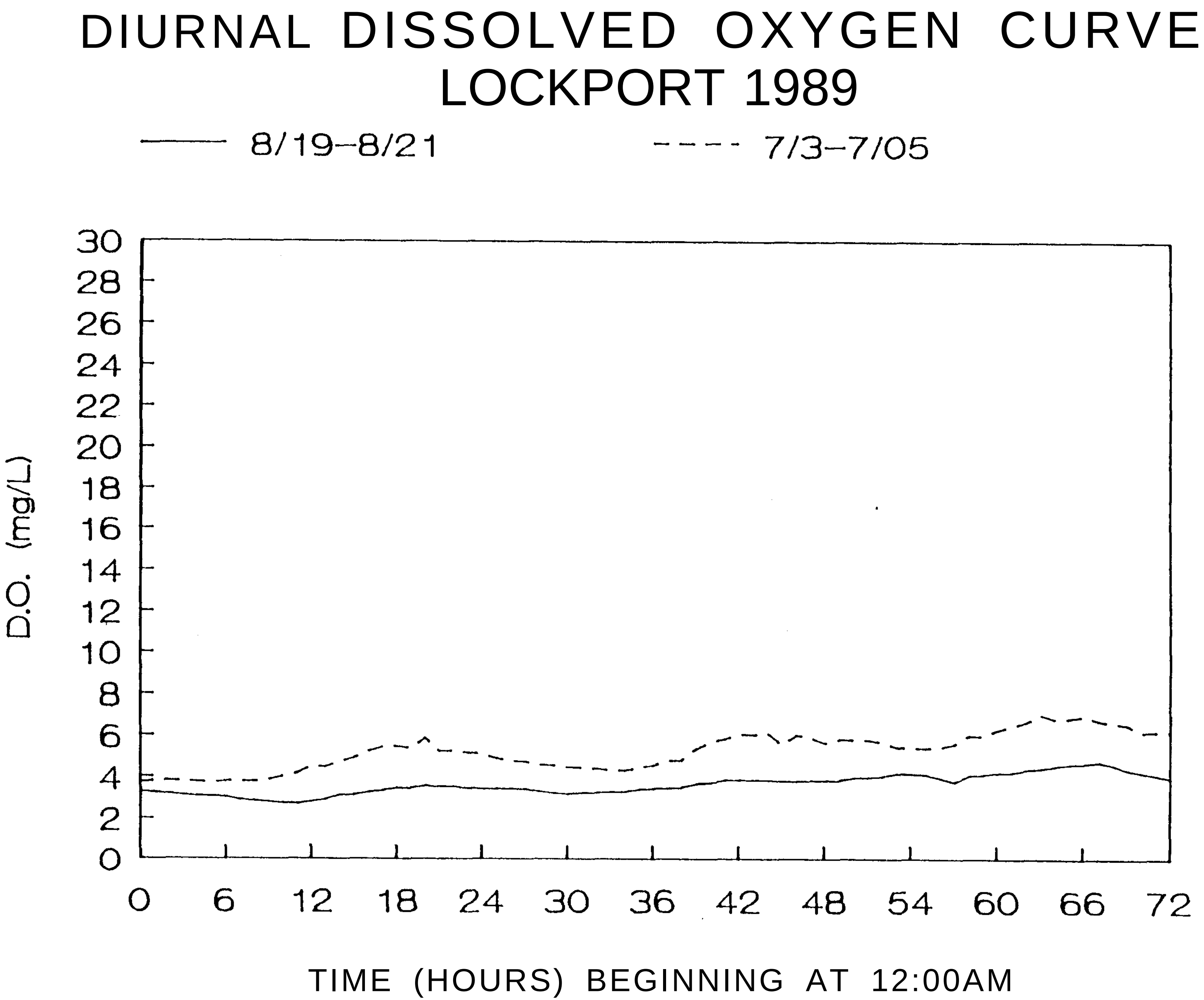
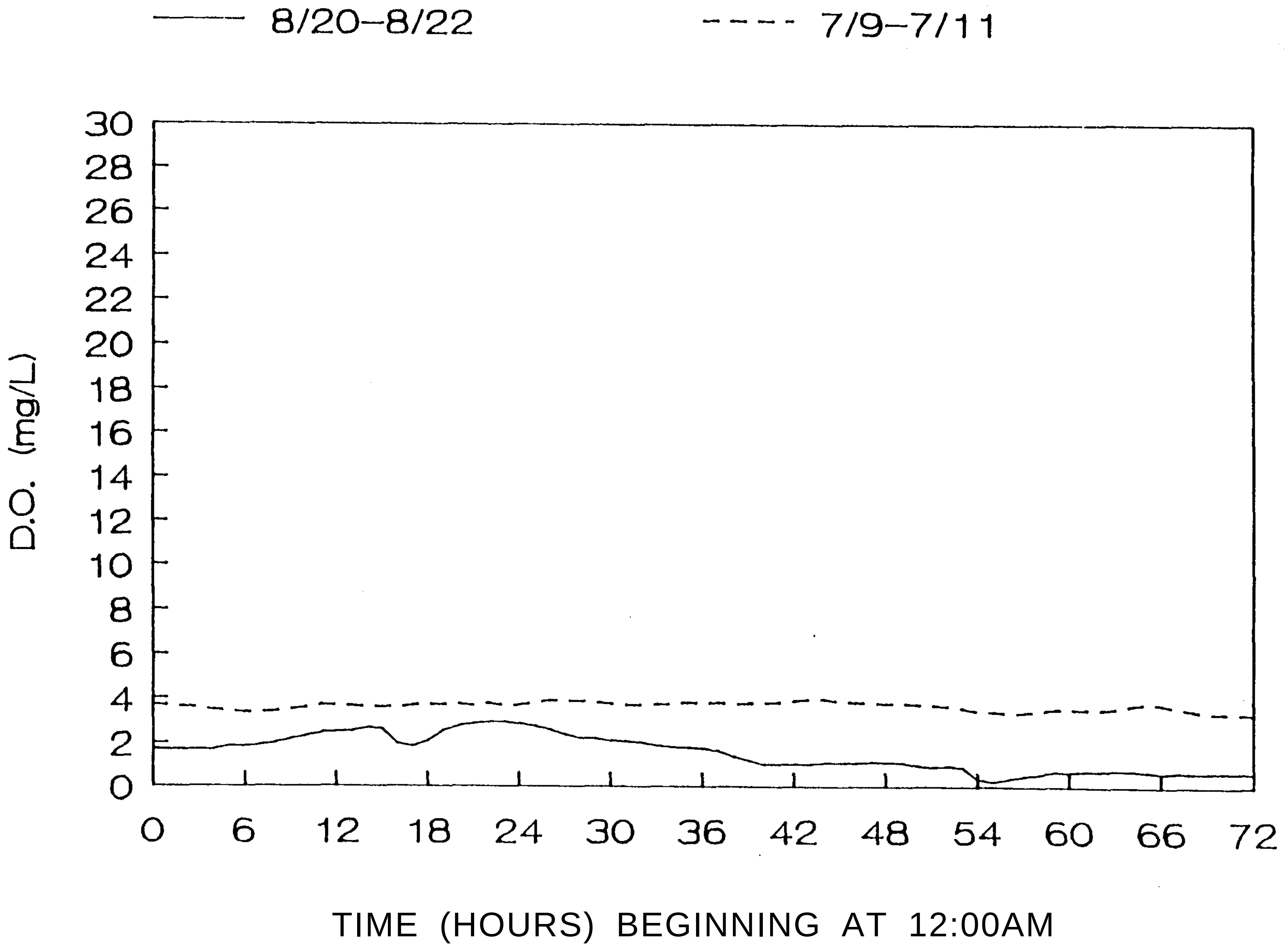
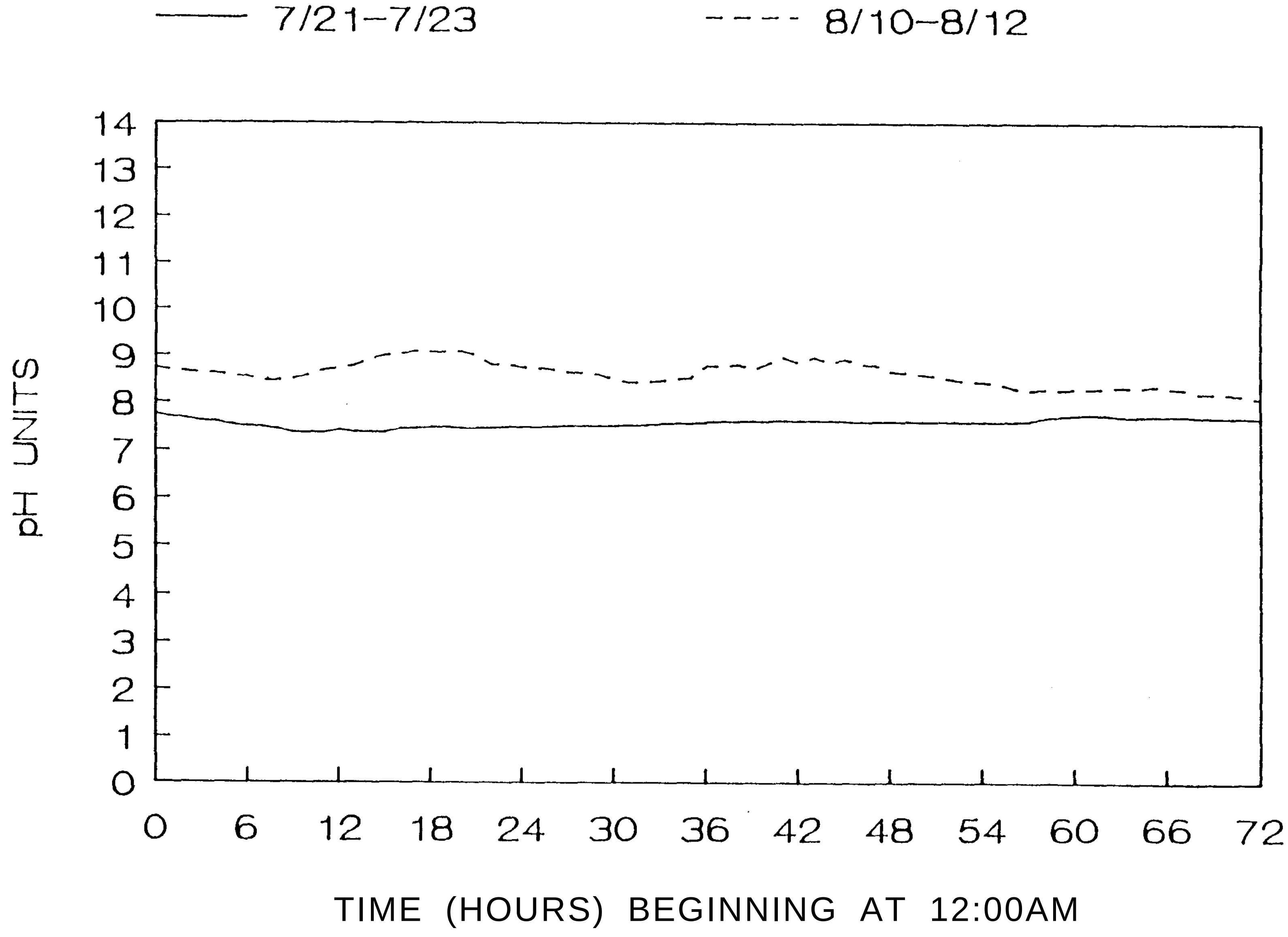

DIURNAL DISSOLVED OXYGEN CURVE
LOCKPORT 1989
8/19–8/21
7/3–7/05
D.O. (mg/L)
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
6
12
18
24
30
36
42
48
54
60
66
72
TIME (HOURS) BEGINNING AT 12:00AM

Figure 12



DIURNAL DISSOLVED OXYGEN CURVE
LOCKPORT 1990

Figure 13



DIURNAL pH CURVE
STARVED ROCK 1990

Figure 14

Comparison of Pre–TARP & Post–TARP 6/13-19/76 Conditions

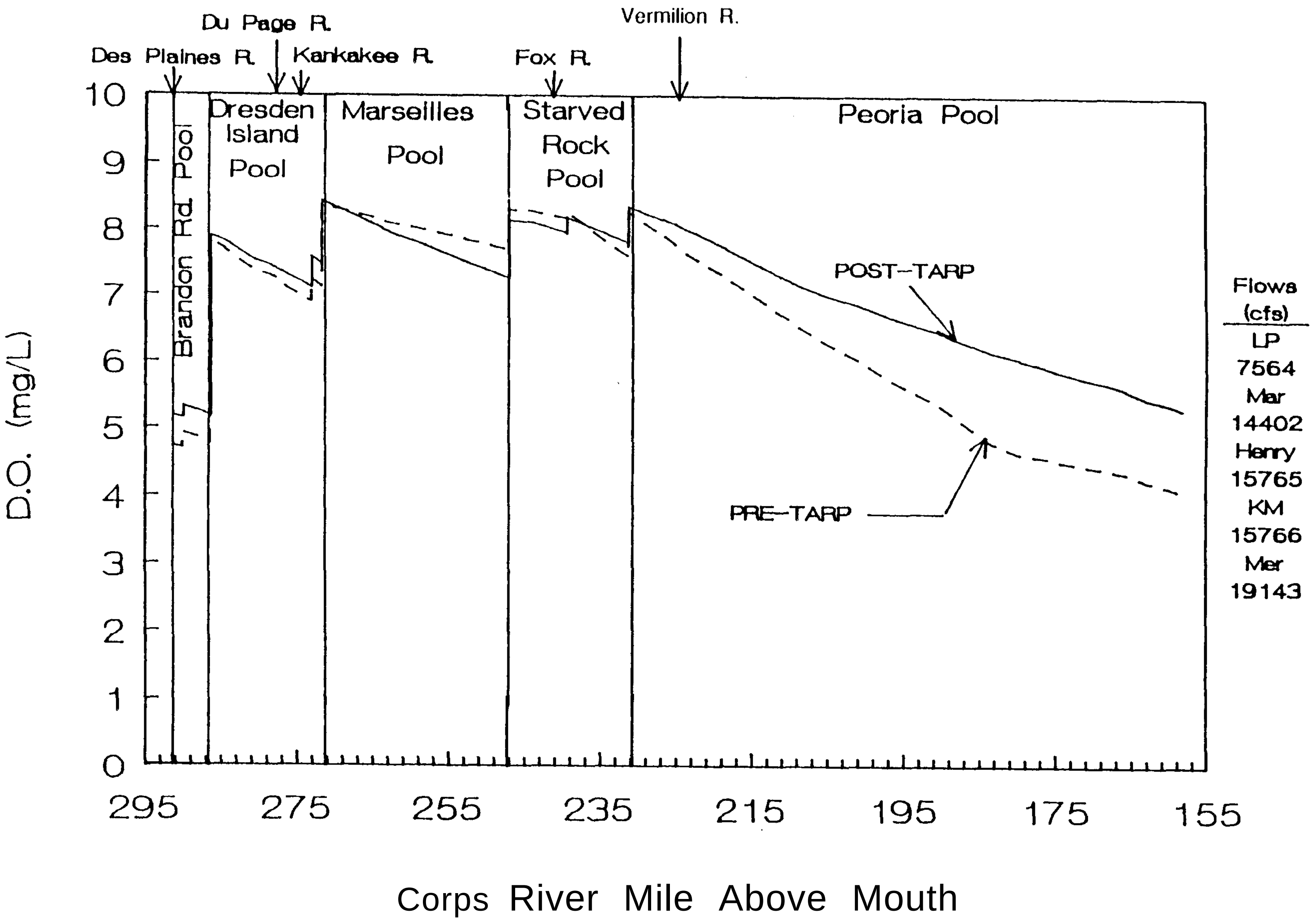


Figure 15

Comparison of Pre–TARP & Post–TARP 9/03/76 Conditions

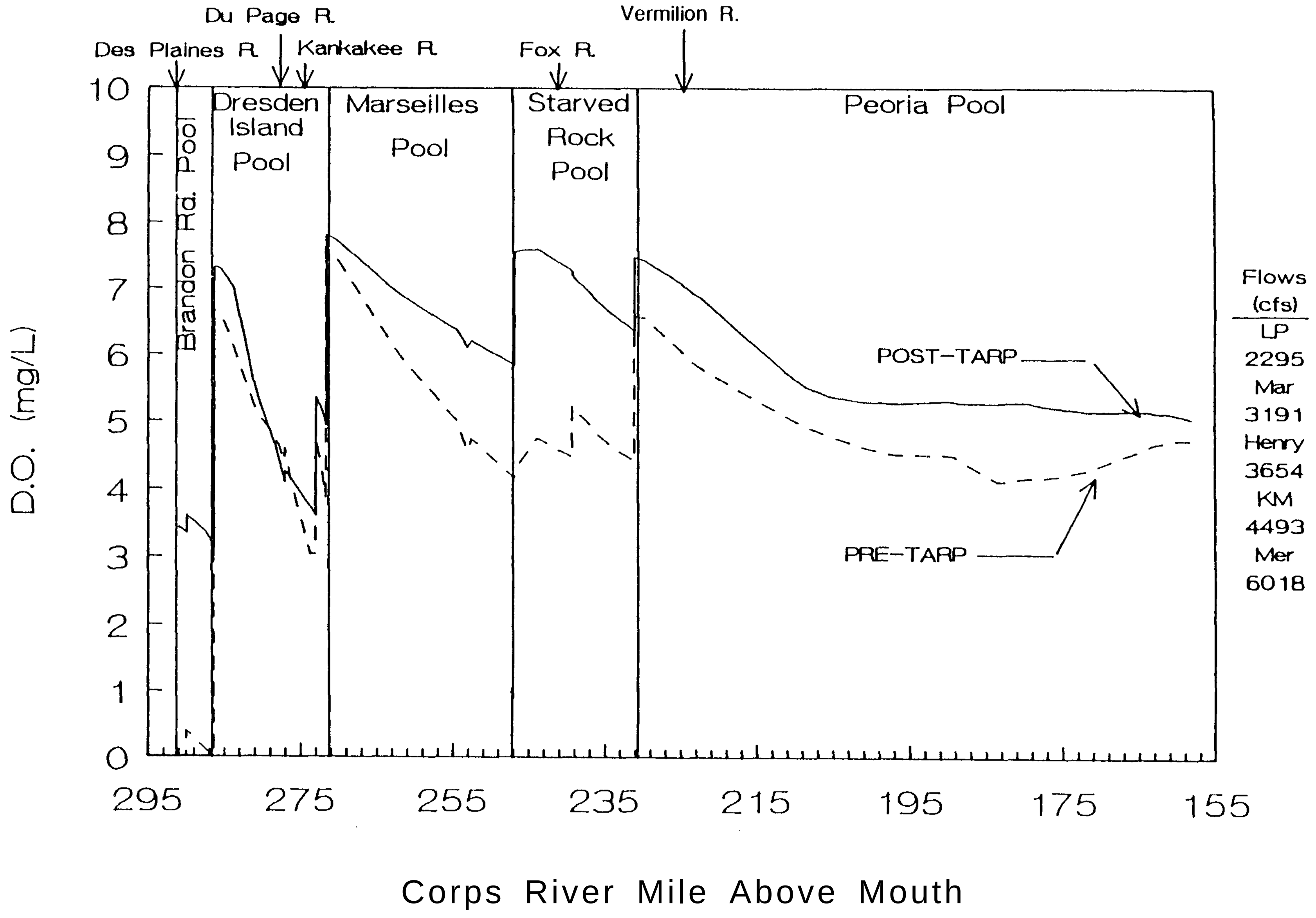


Figure16

Comparison of Pre–TARP & Post–TARP 7/21–27/80 Conditions

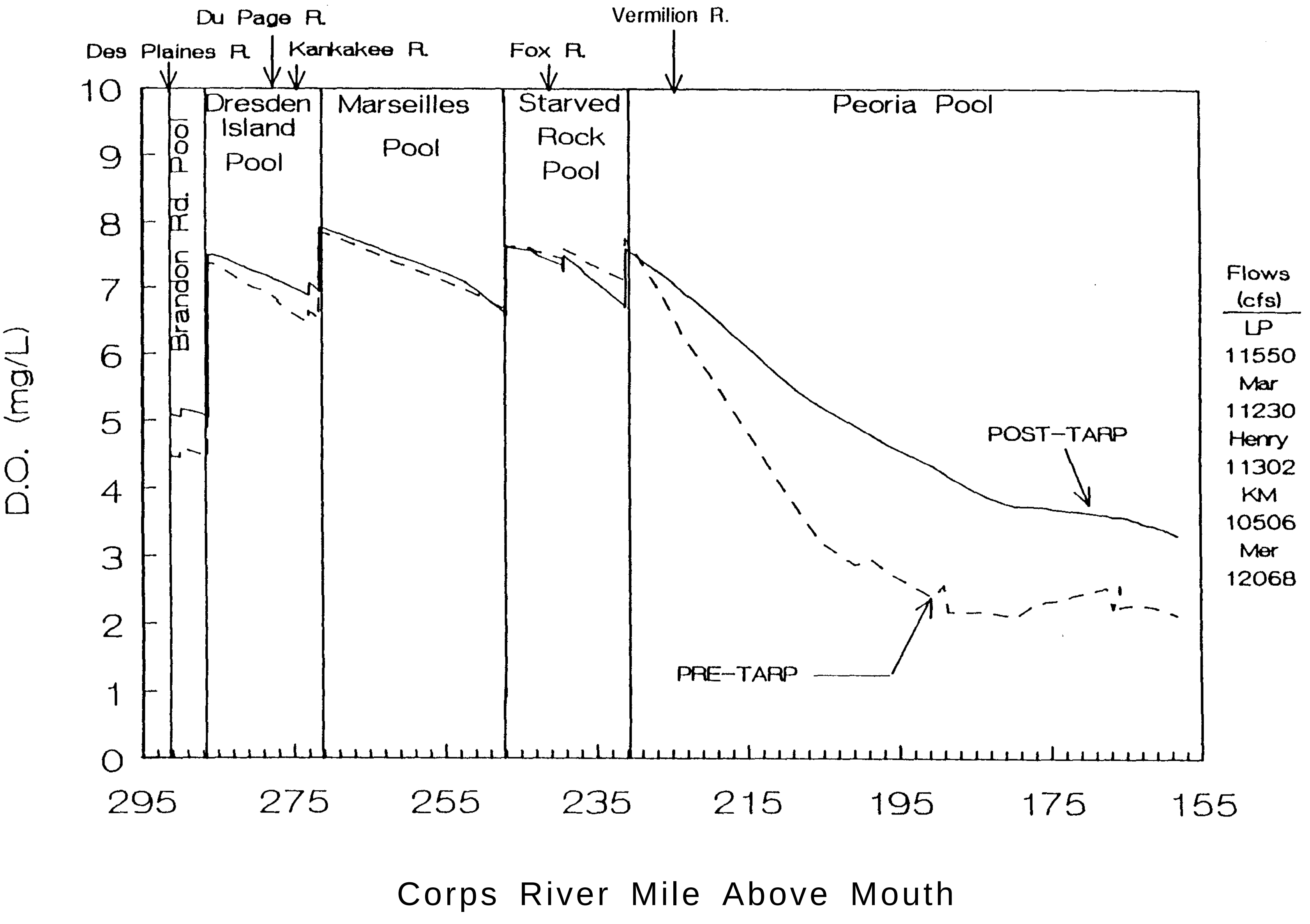


Figure 17

Comparison of Pre–TARP & Post–TARP 7/01/85 Conditions

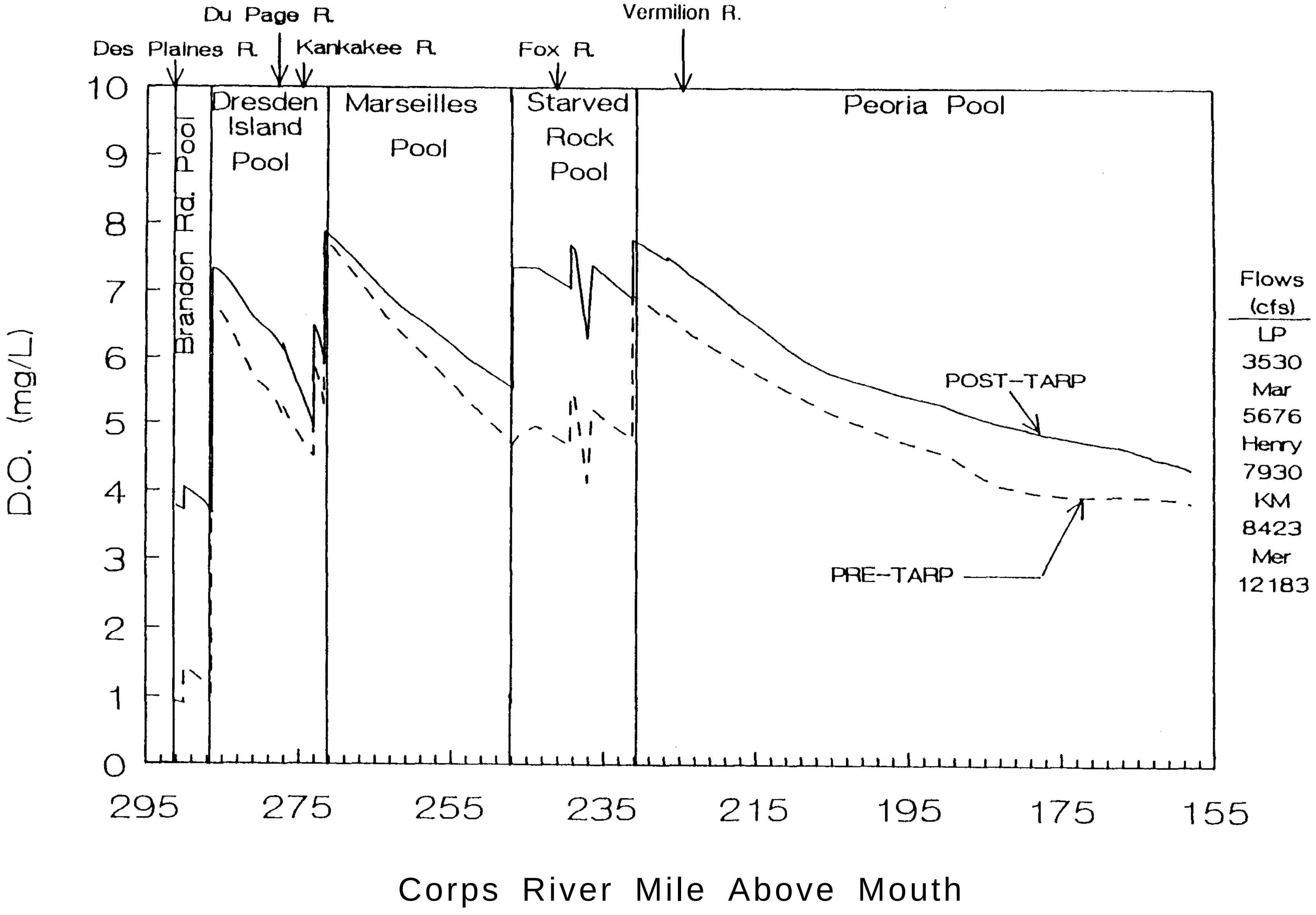


Figure 18

Comparison of Pre–TARP & Post–TARP 8/14-21/87 Conditions

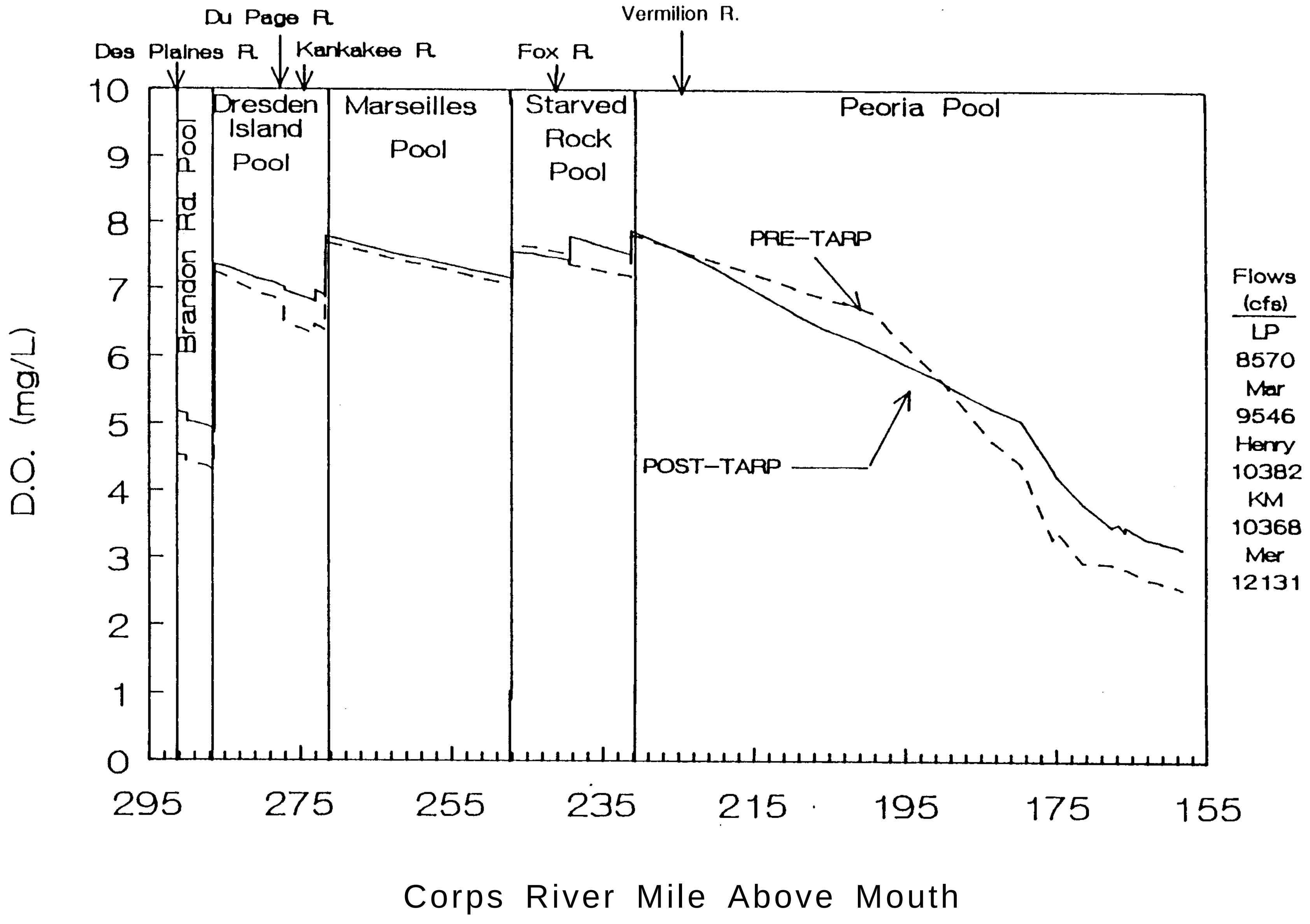


Figure 19

Comparison of Pre–TARP & Post–TARP 8/22/88 Conditions

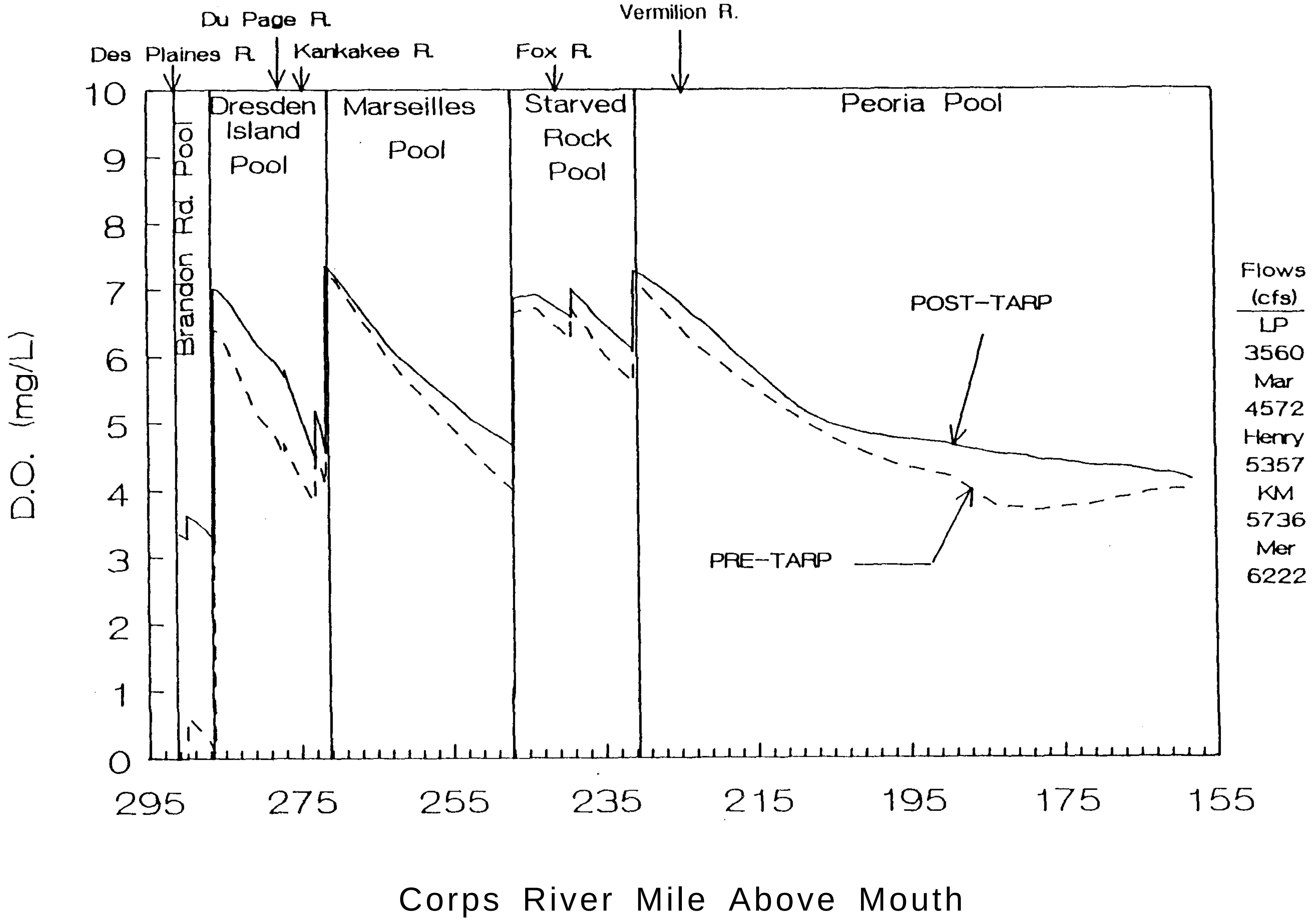


Figure 20

Comparison of Implementation of TARP I for Estimated Waste Load Reductions at Lockport for 6/13–19/197z6

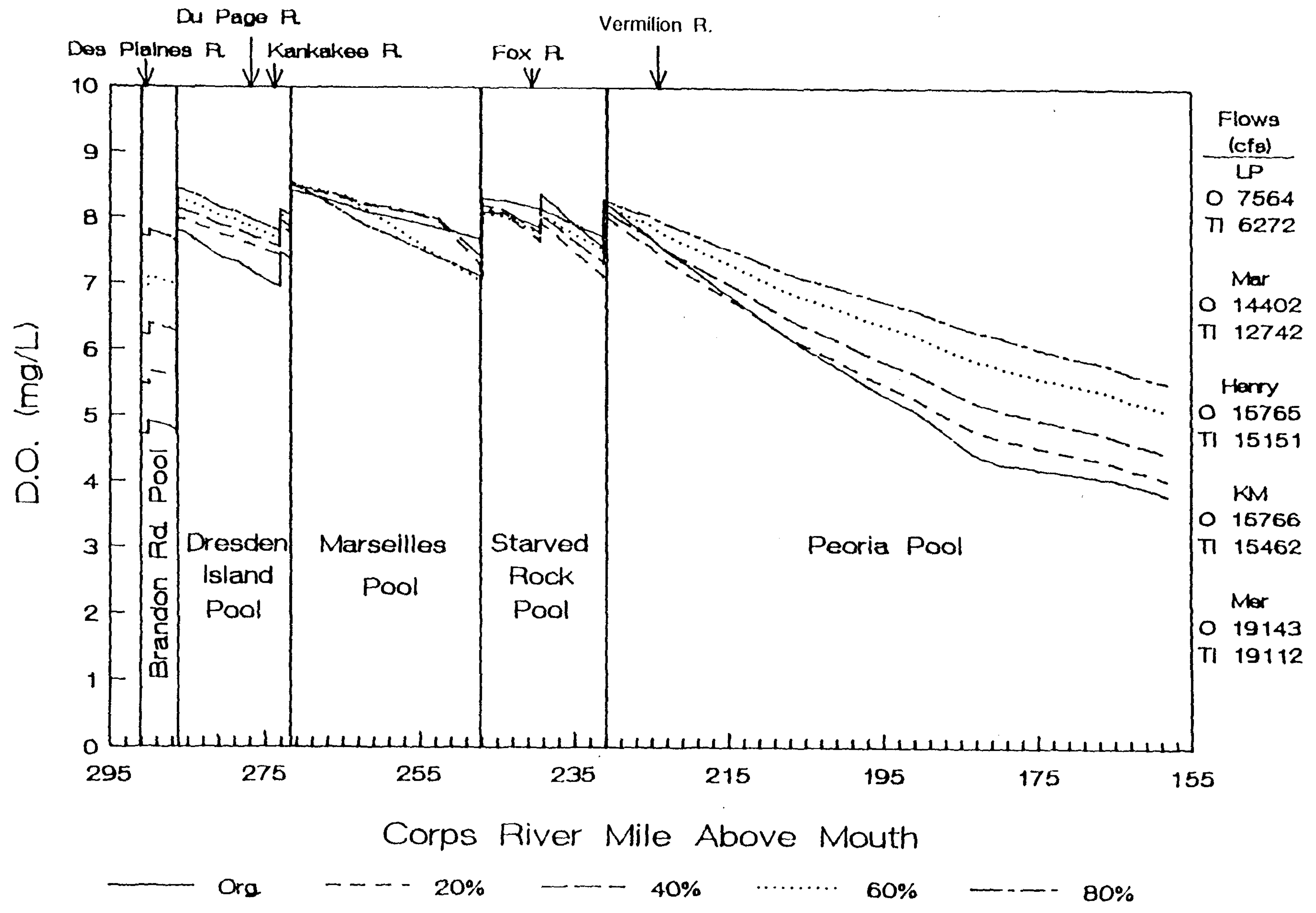


Figure 21

Comparison of Implementation of TARP I for Estimated Waste Load Reductions at Lockport for 7/21-27/1980

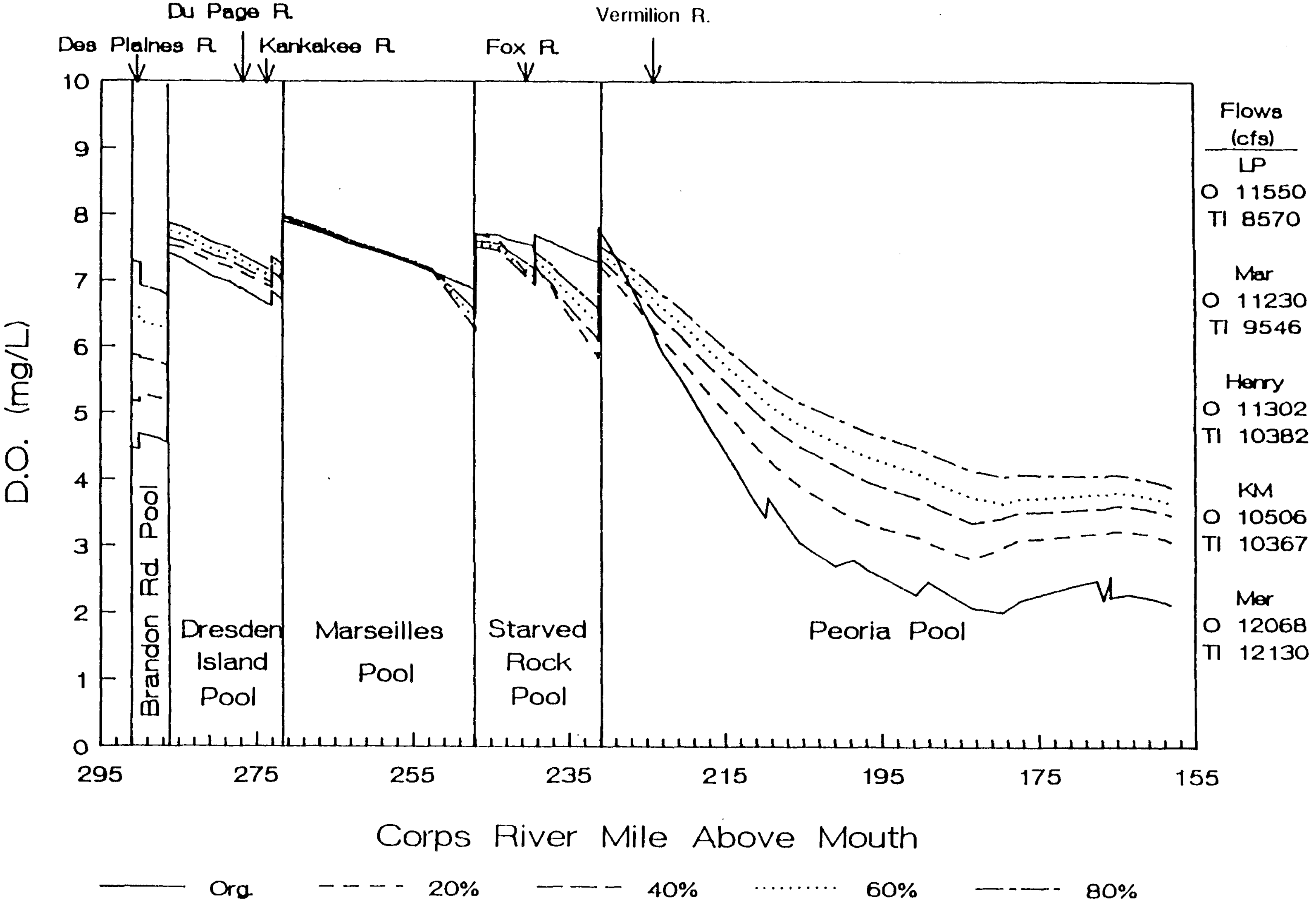


Figure 22

Comparison of Implementation of TARP I for Estimated Waste Load Reductions at Lockport for 8/14-21 /1987

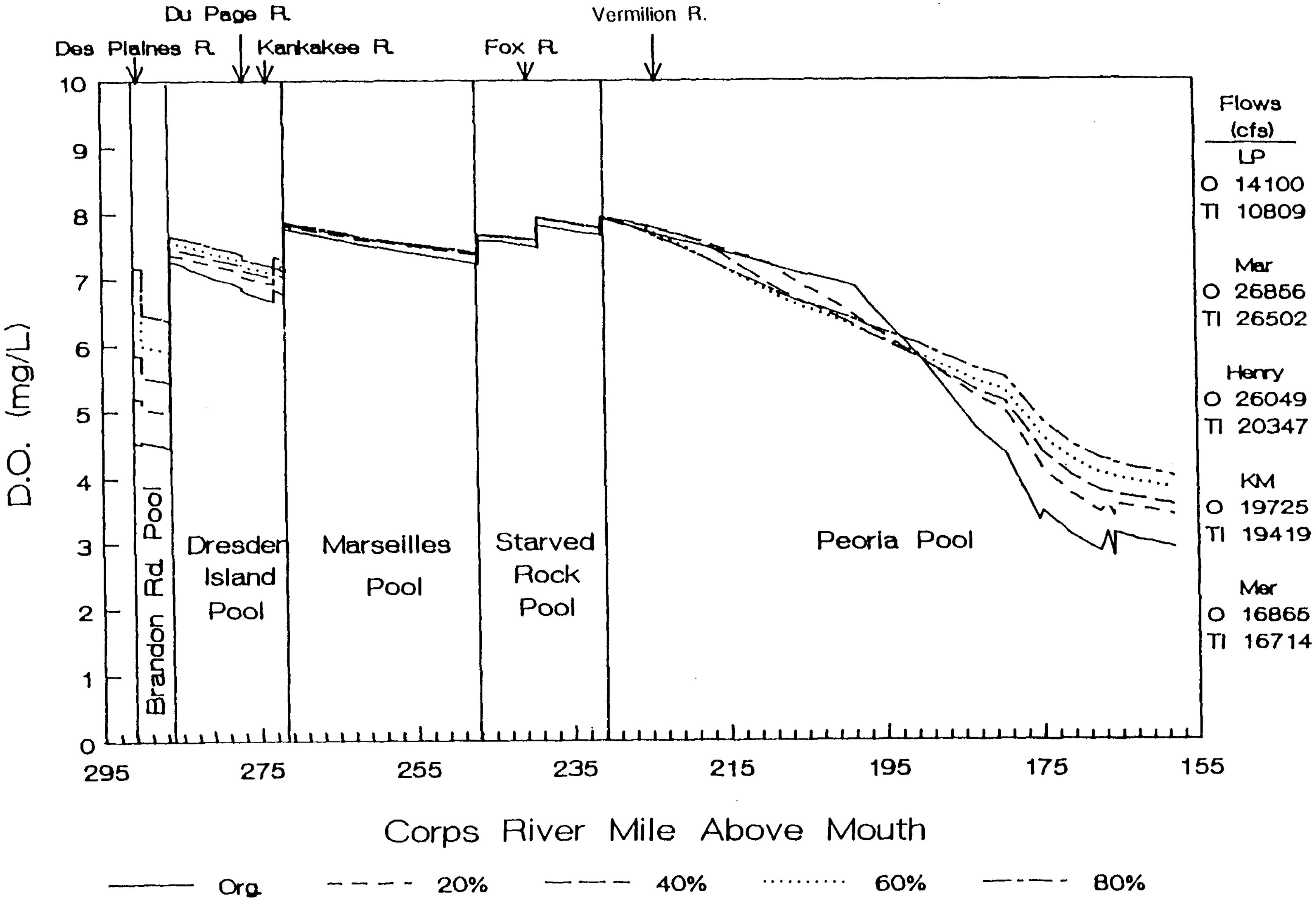


Figure 23

Comparison of Implementation of TARP II for Estimated Waste Load Reductions at Lockport for 6/13–19/1976

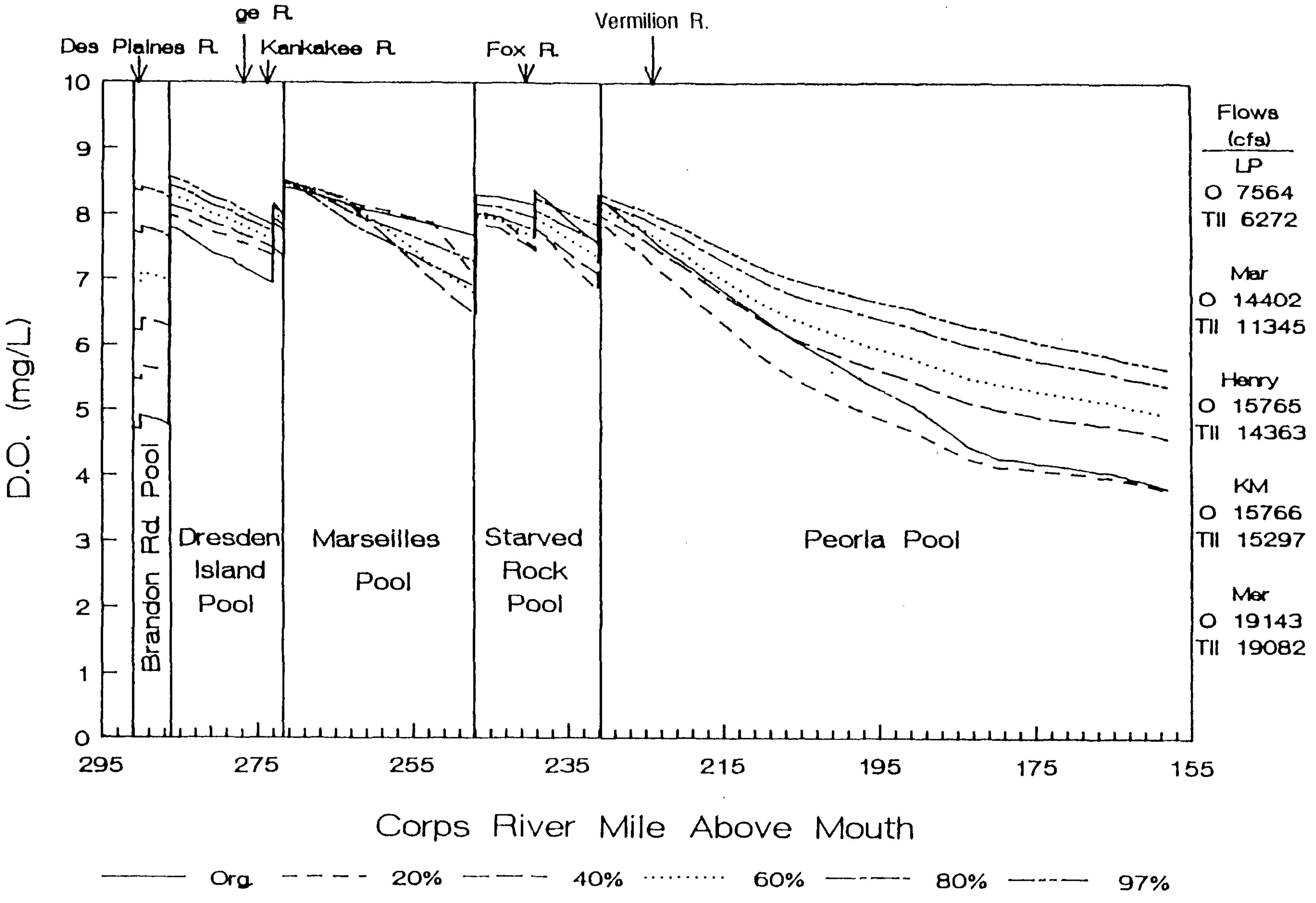


Figure 24

Comparison of Implementation of TARP II for Estimated Waste Load Reductions at Lockport for 7/21—27/1980

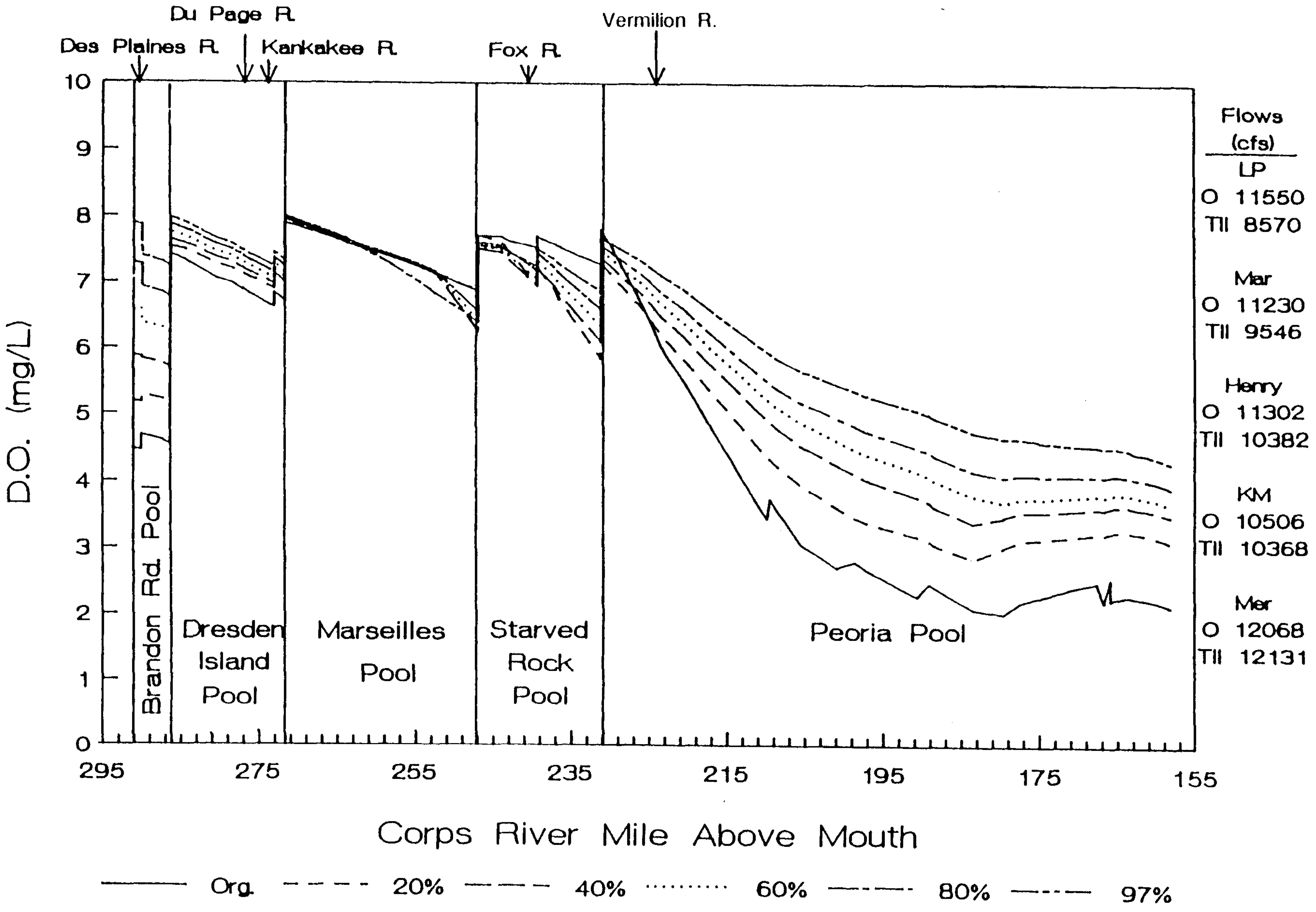


Figure 25

Comparison of Implementation of TARP II for Estimated Waste Load Reductions at Lockport for 8/14—21/1987