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Simulation Modeling of Hydropower Impacts on Dissolved Oxygen in the Upper Ohio River Basin

Steven F. Railsback
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Environmental Sciences Division
Publication No. 3184

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ENVIRONMENTAL SCIENCES DIVISION

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SYMBOLS AND SUBSCRIPTS

SYMBOLS

C dissolved oxygen concentration (milligrams per liter)

D dissolved oxygen deficit (milligrams per liter)

k_1 biochemical oxygen demand (BOD) decay rate coefficient (per day)

k_2 water surface aeration rate coefficient (per day)

L ultimate BOD concentration (milligrams per liter)

Q flow (cubic feet per second)

T temperature (degrees Celsius)

t travel time (days)

V average water velocity (feet per second)

SUBSCRIPTS

AR Allegheny River

a above dam

b below dam

c at the critical time or distance

MR Monongahela River

OR Ohio River

s saturation

g used for hydropower generation

tr tributary

ACKNOWLEDGMENTS

This report is based on research conducted in support of an environmental impact statement on hydroelectric development in the upper Ohio River basin, Federal Energy Regulatory Commission (FERC) Docket No. EL85-19-114. George Taylor is the FERC project manager for this study, and Ron Spath of FERC provided engineering support. Robert Reed is the Environmental Sciences Division project manager.

John Bownds and Martha Stevens of the Energy Division contributed to development of the models. Brady Holcomb of the Computing and Telecommunications Division provided programming support. Brian Worley and Jim Horwedel of the Engineering Physics and Mathematics Division provided assistance with the GRESS software for sensitivity analysis, and Robert Gardner of the Environmental Sciences Division provided the PRISM software for the uncertainty analysis. Michael Sale and Virginia Tolbert reviewed the document.

The modeling methods were reviewed by Mark Dortch of the U.S. Army Corps of Engineers (Corps) Waterways Experiment Station and Ron Yates and others from the Corps Ohio River Division, at a meeting on January 21, 1988, at Cincinnati, Ohio.

ABSTRACT

A model has been developed to assess the impacts of hydropower development at navigation dams on dissolved oxygen (DO) concentrations in the upper Ohio River basin. Field data were used to fit statistical models of aeration at each dam. The Streeter-Phelps equations were used to model DO concentrations between dams. Input data sources were compiled, and the design conditions used for assessment of hydropower impacts were developed. The model was implemented both as Lotus 1-2-3 spreadsheets and as a FORTRAN program. This report contains users' guides for both of these implementations.

The sensitivities and uncertainty of the model were analyzed. Modeled DO concentrations are sensitive to water temperature and flow rates, and sensitivities to dam aeration are relatively high in reaches where dam aeration rates are high. Uncertainty in the model was low in reaches dominated by dam aeration and higher in reaches with low dam aeration rates. The 95% confidence intervals for the model range from about $\pm$ 0.5 mg/L to about $\pm$ 1.5 mg/L.

1. INTRODUCTION

This report documents the dissolved oxygen (DO) simulation model developed by the Oak Ridge National Laboratory (ORNL) to assess cumulative impacts of hydropower development at navigation locks and dams in the upper Ohio River basin. This work was conducted for the Federal Energy Regulatory Commission (FERC) for an environmental impact statement (EIS) for the licensing of 24 proposed hydropower projects (FERC 1988). Figure 1 is a schematic diagram of the basin that was modeled.

The methods used to model DO are described in Sect. 2. Section 3 lists sources of input data that can be used for modeling analyses. Section 5 describes the design conditions used to assess hydropower impacts in the EIS. Sections 6 and 7 serve as users' guides for the model in its two implementations as a FORTRAN program and as Lotus 1-2-3 spreadsheets. Section 8 presents results of sensitivity and uncertainty analyses of the model, and the conclusions of this section should be applied to any additional model studies.

The DO model was developed specifically to evaluate impacts of changes in aeration at dams resulting from hydropower development under low flows and high temperatures when DO problems are most severe. The model was not designed to evaluate impacts of changes in other processes affecting DO concentrations, such as waste loads, surface aeration rates, and water temperatures. The model should not be used for purposes other than evaluating impacts of changes in dam aeration.

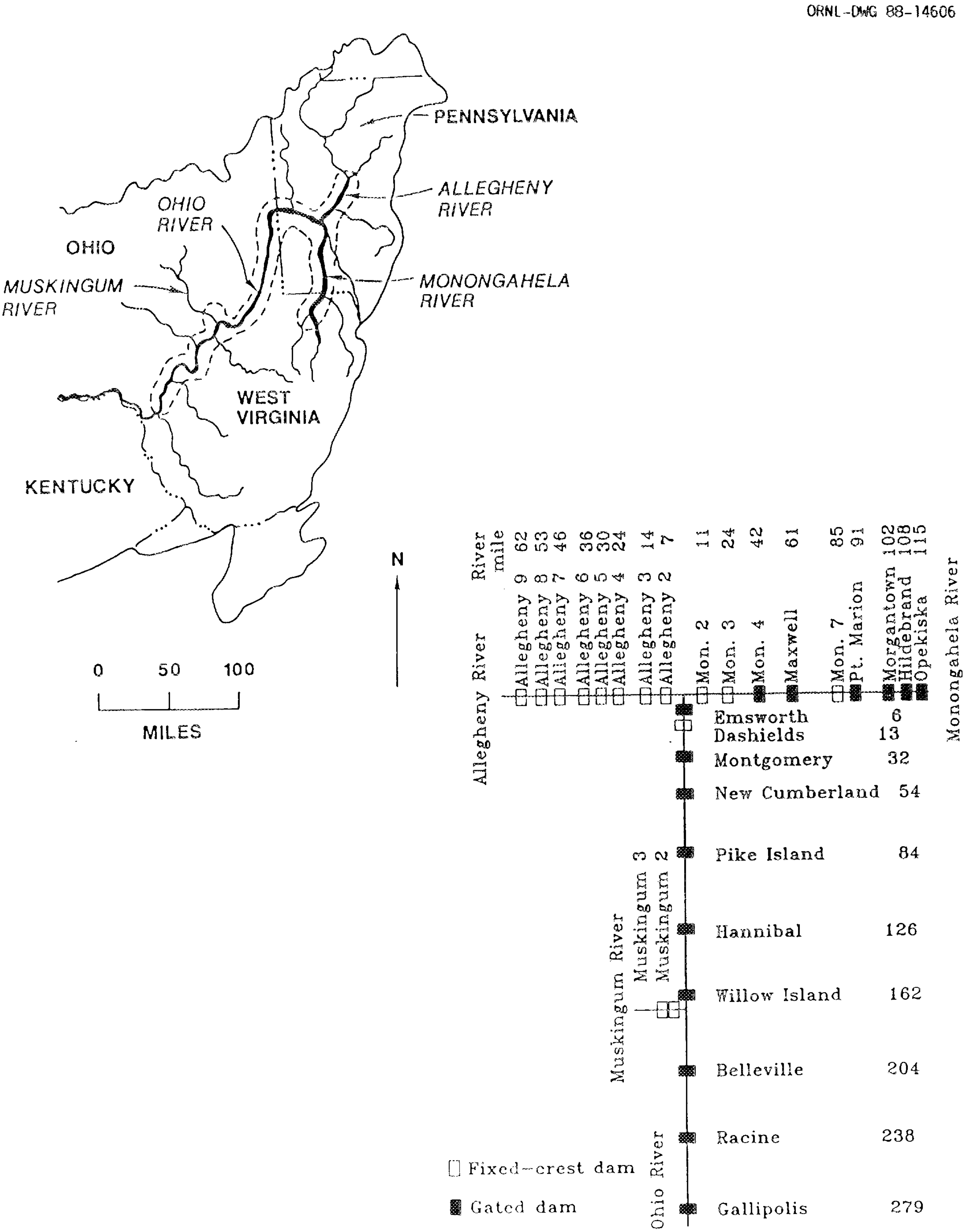

Fig. 1. Map and schematic diagram of Ohio River basin navigation dams.

There are many processes affecting DO concentrations in the Ohio River and its tributaries, such as microbial respiration due to decay of carbonaceous biochemical oxygen demand (BOD), nitrogenous BOD, and sediment BOD; aeration at the water surface and at dams; and algal respiration and photosynthesis (Thomann 1972, USEPA 1985). Models that simulate all these different processes are complex and require many rate parameters and initial conditions whose values often are inadequately known. Because this model was developed to evaluate impacts of changes in only one of these processes, dam aeration, it was simplified as much as possible. Carbonaceous, nitrogenous, and sediment BOD are modeled by using a single rate coefficient for each reach. The effects of algal respiration and photosynthesis on DO are not modeled because historic field data indicate that algae generally have little effect on DO in the Ohio River (FERC 1988; see Appendix B). The model assumes steady-state conditions, since simulation of instantaneous DO concentrations is not required for assessment of general changes resulting from changes in dam aeration.

2. MODEL FORMULATION

2.1. INTRODUCTION

This section presents the equations and assumptions used in the DO model. The same formulation is used in both the spreadsheet and FORTRAN implementations. The model divides the river system into individual reaches and simulates conditions for each reach. Reaches are named by the feature at their upstream end; these features may be dams, point-source BOD dischargers, or tributaries. The model applies the same set of equations to each reach. As used in the EIS, the model starts at Dam 9 at river mile (RM) 62.2 on the Allegheny River and at Tygart Dam on the Tygart River (which becomes the Monongahela River) 151.4 miles above Pittsburgh, and ends at Greenup Dam at RM 341 on the Ohio River. The equations and assumptions used to model DO are described below. Section 3 provides information on determining values for the model parameters, and the parameter values used for the design conditions in the EIS are presented in Sect. 5.

2.2. FLOW, VELOCITY, AND TRAVEL TIME

At the upstream end of each reach, the flow rate (Q) is determined by adding the flow from the reach upstream to the tributary flow (if any). Point-source BOD discharges (Sect. 2.7) are assumed to add zero flow, since the actual flow of such discharges is usually negligible compared to river flows. The assumption is made that, for the low flows of interest in the EIS, the navigation dams maintain constant channel cross-sectional areas, so the velocity is calculated by dividing the flow by the cross-sectional area. The travel time of the reach is equal to the length of the reach divided by the velocity.

2.3. TEMPERATURE

Water temperatures are not modeled, but are input for each reach. Water temperature modeling is very complex, and since the Ohio River Valley Water Sanitation Commission (ORSANCO) electronic monitors and the U.S. Geological Survey (USGS) stations in the basin provide a good base of data for estimating temperatures in each reach, it is unnecessary to model temperatures for the assessment of hydropower impacts.

2.4. DO SATURATION CONCENTRATION

The DO saturation concentration (C_s) is estimated as a function of water temperature (T) using the equation developed by the American Society of Civil Engineers (ASCE 1960):

$$C_s = 14.652 - 0.41022\ T + 0.007991\ T^2 - 0.000077774\ T^3 \quad .$$

2.5. DAM AERATION

At reaches that start with a navigation dam, the water that is not used for hydropower generation or for lockage (the "spill flow") is aerated as it spills over or through the dam. Aeration of the spill flow is modeled by using a linear equation for the DO deficit (the deficit is C_s minus the actual DO concentration):

$$D_b = \beta D_a - \alpha \quad ,$$

where β is the dam aeration coefficient and α is the dam aeration constant. The parameters β and α are determined empirically from measurements made at each dam (Railsback et al. 1988a, 1988b).

2.6. DO AT START OF REACH

The DO concentration at the upstream end of a reach is determined from a mass balance on the DO in water from the upstream reach that is aerated by a dam (i.e., the spill flow if a dam exists), the DO in water from the upstream reach that is not aerated (i.e., that used for hydropower generation and lockage if the reach starts at a dam and the entire flow if the reach does not start with a dam), and the DO in a tributary (if one exists). The DO concentration in the water aerated by a dam (C_b) is determined using the dam aeration equation (Sect. 2.5). The water used for hydropower generation and lockage is assumed to receive no aeration, so its DO concentration is equal to the DO above the dam (C_a). The DO in the tributary is specified as input. The equation for this mass balance is

$$\text{starting DO} = \frac{C_b(Q - Q_g) + C_aQ_g + C_{tr}Q_{tr}}{Q + Q_{tr}} ,$$

where Q is the total river flow, Q_g is the flow that is used for generation and lockage, C_{tr} is the DO concentration in the tributary, and Q_{tr} is the tributary flow.

2.7. BOD AT START OF REACH

The BOD concentration at the start of a reach is determined from a mass balance on the BOD in water from the upstream reach (where the concentration is L_a) and in a tributary (if one exists) (where the concentration is L_{tr}). In addition, BOD from a point source at the beginning of the reach can be added; the point-source loading, in pounds of BOD per day, is input and the resulting increase in concentration depends on the flow rate. The BOD in the tributary is input. The equation for the starting BOD, including both the mass balance and the point source load, is

$$\text{starting L} = \frac{L_aQ + L_{tr}Q_{tr}}{Q + Q_{tr}} + \frac{0.185(\text{point source BOD load})}{Q + Q_{tr}} .$$

Multiplying by 0.185 converts units of (pounds per day)/(cubic feet per second) to milligrams per liter.

2.8. DO AT END OF REACH

The DO deficit and concentration at the end of a reach are calculated using the Streeter-Phelps equation (Streeter and Phelps 1925; USEPA 1985):

$$D(t) = \frac{k_1 L_0}{k_2 - k_1}[\exp(-k_1 t) - \exp(-k_2 t)] + D_0 \exp(-k_2 t) \quad ,$$

where D(t) is the DO deficit at the end of the reach, t is the travel time through the reach in days, D_0 is the starting DO deficit for the reach, L_0 is the starting BOD for the reach, and k_1 and k_2 are the temperature-corrected BOD decay and surface aeration rate coefficients described below. The DO concentration at the end of the reach is equal to C_s - D(t).

2.9. BOD AT END OF REACH

The BOD at the end of a reach (L_t) is calculated using the Streeter-Phelps first-order decay equation (Streeter and Phelps 1925):

$$L(t) = L_0 \exp(-k_1 t) \quad .$$

2.10. BOD DECAY RATE COEFFICIENT (k_1)

The first-order BOD decay rate coefficient k_1 is used to model the rate at which BOD consumes DO. It is theoretically a property of the chemical compounds making up the BOD in the river and changes with temperature. The value of k_1 at 20°C for each reach (per day) is input to the model and is typically adjusted in calibration. The input value of $k_1(20^oC)$ is adjusted for the water temperature T by using the equation (USEPA 1985)

$$k_1(T) = k_1(20^oC) \times 1.047^{(T-20)} \quad .$$

2.11. SURFACE AERATION RATE COEFFICIENT (k_2)

The water surface aeration rate coefficient k_2 is used to model the rate at which oxygen is dissolved into the water from the surface of the rivers. The value of k_2 is a function of the river hydraulics and varies with temperature. The value of k_2 at 20°C (per day) is estimated by the model using the O'Connor-Dobbins equation (USEPA 1985):

$$k_2(20^oC) = 12.9(V^{0.5})/\text{depth}^{1.5} \quad .$$

This value of k_2 at 20°C is adjusted for the water temperature using the equation

$$k_2(T) = k_2(T^oC) \times 1.024^{(T-20)} \quad .$$

The model also allows the value of k_2 to be entered as input instead of calculated. This option is used in reaches like the Hildebrand and Opekiska pools on the Monongahela River where thermal stratification sometimes significantly reduces water surface aeration. An input value of k_2 that is much lower than the value calculated by the O'Connor-Dobbins equation simulates the effects of stratification.

2.12. CRITICAL TIME AND DISTANCE

The lowest DO concentration (highest DO deficit) in a reach can be at the beginning of the reach (if DO concentrations increase throughout the reach), at the end of the reach (if DO concentrations decrease throughout the reach), or at some intermediate point in the reach (a sag point). Setting the derivative of the Streeter-Phelps equation with respect to time equal to zero determines the critical travel time t_c at which the lowest DO concentrations occur. The equation for t_c is

$$t_c = \frac{1}{k_2-k_1} \ln \left\{ \frac{k_2}{k_1} \left[1 - \frac{(k_2 - k_1)D_0}{k_1 L_0} \right] \right\} \quad .$$

If the value of t_c is negative, then the lowest DO concentration occurs at the start of the reach. If the value of t_c is greater than the travel time of the reach, then the lowest DO concentration occurs at the end of the reach. If the value of t_c is greater than zero but less than the travel time of the reach, then the lowest DO concentration occurs at a sag point within the reach and the distance from the start of the reach to the sag point is determined by multiplying t_c by the velocity.

3. INPUT DATA

Many of the parameters used in the model normally will not be changed between model runs. These parameters include the reach names, river miles, cross-sectional areas, depths, dam aeration parameters, and k_1. Other input parameters such as river and tributary flows, the flow used for generation at dams, water temperatures, and BOD loads are more likely to be changed between model runs. Reasonable values of these parameters must be determined from available data sources. Recommended ways of evaluating these parameters are listed below. The values used for the design conditions in the EIS are provided in Sect. 5.

3.1. FLOWS

Several sources of data on flows in the Ohio River exist. The Ohio River Water Quality Fact Book (ORSANCO 1986) includes monthly mean flows at a number of locations on the Ohio River main stem and at the downstream ends of the Allegheny and Monongahela rivers. There is a USGS stream gage (No. 03086000) at Sewickley, Pennsylvania, just upstream of Dashields Dam at RM 13.3, which provides probably the best flow record on the upper Ohio River. Table 1 includes monthly mean flows from the Sewickley gage. The values in the ORSANCO book are determined from U.S. Weather Service estimated daily flows and do not always agree with monthly means from the USGS station. The Corps of Engineers (Corps) Pittsburgh District has developed annual flow duration curves for

Table 1. Mean monthly flows in the Ohio River basin

	Station					
	Monongahela		Allegheny		Ohio	Muskingum
Month	Point Marion	Dam 2	Dam 7	Dam 4	(Dashields)	(McConnelsville)
Oct	2,000	5,300	8,000	9,100	14,800	2,400
Nov	3,100	9,500	13,600	15,000	25,000	4,500
Dec	5,800	15,900	18,800	23,900	39,700	7,700
Jan	7,700	16,700	20,800	24,000	43,800	10,100
Feb	8,500	20,900	21,000	27,700	49,000	12,000
March	8,500	24,100	33,600	40,600	67,300	15,500
April	6,000	19,100	27,800	36,100	56,700	13,700
May	4,200	13,700	18,500	23,100	37,400	9,200
June	3,500	9,700	11,300	14,900	24,600	6,400
July	2,000	6,300	6,700	8,700	15,300	4,300
Aug	2,100	6,000	4,900	6,500	13,000	3,400
Sept	1,600	4,600	5,000	6,000	10,700	2,600
Annual	4,600	12,600	15,600	19,600	33,000	7,700

Source: USGS unpublished data, WATSTORE data base.

upper Ohio River dams (Fig. 2), which can be used to determine how frequently certain flow rates occur, though monthly flow duration curves would be more useful for determining flows during summer when DO concentrations are most critical.

Flow data on the Allegheny and Monongahela rivers are available from the following USGS gaging stations: Allegheny at Kittanning (above dam 7, No. 03036500), Allegheny at Natrona (above dam 4, No. 03049500), Monongahela at Greensboro (above dam 7, No. 03072500), Monongahela at Elizabeth (above dam 3, No. 03075070; this gage replaced the one at dam 4, which was discontinued in 1977), and Monongahela at Braddock (above dam 2, No. 03085000). Monthly mean flows from the gages with the best records are in Table 1. The Corps also has annual flow duration curves for the Allegheny (Fig. 3) and Monongahela (Fig. 4) rivers. A comparison of monthly mean flows and 7Q10 flows (flows with a 7-d duration and a return period of 10 years) in the Allegheny and Monongahela rivers showed that approximately 60% of the flow in the Ohio River at Pittsburgh comes from the Allegheny and 40% comes from the Monongahela.

Flow rates in major tributaries can be estimated by using the difference in monthly mean flows between the stations on the main rivers above and below where the tributary enters or by using USGS gaging data where available. Tributaries included in the model as used for the EIS are the Kiskiminetas at Allegheny RM 30.0, the West Fork at Monongahela RM 128.7, the Cheat at RM 89.6, the Youghiogheny at Monongahela RM 15.5, the Beaver at Ohio RM 25.4,

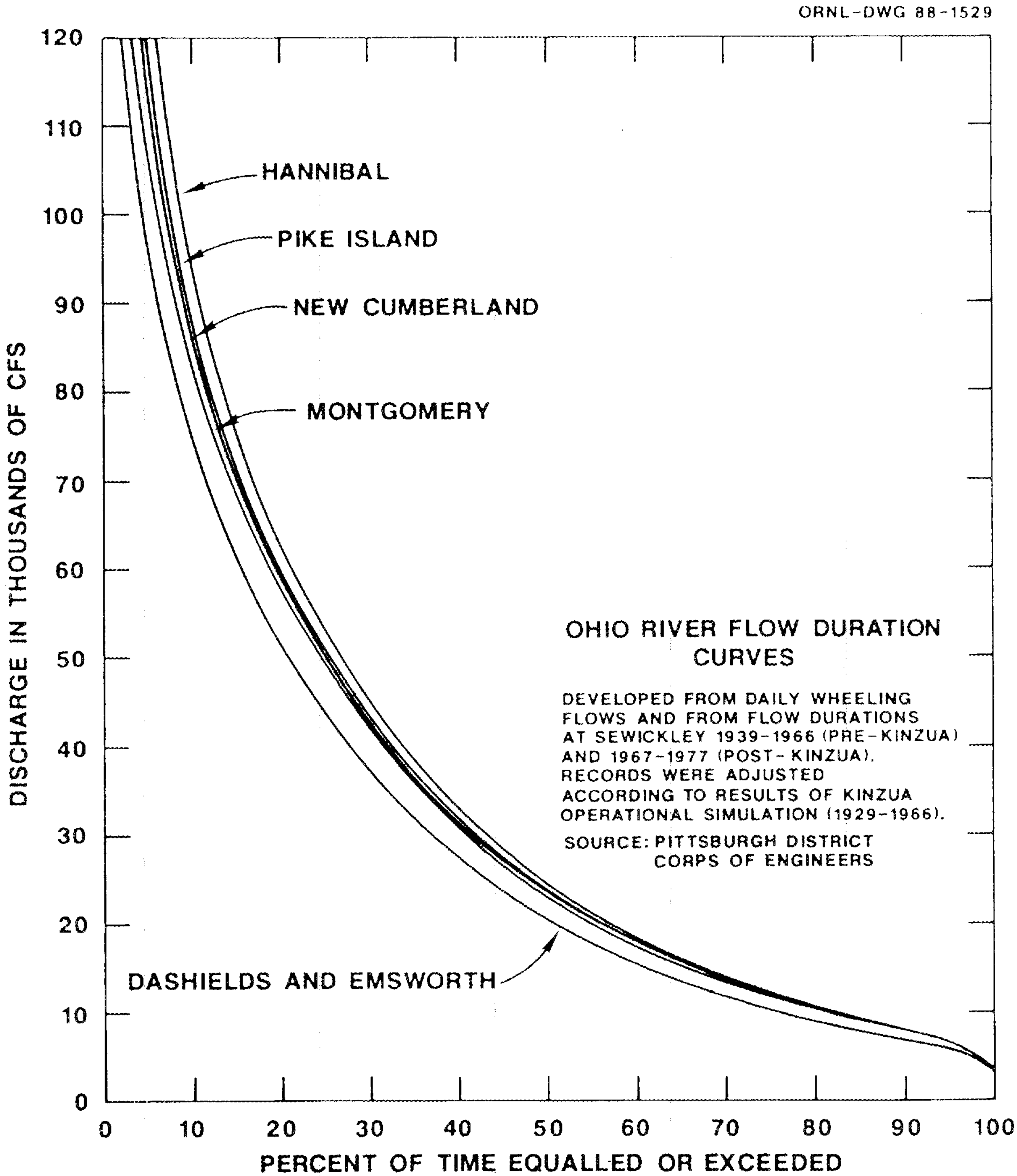

Fig. 2. Ohio River annual flow duration curves.

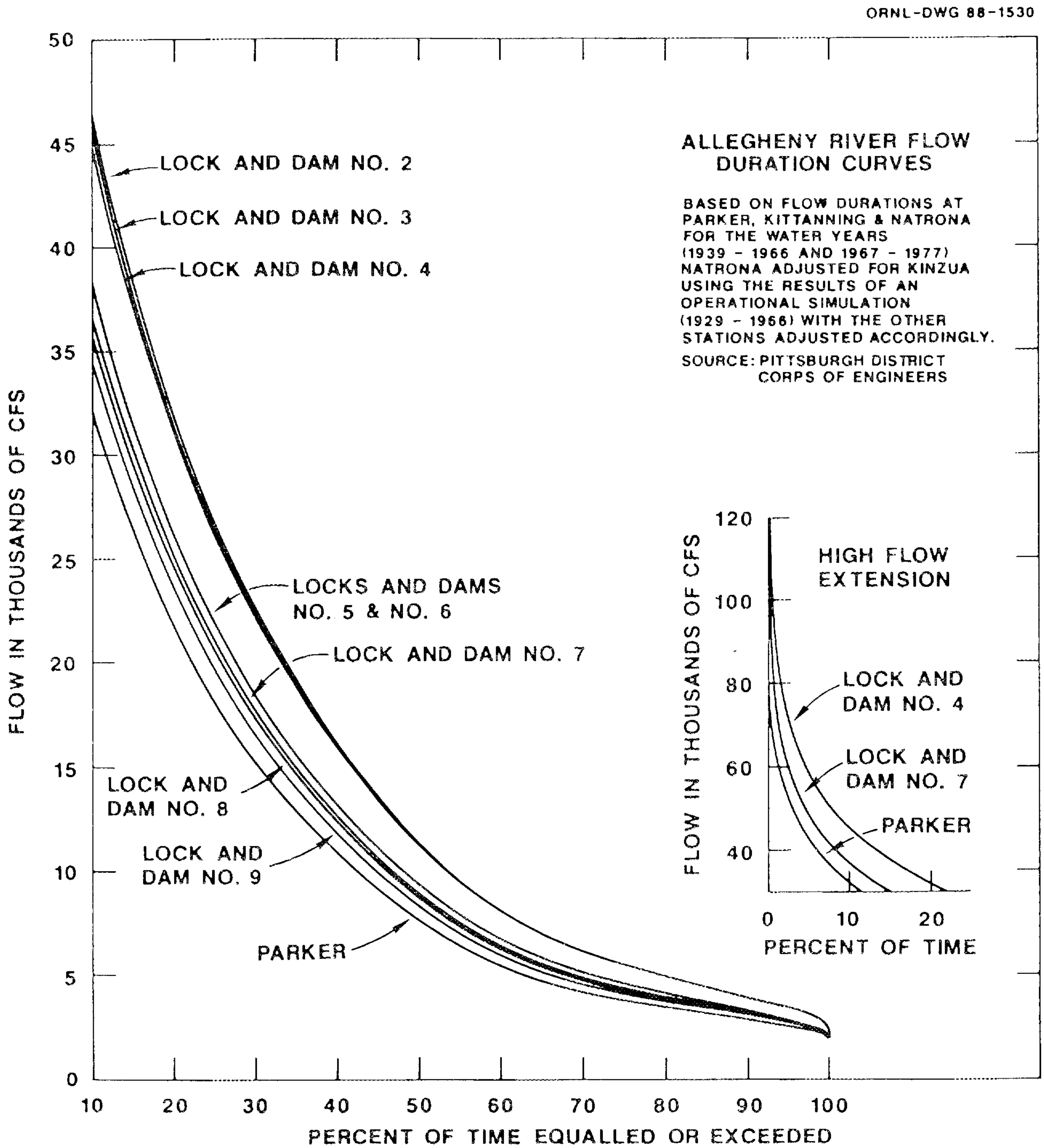

Fig. 3. Allegheny River annual flow duration curves.

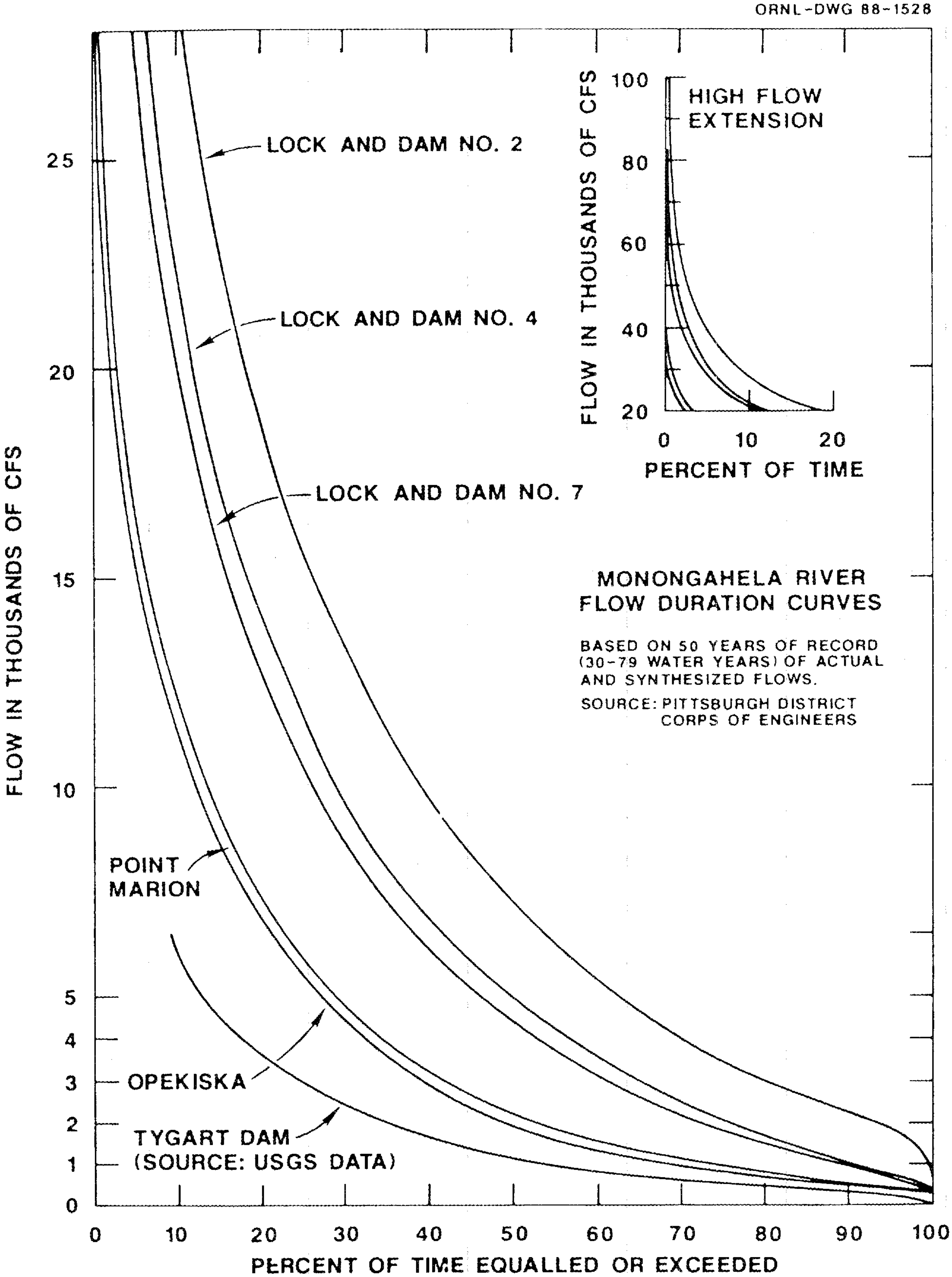

Fig. 4. Monongahela River annual flow duration curves.

the Muskingum at Ohio RM 172.0, the Little Kanawha at Ohio RM 184.6, the Hocking at Ohio RM 199.3, and the Kanawha at Ohio RM 265.7.

The model results are sensitive to the flow rate (Sect. 8.2.3), so the flow rates should be selected carefully and the variation of model results with changes in flow should be at least qualitatively investigated for all model applications.

3.2. FLOW NOT AERATED AND SPILL FLOW

The parameter called "flow not aerated" describes how much flow does not pass over each dam and therefore is not aerated. This parameter is a decision variable because it is a function of the hydropower operating scenario being simulated, not of any physical characteristic of the system. The value of this parameter should include the flow used for hydropower generation, plus the flow used for lockage. Leakage flow should not be included because the dam aeration data on which the models are based include the effects of leakage flows on aeration (i.e., leakage occurred when the data were collected, so leakage is intrinsically included in the aeration measurements and models). Values of lockage flows estimated by the Corps for each dam are included in Table 2.

The value of the "flow not aerated" parameter should be determined by (a) adding the flow used for generating power to the lockage flow and (b) checking to make sure that the total river

Table 2. Hydrologic information for Ohio River basin navigation dams

Dam	Normal Pool elevation (ft)	River mile	7Q10 (cfs)	Leakage (cfs)	Lockage (cfs)
Allegheny 9	828	62.2			
Allegheny 8	800	52.6			
Allegheny 7	782.1	45.7	2250	150	7
Allegheny 6	769	36.3	2250	150	8
Allegheny 5	756.8	30.4	2250	150	17
Allegheny 4	745	24.2	2900	150	27
Allegheny 3	734.5	14.5	2900	150	40
Allegheny 2	721	6.7	2900	150	43
Opekiska	857	115.4	340	200	23
Hildebrand	835	108.0	340	400	25
Morgantown	814	102.0	340	400	40
Point Marion	797	90.8	345	400	143
Monongahela 7	778	85.0	480	150	86
Maxwell	763	61.2	520	350	230
Monongahela 4	743.5	41.5	550	400	138
Monongahela 3	726.9	23.8	550	150	82
Monongahela 2	718.7	11.2	1310	150	102
Emsworth	710	6.2	4730	650	223
Dashields	692	13.3	4730	150	112
Montgomery	682	31.7	5830	1150	212
New Cumberland	664.5	54.4	5830	2900	347
Pike Island	644	84.2	5830	450	385
Hannibal	623	126.4	5830	900	284
Willow Island	602	161.7	5830	2000	287
Belleville	582	203.9	6470	1500	306
Racine	560	237.5	6670	3000	329
Gallipolis	538	279.2	8850	2300	300

Source: U.S. Army Corps of Engineers, Ohio River Division, navigation charts and letter to ORNL, Oct. 26, 1987.

flow minus the flow not aerated is not less than the required spill flow. (If the river flow minus the flow not aerated is less than the required spill flow, then generation must be reduced or eliminated to maintain the spill flow requirement.)

Both the FORTRAN and spreadsheet implementations of the model can be used with the spill flow rather than the flow not aerated as input. If the spill flows are used as input, the flow not aerated is calculated as the total river flow minus the spill flow. In this case, the user must check to make sure that the difference between the total river flow and the spill flow is sufficient to allow generation. (This difference must be greater than the minimum flow required for generation at each hydropower plant that operates.)

3.3. WATER TEMPERATURE

Water temperatures for each reach are specified as input. Temperatures in the Allegheny, Monongahela, and Ohio rivers are artificially raised by power plants and tend to increase with distance downstream. Reasonable temperature values can be estimated from ORSANCO monitor data on the Ohio River and at the downstream ends of the Allegheny and Monongahela rivers and from USGS data collected on the Allegheny and Monongahela. Frequency distributions for the months of June through October have been determined from daily mean temperatures measured at the ORSANCO monitors (Figs. 5 through 11, which also include DO concentration

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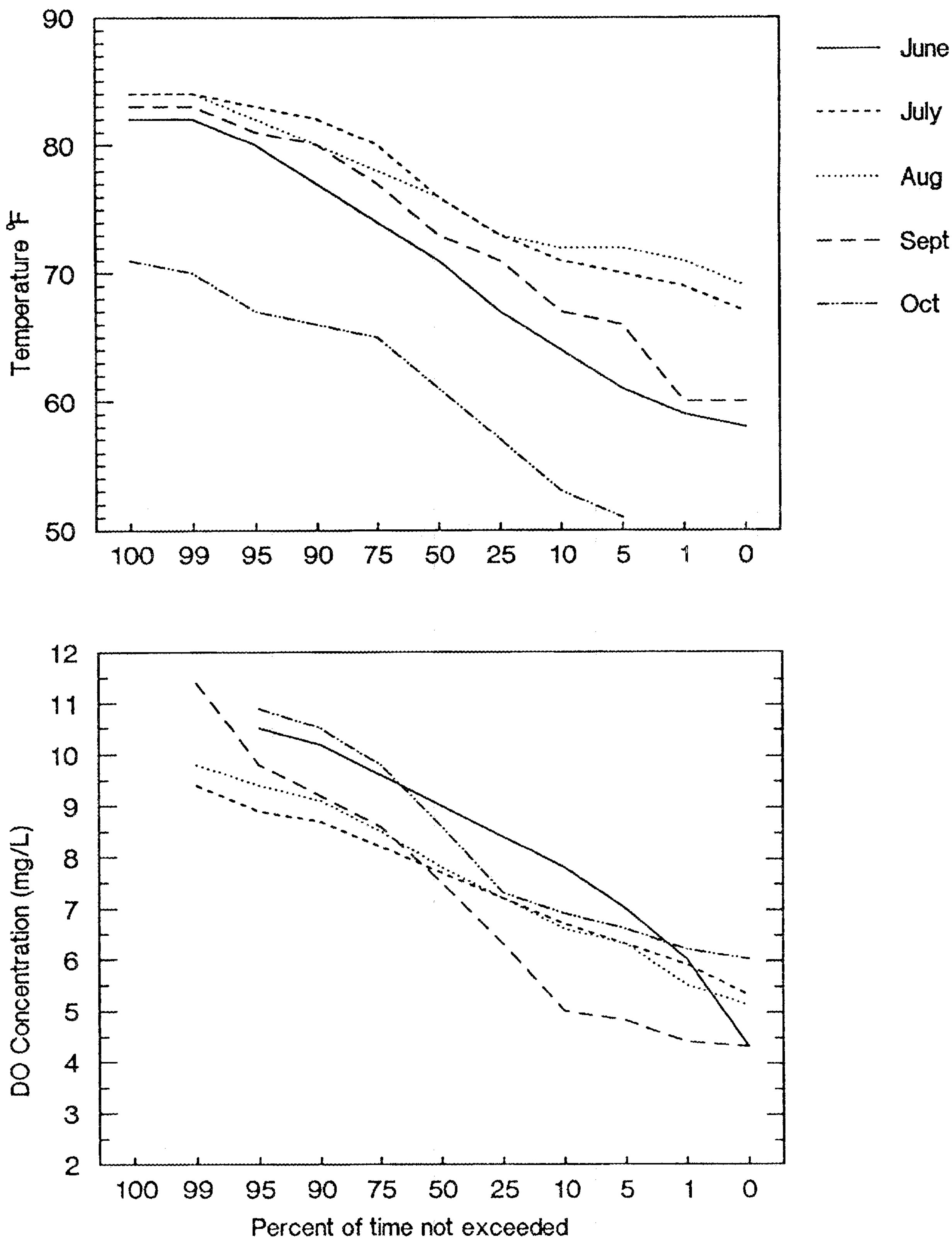

Fig. 5. Allegheny River mile 13.3 summer temperature and DO duration curves (ORSANCO data from 1980-1986).

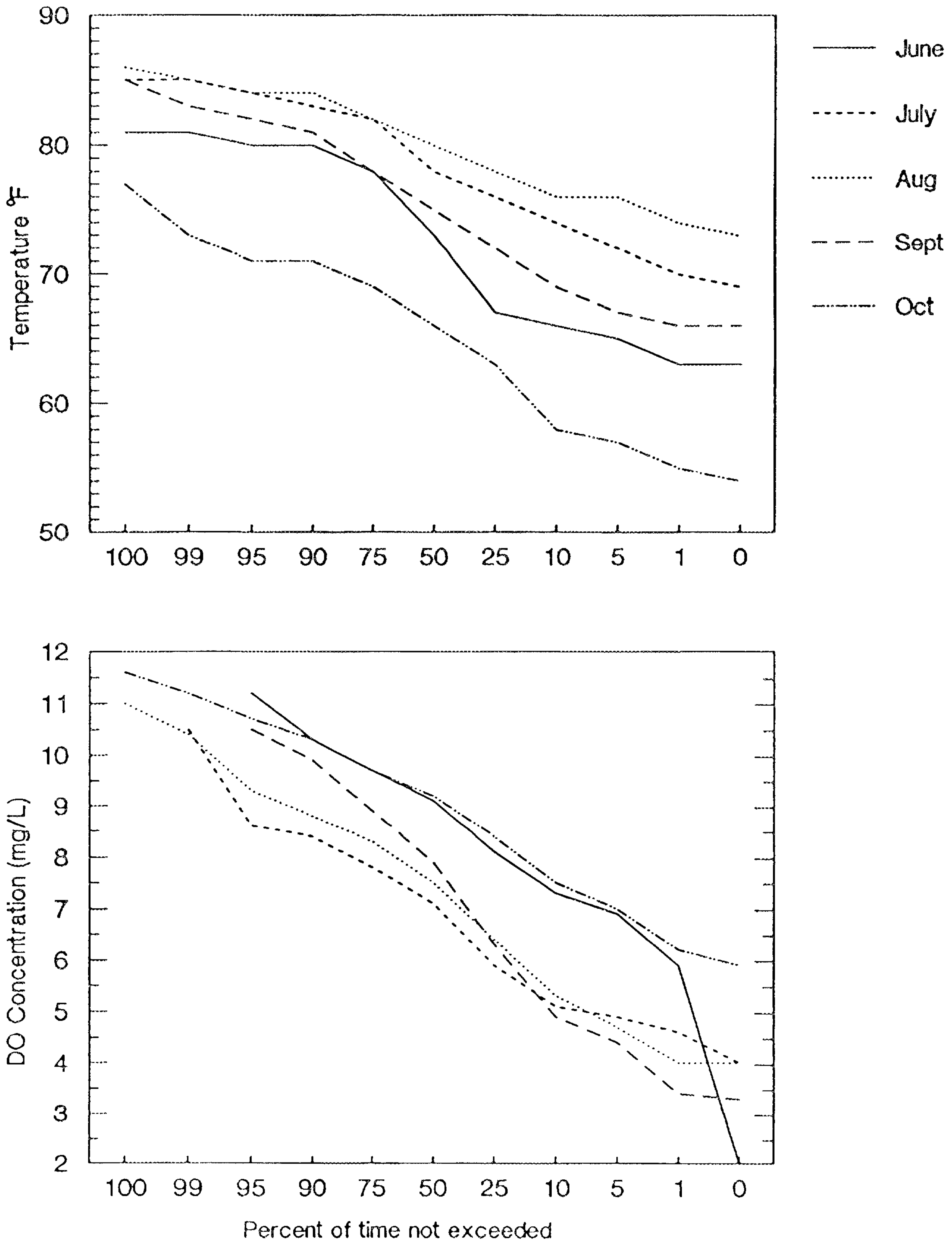

Fig. 6. Monongahela River mile 4.5 summer temperature and DO duration curves (ORSANCO data from 1980-1986).

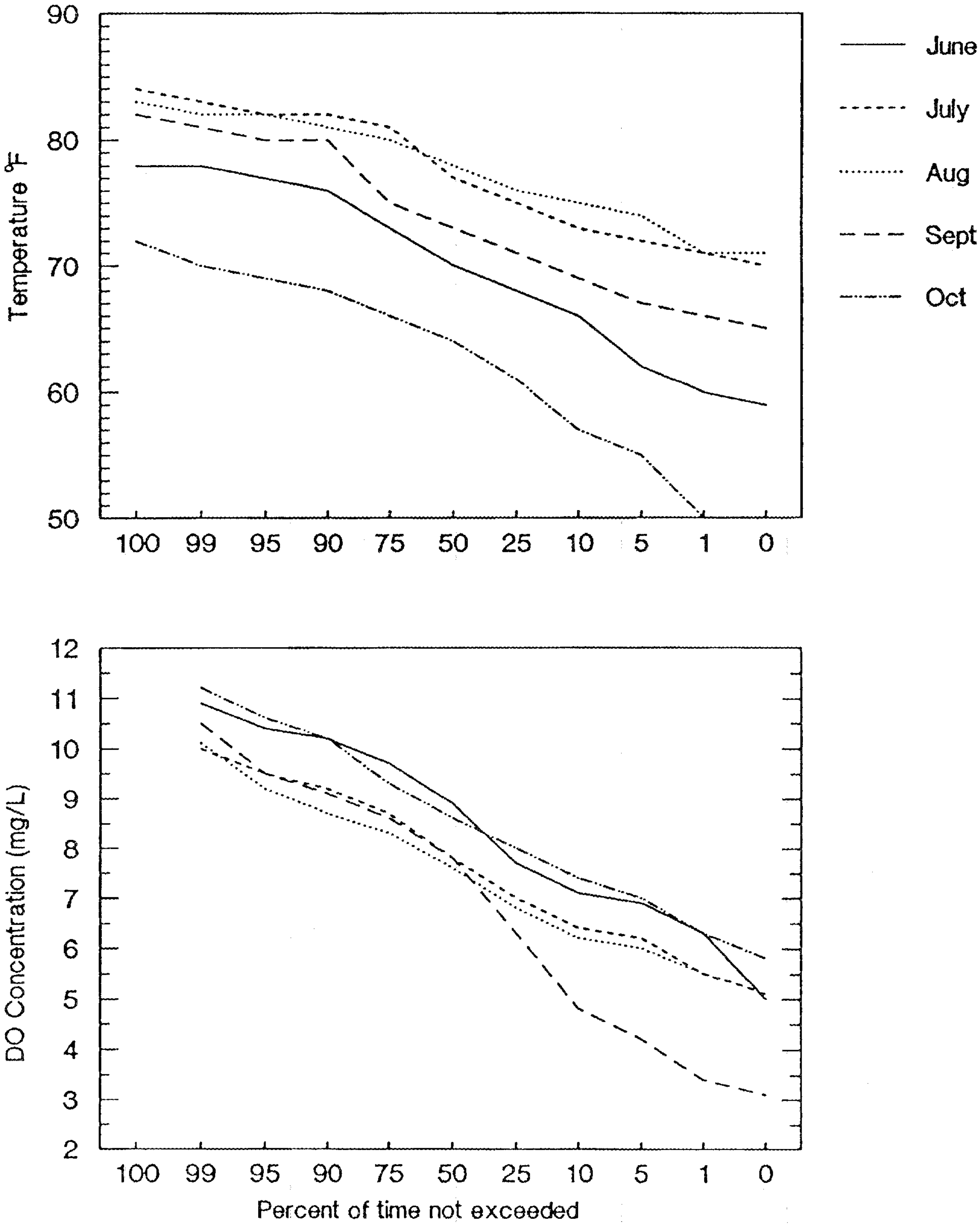

Fig. 7. Ohio River mile 15 temperature and DO duration curves (ORSANCO data from 1980-1986).

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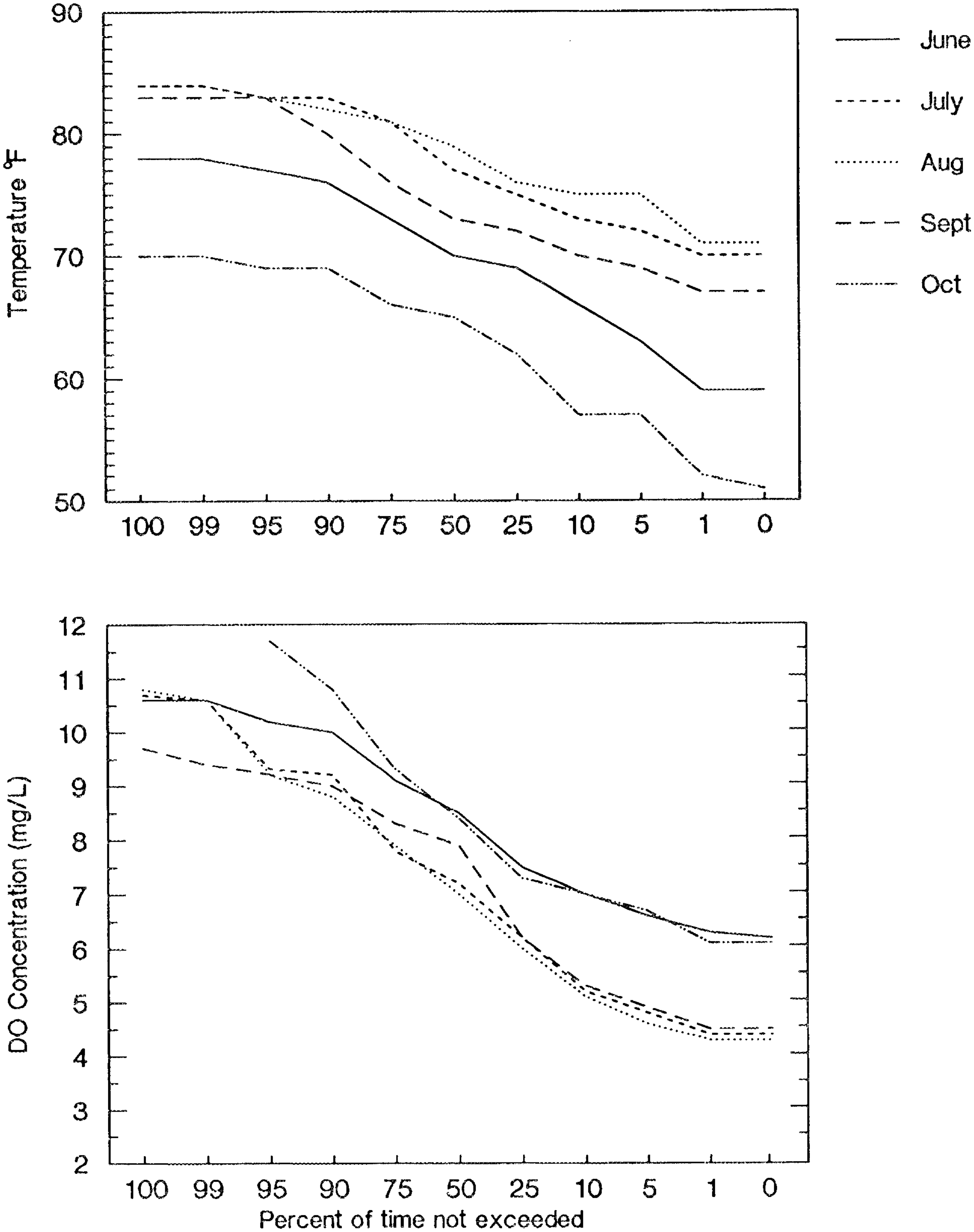

Fig. 8. Ohio River mile 40 temperature and DO duration curves (ORSANCO data from 1980-1986).

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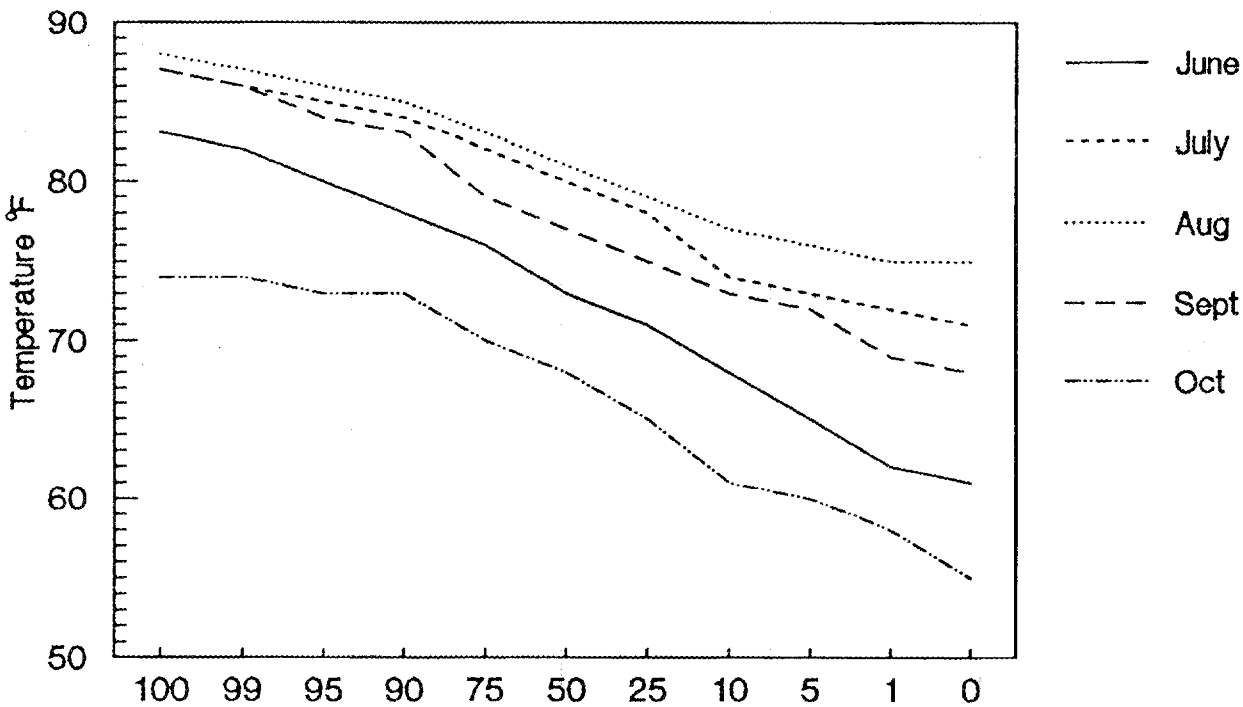

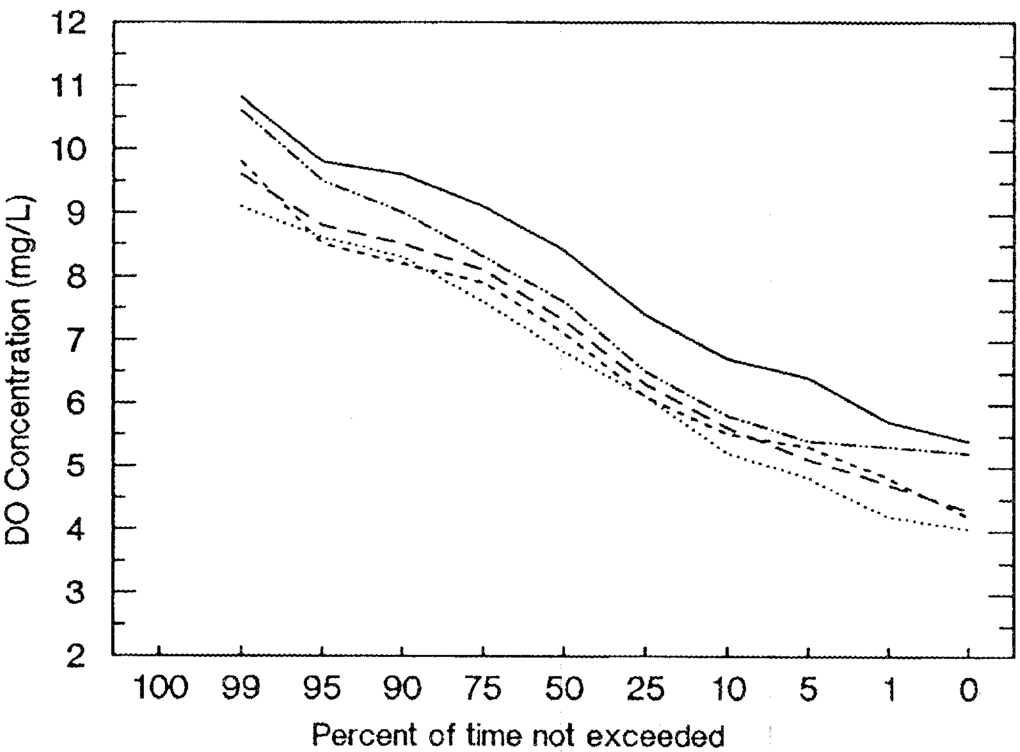

Fig. 9. Ohio River mile 102 temperature and DO duration curves (ORSANCO data from 1980-1986).

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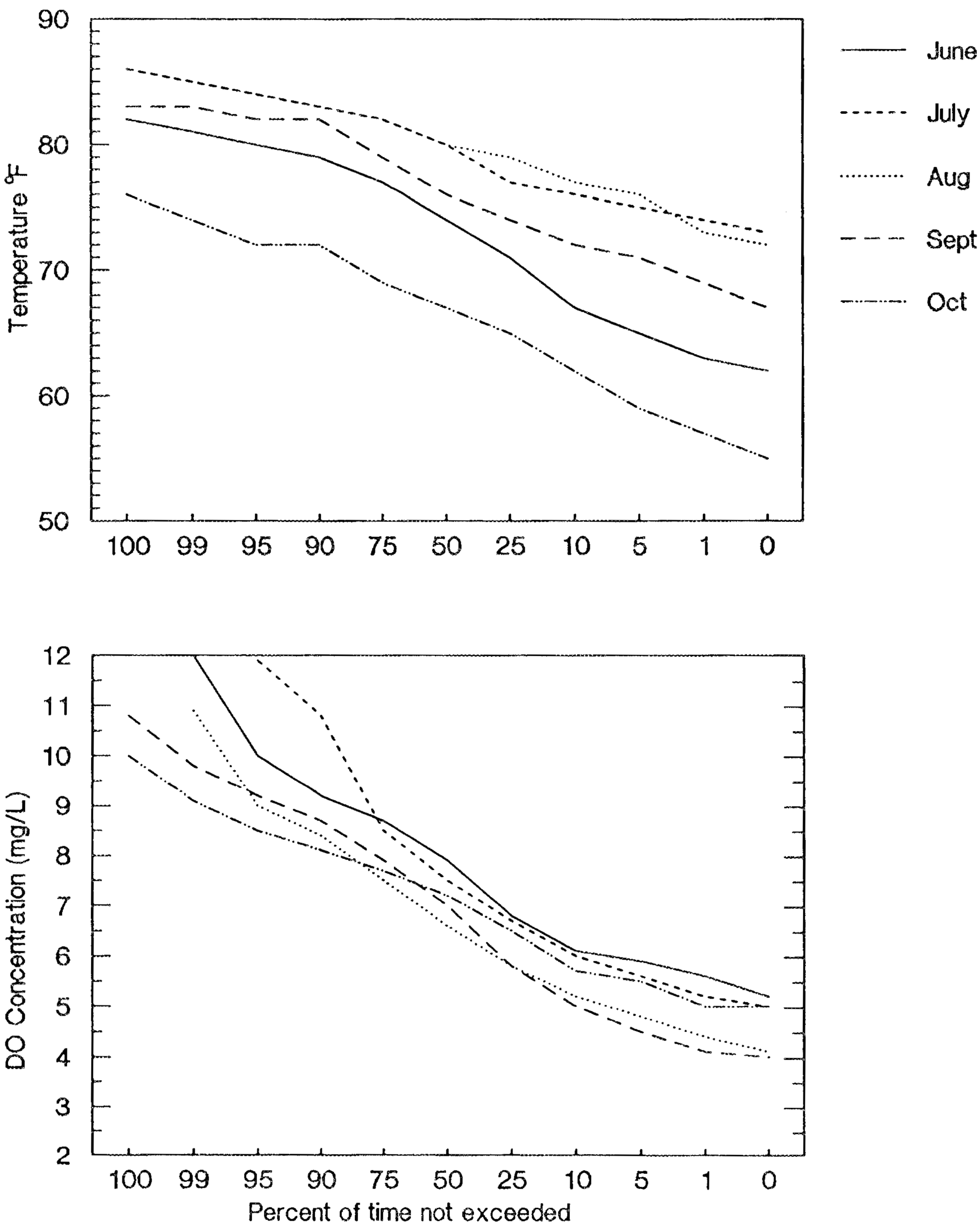

Fig. 10. Ohio River mile 260 temperature and DO duration curves (ORSANCO data from 1980-1986).

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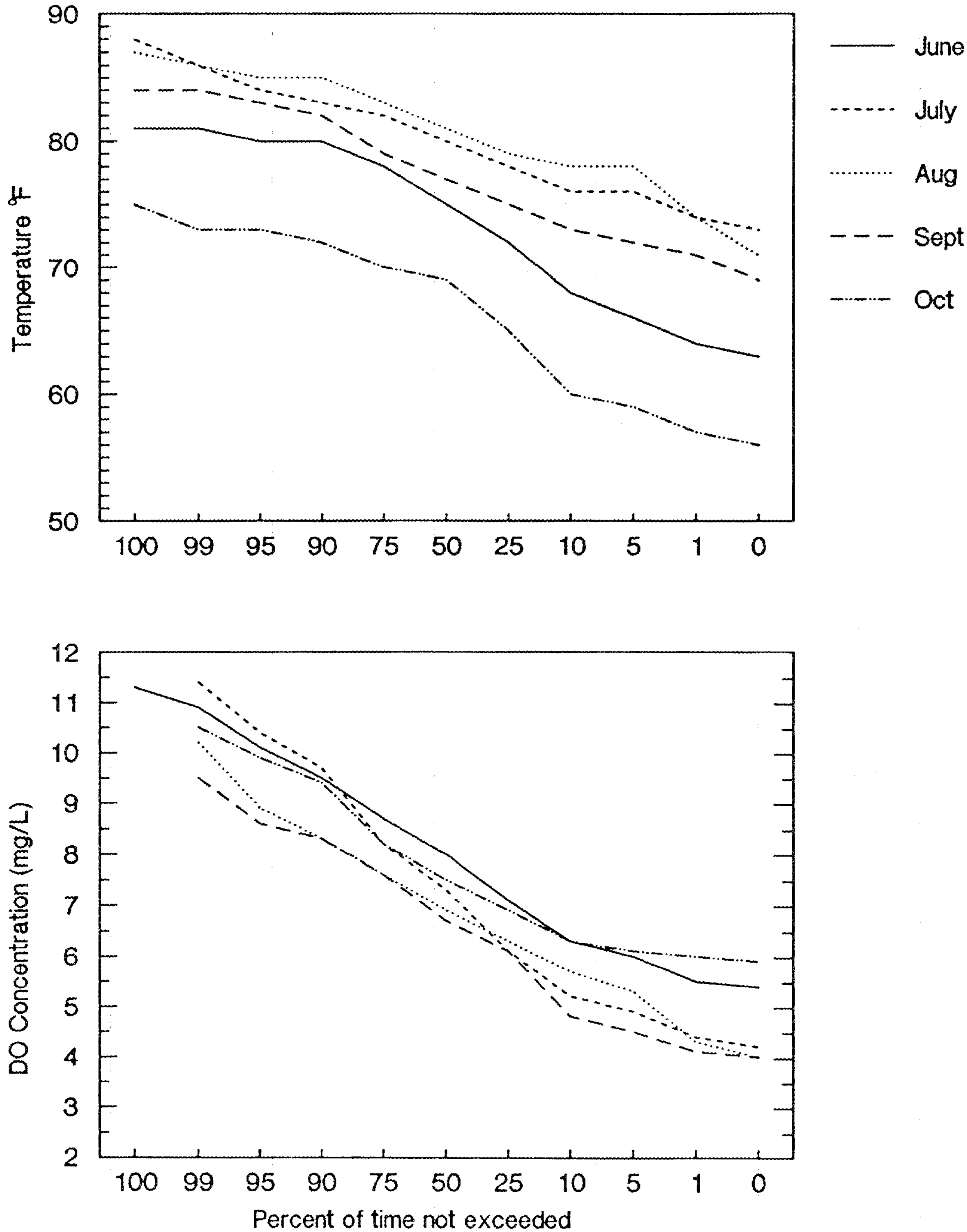

Fig. 11. Ohio River mile 279 temperature and DO duration curves (ORSANCO data from 1980-1986).

distributions). These distributions can be used to determine typical and extreme temperatures for July through October, the months with the highest temperatures. Monthly mean temperatures on the Allegheny and Monongahela rivers, as measured by the USGS, are listed in Table 3. The USGS values are based on far fewer observations than the ORSANCO data, so their uncertainty is higher.

The model results are sensitive to water temperature (Sect. 8.2.3); therefore, the temperatures should be selected carefully and the effects of varying temperature on the results should be investigated for all model applications.

3.4. BOD LOADINGS

BOD loading input values are in units of pounds per day of ultimate BOD. Values of BOD loadings from major industrial and municipal wastewater dischargers were obtained from the Environmental Protection Agency's Permit Compliance System data base and from wastewater permit files of the states of Pennsylvania, Ohio, and West Virginia. However, calibration of the model indicated that the major point source dischargers of BOD do not account for all of the BOD in the rivers. Non-point sources of BOD, such as decay of organisms, wastewater from illegal sewer connections to storm drains, and septic field runoff, appear to account for most of the oxygen demand. All oxygen demand is modeled by using point sources at the start of

Table 3. Mean monthly water temperatures for the Allegheny and Monongahela rivers

Month	Allegheny (Dam 7)	Monongahela (Dam 4)	Monongahela (Point Marion)
October	16	16	16
November	9.2	11	9.2
December	3.7	6.1	3.9
January	2.2	4.6	2.3
February	2.5	5.0	3.3
March	4.0	5.9	5.7
April	8.8	11	11
May	15	17	16
June	21	22	21
July	24	25	24
August	24	24	24
September	22	22	21

Source: USGS, WATSTORE data base.

each reach, so large values of BOD loading must be input at the start of most reaches to simulate the non-point source loads. The values used for the EIS analyses were determined from calibration of the model. ORSANCO monitoring data indicate that the sum of the 5-d BOD plus the estimated nitrogenous BOD (an estimate of the ultimate BOD) in the Ohio River and tributaries averages around 2-3 mg/L in summer.

3.5. BOD DECAY RATE COEFFICIENT

No measured values of the BOD rate decay coefficient k_1 were found for the Ohio River system. The biggest municipal wastewater discharger in the system, ALCOSAN, has not measured k_1 for its effluent. However, a measured value for any particular discharger would not necessarily be valid for use in the model because most of the BOD does not appear to come from point-source wastewater dischargers. Typical values for k_1 that include sediment BOD (as k_1 in this model does) in deep rivers range between 0.08 and 0.5 (USEPA 1985, p. 147). Calibration of the model to measured data is recommended for estimating k_1.

3.6. OTHER PARAMETERS

The channel cross-sectional area and depth for each reach were determined from cross sections measured by the Corps. The values were averaged over the length and width of the reach, with the navigation pools at normal elevation. (The normal elevations were determined from Corps navigation charts.) A FORTRAN program was written at ORNL that, for any starting and ending river miles and pool elevation, (1) searches a file containing the Corps' cross-sectional data to find the cross sections between the specified river miles; (2) determines the cross-sectional area and average depth for each such cross section; and (3) determines the average cross-sectional area and depth, weighted by river mile between cross sections, for the reach.

The dam aeration coefficients and constants were determined by using statistical analyses of field data (Railsback et al. 1988a, 1988b). In some cases the dam aeration parameters are different in the sample data set (sample input file, columns 9 and 10, Sect. 6.1) than in Railsback et al. (1988a and 1988b) because the data have been analyzed for different purposes. The values in Table 5 are recommended. For reaches that do not start with a dam, the value of the dam aeration coefficient β must be set to 1, and the value of the dam aeration constant α must be set to zero to ensure that no aeration is modeled.

It is recommended that the starting DO concentration in the Monongahela River be set approximately equal to saturation. The starting point of the Monongahela River model is Tygart Dam, which discharges water at or near DO saturation. The starting DO concentration in the Allegheny River, above dam 9, is estimated from Corps data collected in 1983. The starting BOD concentrations in the Allegheny and Monongahela were estimated from calibration, since sufficient data are not available. The model results, especially for the Allegheny River between dam 9 and dam 5, are sensitive to starting (initial) DO concentrations (Sect. 8.2.3). The starting DO concentration in the Allegheny should be selected carefully, and the effects of varying starting DO concentrations should be investigated for all model applications.

4. OUTPUT VALUES

The FORTRAN model implementation produces an output table resembling the spreadsheet models, so the two implementations produce outputs in similar formats. Table 4 is a sample spreadsheet for the Allegheny River, with parameters and results for the design conditions used in the EIS with the hydropower projects as proposed by the applicants. The model determines three DO concentrations for each reach. The output parameter "starting DO" is the DO concentration at the beginning of a reach; this value includes the effects of dam aeration and tributary inflows if the reach starts with a dam or a tributary. The output parameter "final DO" is the DO concentration at the downstream end of the reach. The output parameter "critical DO" is the lowest DO concentration in the reach, which may occur at the beginning or end of the reach or at some intermediate location. The parameter "critical distance" is the river mile where the lowest DO concentration in the reach occurs.

The spreadsheet implementation of the model includes an output variable "DO index," which may be of use in comparing DO impacts of alternative hydropower development schemes. The parameter is the integral of the DO concentration over distance through the reach. A sum of the DO indexes for all reaches is calculated at the right side of the spreadsheet. The DO index can be used to compare the total amount of DO in the river under various conditions and hydropower scenarios.

Table 4. Sample spreadsheet

Allegheny Model, with hydro
Design conditions

Reach	Allegheny 9	Allegheny 8	Allegheny 7	All 6	All 5
River mile	62.20	52.60	45.7	36.3	30.4
Reach length	50688	36432	49632	31152	2112
Trib Q	0	0	0	0	0
Flow, cfs	5850	5850	5850	5850	5850
X-Sect. area	13700	10100	11200	13000	12300
depth, ft	15.00	11.00	11.00	15.00	14.00
Velocity	0.43	0.58	0.52	0.45	0.48
Travel time, d	1.37	0.73	1.10	0.80	0.05
Trib DO	0.00	0.00	0.00	0.00	0.00
Trib BOD	0.00	0.00	0.00	0.00	0.00
BOD loading, #/	4000.00	4000.00	4000.00	4000.00	4000.00
Dam aer coef	0.58	0.61	0.90	0.69	0.57
Dam aer const	0.00	0.62	0.00	0.00	0.00
Flow not aerat	3600.00	3600.00	5450.00	4850.00	4680.00
DO above dam	6.00	6.13	6.37	6.12	5.99
Starting BOD	4.00	3.49	3.01	2.35	2.01
Reach temp.	25.00	26.00	27.00	27.00	27.00
DO Saturation	8.13	7.97	7.81	7.81	7.81
k1 (20 deg)	0.1000	0.2000	0.2000	0.2000	0.1000
k2 (20 deg)	0.1451	0.2691	0.2555	0.1490	0.1698
k1 (T)	0.1258	0.2635	0.2758	0.2758	0.1379
k2 (T)	0.1634	0.3103	0.3017	0.1759	0.2005
Initial defici	1.78	1.32	1.43	1.60	1.67
Final deficit	1.99	1.60	1.69	1.82	1.66
Starting DO	6.34	6.65	6.38	6.21	6.14
Final DO	6.13	6.37	6.12	5.99	6.15
Final BOD	3.37	2.88	2.22	1.88	1.99
Crit. time, ra	3.16	2.01	1.70	2.29	-1.57
Crit. time, in	3.16	2.01	1.70	2.29	0.00
Crit. time, fi	1.37	0.73	1.10	0.80	0.00
Crit. Def.,raw	2.07	1.75	1.72	1.96	1.72
Crit. def., in	2.07	1.75	1.72	1.96	1.67
Crit. def., fi	1.99	1.60	1.69	1.82	1.67
Crit. DO	6.13	6.37	6.12	5.99	6.14
Crit. distance	52.6	45.7	36.3	30.4	30.4
DO index	3.65	2.74	3.58	2.19	0.15
	1	2	3	4	5

Table 4 (continued)

Reach	KiskiminetasAll 4		AllValleyJt All 3		AllValleyJt
River mile	30.0	24.2	21.2	14.5	13.5
Reach length	30624	15840	35376	5280	35904
Trib Q	1690	0	0	0	0
Flow, cfs	7540	7540	7540	7540	7540
X-Sect. area	12300	12300	18600	15900	15900
depth,ft	14.00	14.00	26.00	15.00	15.00
Velocity	0.61	0.61	0.41	0.47	0.47
Travel time, d	0.58	0.30	1.01	0.13	0.88
Trib DO	6.00	0.00	0.00	0.00	0.00
Trib BOD	5.00	0.00	0.00	0.00	0.00
BOD loading,#/	0.00	0.00	1500.00	0.00	1000.00
Dam aer coef	1.00	0.56	1.00	0.92	1.00
Dam aer const	0.00	0.00	0.00	0.67	0.00
Flow not aerat	0.00	7140.00	0.00	7240.00	0.00
DO above dam	6.11	6.13	6.18	6.00	6.03
Starting BOD	2.67	2.46	2.40	2.09	2.07
Reach temp.	27.00	27.00	27.00	28.00	28.00
DO Saturation	7.81	7.81	7.81	7.66	7.66
k1 (20 deg)	0.1000	0.1000	0.1000	0.1000	0.1000
k2 (20 deg)	0.1928	0.1928	0.0620	0.1529	0.1529
k1 (T)	0.1379	0.1379	0.1379	0.1444	0.1444
k2 (T)	0.2276	0.2276	0.0731	0.1849	0.1849
Initial defici	1.70	1.64	1.63	1.63	1.63
Final deficit	1.68	1.63	1.81	1.63	1.61
Starting DO	6.11	6.17	6.18	6.03	6.03
Final DO	6.13	6.18	6.00	6.03	6.05
Final BOD	2.46	2.36	2.09	2.05	1.83
Crit. time, ra	-0.37	-0.74	5.52	0.01	-0.04
Crit. time, in	0.00	0.00	5.52	0.01	0.00
Crit. time, fi	0.00	0.00	1.01	0.01	0.00
Crit. Def.,raw	1.70	1.65	2.11	1.63	1.63
Crit. def., in	1.70	1.64	2.11	1.63	1.63
Crit. def., fi	1.70	1.64	1.81	1.63	1.63
Crit. DO	6.11	6.17	6.00	6.03	6.03
Crit. distance	30.0	24.2	14.5	14.4	13.5
DO index	2.17	1.13	2.49	0.37	2.51
	6	7	8	9	10

Table 4 (continued)

Reach	All 2	Confluence
River mile	6.7	0.0
Reach length	35376	0
Trib Q	0	0
Flow, cfs	7540	7540
X-Sect. area	13700	13700
depth,ft	15.00	15.00
Velocity	0.55	0.55
Travel time, d	0.74	0.00
Trib DO	0.00	0.00
Trib BOD	0.00	0.00
BOD loading,#/	0.00	0.00
Dam aer coef	0.12	1.00
Dam aer const	0.92	0.00
Flow not aerat	6640.00	0.00
DO above dam	6.05	6.34
Starting BOD	1.83	1.64
Reach temp.	28.00	28.00
DO Saturation	7.66	7.66
k1 (20 deg)	0.1000	0.1000
k2 (20 deg)	0.1647	0.1647
k1 (T)	0.1444	0.1444
k2 (T)	0.1991	0.1991
Initial defici	1.33	1.32
Final deficit	1.32	1.32
Starting DO	6.33	6.34
Final DO	6.34	6.34
Final BOD	1.64	1.64
Crit. time, ra	-0.04	-0.79
Crit. time, in	0.00	0.00
Crit. time, fi	0.00	0.00
Crit. Def.,raw	1.33	1.33
Crit. def., in	1.33	1.32
Crit. def., fi	1.33	1.32
Crit. DO	6.33	6.34
Crit. distance	6.7	0.0
DO index	2.59	0.00
	11	12

5. DESIGN CONDITIONS USED FOR ASSESSMENT

A set of design conditions was developed for the DO analyses used in the EIS. These conditions were selected to approximate those when impacts of hydropower generation would be most severe (FERC 1988; Railsback et al. 1988a). The design conditions are described here so they can be reproduced or modified for additional assessments.

5.1. FLOWS

The design river flows are approximately the lowest flows at which all the proposed hydropower projects would operate. (The river flow must be higher than the minimum generating flow of the proposed turbines, plus any spill and lockage flows.) The proposed projects all would operate at 2.6 times the 7Q10 flows, except on the upper Monongahela River where the 7Q10 flows are very low. The design flows are approximately 2.6 times the 7Q10, except that the discharge from Tygart Lake is higher to allow operation of the projects on the upper Monongahela River. The design flows (starting flows at Allegheny 9 and Tygart dams, and tributary flows) are listed in the sample input file, column 3 (Sect. 6.1).

5.2. TEMPERATURES

The temperatures used for design conditions are those exceeded only 10% of the time in August, as determined from the ORSANCO electronic monitors. In the Allegheny and Monongahela rivers, the temperature exceeded only 10% of the time in August at the ORSANCO monitors above Point Pittsburgh (at RM 13.3 on the Allegheny and RM 4.5 on the Monongahela) is 28^{o}C. When the Corps water quality survey was conducted in 1983, the temperature at these monitors was 28^{o}C, so the temperatures measured by the Corps in 1983 were used for the other reaches upstream of Pittsburgh. In the Ohio River, the temperatures exceeded 10% of the time at the ORSANCO monitors are 28^{o}C at RM 15, 29^{o}C at RM 102, 28^{o}C at RM 260, and 29^{o}C at RM 279 (Table 5, column 12, Sect. 6.1).

5.3. BOD LOADS

To the extent possible, measured values of BOD discharged by major wastewater plants were obtained from state agencies and used in the model; however, calibration indicated that major point-source dischargers that monitor effluent BOD do not contribute enough oxygen demand to reproduce the observed conditions (Section 3.4). BOD loadings that simulate non-point source loads for each reach were estimated by calibration to conditions measured by the Corps in 1983 (sample input file, column 8, Sect. 6.1).

5.4. TRIBUTARY DO AND BOD

Few data are available on DO and BOD concentrations in tributaries. To reduce the effects of tributaries on model results, the tributary DO and BOD concentrations were generally set approximately equal to the concentrations occurring in the main rivers (sample input file, columns 6 and 7, Sect. 6.1). The DO concentration in the Youghigheny River was reduced to match conditions during the 1983 calibration period.

5.5. BOD DECAY RATE COEFFICIENT

The BOD decay rate coefficient k_1 was determined through calibration to 1983 data (Sect. 3.5). The values obtained were relatively constant throughout a river. The design condition values of k_1 are generally 0.18 in the Allegheny and Monongahela rivers and 0.10 in the Ohio River (sample input file, column 13, Sect. 6.1). Typical values for k_1 that include sediment BOD (as does k_1 in this model) in deep rivers range between 0.08 and 0.5 (USEPA 1985, p. 147).

6. FORTRAN IMPLEMENTATION

The Ohio River basin DO model is implemented as a FORTRAN program that executes, or can be modified to execute, on any machine with a FORTRAN compiler. A version compiled for IBM-compatible personal computers has been provided to FERC; the source code for this version uses 4.01 (or a later version) of the Microsoft FORTRAN 77 compiler. The FORTRAN implementation is recommended for routine use when the model structure does not need to be modified. The model reads input from a file and writes output to the computer screen and to files which can be used for graphics. A listing of the program is found in Appendix A.

6.1. INPUT FILE AND PARAMETERS

The input file must be named ORMDL.DAT and must reside in the same disk drive and directory as the program. An example of the input file (with input for the design conditions used for the assessment) is presented as Table 5. (Table 6 provides definitions of abbreviated reach names used in Table 5.) Section 3 describes how input values can be determined, and Sect. 5 describes the input used (in Table 5) for the design conditions in the EIS.

The file starts with a line containing the flag variable QTYPE that indicates whether the flow variable at navigation dams is the flow not aerated or a spill flow (Sect. 6.1.11). If QTYPE is set to 1, the dam flow variable QGEN for each reach is the flow

Table 5. Sample input file with parameters for design conditions with hydropower as proposed by applicants

```
QTYPE      1        (QTYPE = 1 FOR FLOW NOT AERATED; =0 FOR SPILL FLOW)
NRAGY     11
NRMON     18
NROHIO    24
IDOAGY    6.0
IDOMON    8.0
ILAGY     4.0
ILMON     5.0
IQAGY     5850
IQMON     1750
1    2    3      4       5   6    7    8     9      10     11      12    13   14
Reach RM     TribQ  XSEC Dpth Trib Trib BOD      DAM    DAM    QGEN/  T   k1    k2
                             DO   BOD  Load     coef   cnst   Spill
1234567891123456789212345678931234567894123456789512345678961234567897123456789O
All 9   62.2      0  13700  15  0.0  0.0      0  0.58   0.00    3600  25 0.10 0.000
All 8   52.6      0  10100  11  0.0  0.0   4000  0.61   0.62    3600  26 0.20 0.000
All 7   45.7      0  11200  11  0.0  0.0   4000  0.90   0.00    5450  27 0.20 0.000
All 6   36.3      0  13000  15  0.0  0.0   4000  0.69   0.00    4850  27 0.20 0.000
All 5   30.4      0  12300  14  0.0  0.0   4000  0.57   0.00    4680  27 0.10 0.000
Kiski   30.0   1690  12300  14  6.0  5.0      0  1.00   0.00       0  27 0.10 0.000
All 4   24.2      0  12300  14  0.0  0.0      0  0.56   0.00    7140  27 0.10 0.000
AVJt    21.2      0  18600  26  0.0  0.0   1500  1.00   0.00       0  27 0.10 0.000
All 3   14.5      0  15900  15  0.0  0.0      0  0.92   0.67    7240  28 0.10 0.000
AVJt    13.5      0  15900  15  0.0  0.0   1000  1.00   0.00       0  28 0.10 0.000
All 2    6.7      0  13700  15  0.0  0.0      0  0.12   0.92    6640  28 0.10 0.000
T Dam  151.4      0   2900   6  0.0  0.0      0  1.00   0.00       0  24 0.15 0.000
HdNav  131.5      0   5000  15  9.0  0.0   2000  1.00   0.00       026.5 0.10 0.005
W.Fk   128.7     40   9000  18  8.0  0.0   4000  1.00   0.00       026.5 0.10 0.005
Ope    115.4      0   8550  19  0.0  0.0   4000  1.00   0.00    1475  26 0.10 0.000
Hild   108.0      0   8600  17  0.0  0.0   4000  0.32  -0.10    1475  26 0.10 0.000
C.Mrg  105.5      0   8600  17  0.0  0.0   4000  1.00   0.00       0  26 0.10 0.000
Morg   102.0      0   8400  17  0.0  0.0      0  0.65   0.21    147526.5 0.10 0.000
PM      90.8      0   4700  10  0.0  0.0   4000  0.40   0.64    1595  27 0.10 0.000
Cheat   89.6    730   8600  14  6.0  5.0   4000  1.00   0.00       0  27 0.10 0.000
Mon 7   85.0      0  10900  16  6.0  5.0   4000  0.36   0.07      86  27 0.10 0.000
Max     61.2    105  11300  16  7.0  2.0   5000  0.69   0.22    2625  27 0.10 0.000
Mon 4   41.5     80   7700  10  7.0  0.0   6000  0.61   0.18    2255  27 0.10 0.000
Mon 3   23.8      0   7200  10  7.0  0.0   5000  0.81  -0.14      80  32 0.10 0.000
PA4472  21.8      0   9450   9  0.0  0.0   2000  1.00   0.00       0  32 0.10 0.000
P26913  17.3      0   7900  11  0.0  0.0   2000  1.00   0.00       0  31 0.10 0.000
Yough   15.5   3120  10600  13  7.0  2.0   2000  1.00   0.00       0  30 0.10 0.000
Mon 2   11.2      0   8300  10  0.0  0.0   2000  0.93   0.20     100  29 0.10 0.000
PA4481   7.6      0  11800  12  0.0  0.0   2000  1.00   0.00       0  29 0.20 0.000
Conf     0.0      0  20000  20  5.9  .74      0  1.00   0.00       027.8 0.18 0.000
ALCOS    3.1      0  23000  19  0.0  0.0 193000  1.00   0.00       027.7 0.18 0.000
Ems      6.2      0  17000  15  0.0  0.0      0  0.64   0.12    947027.6 0.18 0.000
Dash    13.3      0  21000  17  0.0  0.0      0  0.72   0.67   1240027.6 0.18 0.000
LTV     22.4      0  30000  23  0.0  0.0   5000  1.00   0.00       027.5 0.18 0.000
```

Table 5 (continued)

Beavr	25.4	2860	33000	25	6.0	2.0	0	1.00	0.00	027.3	0.18	0.000
Mont	31.7	0	29000	22	0.0	0.0	20000	0.78	0.61	1521027.5	0.18	0.000
New C	54.4	0	17000	14	0.0	0.0	20000	0.38	0.50	16260 29	0.18	0.000
Weirt	62.5	0	30500	23	5.0	10.0	20000	1.00	0.00	0 29	0.18	0.000
PikeI	84.2	0	14000	14	0.0	0.0	20000	0.72	0.23	16260 29	0.18	0.000
RM100	100.0	0	30000	26	0.0	0.0	20000	1.00	0.00	028.5	0.18	0.000
Hann	126.4	0	19000	17	0.0	0.0	30000	0.89	0.28	1626028.6	0.18	0.000
RM140	140.0	0	33500	23	0.0	0.0	30000	1.00	0.00	028.6	0.18	0.000
W I	161.7	0	13000	12	0.0	0.0	30000	0.97	0.17	1626028.6	0.18	0.000
Musk	172.0	1660	26000	19	7.0	2.0	30000	1.00	0.00	028.6	0.18	0.000
L Kan	184.6	0	33000	27	6.0	3.0	30000	1.00	0.00	028.6	0.18	0.000
duPnt	196.8	0	33000	27	0.0	0.0	30000	1.00	0.00	028.6	0.18	0.000
HockR	199.3	520	42000	33	6.0	3.0	30000	1.00	0.00	028.6	0.18	0.000
Bell	203.9	0	31000	24	0.0	0.0	30000	0.89	0.00	1845428.6	0.18	0.000
Racin	237.5	0	25000	24	0.0	0.0	30000	1.00	0.00	1845428.6	0.18	0.000
Kan R	265.7	5700	38000	26	6.0	3.0	0	1.00	0.00	028.6	0.18	0.000
Galli	279.2	0	35000	25	0.0	0.0	20000	0.84	0.08	2325428.6	0.18	0.000
Hntng	308.3	0	35000	25	2.0	50.0	0	1.00	0.00	028.6	0.18	0.000
Grnup	341.0	0	35000	25	0.0	0.0	0	1.00	0.00	028.6	0.18	0.000

Table 6. Model Reach Names and Starting River Miles

Abbreviation (in Table 5)	River mile	Reach description
		Allegheny River
All 9	62.2	Allegheny River dam 9
All 8	52.6	Allegheny River dam 8
All 7	45.7	Allegheny River dam 7
All 6	36.3	Allegheny River dam 6
All 5	30.4	Allegheny River dam 5
Kiski	30.0	Kiskiminetas River
All 4	24.2	Allegheny River dam 4
AVJt	21.2	Allegheny Valley Joint Sanitary wastewater plant
All 3	14.5	Allegheny River dam 3
AVJt	13.5	Allegheny Valley Joint Sanitary wastewater plant
All 2	6.7	Allegheny River dam 2
		Monongahela River
T Dam	151.4	Tygart Dam, on the Tygart River
HdNav	131.5	Head of navigation, Tygart River
W.Fk	128.7	West Fork River
Ope	115.4	Opekiska Dam
Hild	108.0	Hildebrand Dam
C.Mrg	105.5	City of Morgantown wastewater plant
Morg	102.0	Morgantown Dam
PM	90.8	Point Marion Dam
Cheat	89.6	Cheat River
Mon 7	85.0	Monongahela dam 7
Max	61.2	Maxwell Dam
Mon 4	41.5	Monongahela dam 4
Mon 3	23.8	Monongahela dam 3
PA4472	21.8	Wastewater discharge permit PA4472
P26913	17.3	Wastewater discharge permit PA26913
Yough	15.5	Youghiogheny River
Mon 2	11.2	Monongahela dam 2
PA4481	7.6	Wastewater discharge permit PA4481

Table 6 (continued)

Abbreviation (in Table 5)	River mile	Reach description
		Ohio River
Conf	0.0	Confluence of Allegheny and Monongahela
ALCOS	3.1	ALCOSAN wastewater plant
Ems	6.2	Emsworth Dam
Dash	13.3	Dashields Dam
LTV	22.4	LTV Steel wastewater plant
Beavr	25.4	Beaver River
Mont	31.7	Montgomery Dam
New C	54.4	New Cumberland Dam
Weirt	62.5	Weirton Steel wastewater plant
PikeI	84.2	Pike Island Dam
RM100	100.0	intermediate reach at RM 100
Hann	126.4	Hannibal Dam
RM140	140.0	intermediate reach at RM 140
W I	161.7	Willow Island Dam
Musk	172.0	Muskingum River
L Kan	184.6	Little Kanawha River
duPnt	196.8	Du Pont wastewater plant
HockR	199.3	Hocking River
Bell	203.9	Belleville Dam
Racin	237.5	Racine Dam
Kan R	265.7	Kanawha River
Galli	279.2	Gallipolis Dam
Hntng	308.3	City of Huntington wastewater plant
Grnup	341.0	Greenup Dam

not aerated (the flow used for hydropower generation and lockage). If QTYPE is set to zero, the dam flow variable QGEN for each reach is the required spill flow (the flow that passes over the dam). It is assumed that all flow not passing over the dams is used for hydropower generation and lockage. When spill flows are used, care must be taken to ensure that the resulting generating flows (the total river flow minus the spill flow) are greater than the minimum flow required for generation; otherwise, hydropower will be simulated under conditions where it would not actually occur due to insufficient flow.

The next nine lines of the input file contain the following initial conditions: the number of reaches in the Allegheny (line 2), Monongahela (line 3), and Ohio (line 4) rivers; the initial DO concentrations in the Allegheny (line 5) and Monongahela (line 6) rivers; the initial BOD concentrations in the Allegheny (line 7) and Monongahela (line 8) rivers; and the initial flow rates in the Allegheny (line 9) and Monongahela (line 10) rivers. These values should start in column 9.

After four title lines that the program ignores, the parameters for each reach are listed (one line per reach). The values on each line must be in the proper columns. It is recommended that the sample input file be used as a template for new runs. In the sample input file, all parameters except the reach name are right justified in the proper columns. The input parameters are as follows:

1. Reach name (columns 1-6). (Refer to Table 6 for definitions.)

2. River mile at the start of the reach (columns 7-11). River miles are measured from the confluence of the Allegheny and Monongahela at Pittsburgh (decreasing with downstream distance on the Allegheny and Monongahela and increasing with downstream distance on the Ohio).

3. Tributary inflow, in cubic feet per second (columns 12-18).

4. Average cross-sectional area, in square feet (columns 19-25).

5. Average depth, in feet (columns 26-29).

6. Tributary DO concentration, in milligrams per liter (columns 30-34).

7. Tributary BOD concentration, in milligrams per liter (columns 35-39).

8. Point-source BOD loading, in pounds per day (columns 40-46).

9. Dam aeration coefficient, dimensionless (columns 47-52). If the reach does not start with a dam, the value of this parameter must equal 1.

10. Dam aeration constant, in milligrams per liter (columns 53-58). If the reach does not start with a dam, the value of this parameter must be zero.

11. Flow not aerated, or spill flow, in cubic feet per second (columns 59-65). This is the flow used for hydropower generation and lockage, or the spill flow, depending on the value of the flag variable in the first line of the file. If the flag variable is equal to 1, then this is the flow not aerated. If the flag variable is equal to 0, then this is the required spill flow and the model assumes that all flow except the spill flow is not aerated. If a change is made from using the flow not aerated to using the spill flow as input, the value of this parameter must be changed for all dams in the model. If the reach does not start with a dam, the value should be set to zero.

12. Water temperature, in degrees Celsius (columns 66-69).

13. BOD decay rate coefficient k_1, per day (columns 70-74).

14. Water surface reaeration rate coefficient k_2, per day (columns 75-80). If a zero is entered, the program calculates k_2 from the O'Connor-Dobbins equation.

6.2. OUTPUT FILES

The FORTRAN program writes an output table that resembles the spreadsheet version of the model. The values in the output table are calculated in the same way as those in the spreadsheet. (Section 7 explains how each of these values is determined.) The program also writes three output files that are designed to be imported into Lotus 1-2-3 or other programs for plotting. The files are ALLEGHNY.OUT, MONONGLA.OUT, and OHIO.OUT. Each file is a table of river miles and DO concentrations, from upstream to downstream, with one line per pair of river mile and DO values. There are three lines for each reach in the model; the lines contain river mile and DO concentration for the beginning of the reach (including DO from dam aeration or tributaries), the critical point (which may be the beginning of the reach, the end of the reach, or in between), and the end of the reach.

Examples of the FORTRAN model output table and files are provided in Appendix B.

6.3. PROGRAM EXECUTION

Obtaining new model results requires editing the input file and executing the program. New input parameters are entered by using a text editor or word processor to edit the input file, replacing old parameter values with new ones. The sample input file should be used as a template for changes.

The steps for executing the model are as follows:

1. Have the copy of the input file ORMDL.DAT in the same disk drive and directory as the program OHIOMDL.EXE. Previous versions of the input file can be saved by giving them other names or by storing them in a different drive or directory.

2. If any existing versions of the output files ALLEGHNY.OUT, MONONGLA.OUT, or OHIO.OUT are to be saved, they must be renamed or moved to another drive or directory. The program automatically overwrites these files with new output.

3. Execute the model by typing **ohiomdl**. The program looks for the input file ORMDL.DAT and writes output for graphing to the files ALLEGHEN.OUT, MONONGAH.OUT, and OHIO.OUT. There is no interactive input to the program.

By default, the tabular output is sent to the computer screen. The tabular output can be routed to the printer by using the computer's Print Screen facility. (For example, pressing CTRL-PRINT SCREEN on an IBM personal computer sends everything that goes to the screen to the printer also until CTRL-PRINT SCREEN is pressed again.) On a computer using the DOS (IBM-compatible) operating system, the tabular output can be routed to the printer instead of to the screen by typing the command **ohiomdl > prn**. Also with DOS, the tabular output can be routed to a file by typing the command **ohiomdl > FILENAME**, which overwrites the file FILENAME with the new output, or by typing the command **ohiomdl >> FILENAME**, which appends the new output to the end of an existing file FILENAME.

The FORTRAN code for the DO model is listed in Appendix A. Appendix B is a sample output that was generated from the input file in Table 5.

7. SPREADSHEET IMPLEMENTATION

The DO model is also implemented on Lotus 1-2-3 spreadsheets that can be used with IBM-compatible personal computers. There are separate spreadsheets for the Allegheny, Monongahela, and Ohio rivers. Spreadsheets modeling individual scenarios for the same river can be saved separately and retrieved later. It is highly recommended that the models be used by persons experienced with Lotus 1-2-3 because several kinds of errors that are not readily detectable can be made. Such potential errors include having formulas that refer to incorrect cells for input values, overwriting formulas with values, and failing to recalculate the spreadsheet before using the results.

Each column of the spreadsheet models a river reach, with the reach defined by the feature (dam, discharger, tributary) at its upstream end. Each row of the spreadsheet is a model variable. Values for variables must be either entered into the spreadsheet as input or calculated from other variables. New variables for any additional model calculations can be added simply.

Graphic output is obtained with the graph routine in 1-2-3, which is programmed to produce a plot of DO concentration vs river mile.

New reaches can be added to the model by doing the following:

1. Type **/WIC** to insert a new column into the spreadsheet. The new column goes to the right of the reach that is to be divided into two reaches.

2. Type /C to copy the column from the left into the new blank column; however, if the column to the left is the first reach of the model, copy the column from the right instead. (The first reach is different from the others.)

3. For the row labeled "Reach Length," copy the value from the column to the right of the new column into the new column and into the column to the left of the new column.

4. For the rows labeled "Q" (reach discharge), "Starting DO," and "Starting BOD," copy the values from the new column into the column to the right of the new one.

However, if the new column will be the second reach in the model, for the three rows "Q" (reach discharge), "Starting DO," and "Starting BOD," copy the values from the column that is two columns to the right of the new one (the column which is now the fourth reach in the model) into the new column and into the column to the right of the new model.

Steps 3 and 4 are required because values in some rows are calculated using values from the columns to the right and left of the new one. These steps can be done automatically by invoking a 1-2-3 macro that is built into the spreadsheets, except when the new column is to be the first or second reach of the model. The macro is invoked by (1) placing the cursor at the top of the column to the right of where the new reach goes and then (2) pressing ALT-I. The new column and the columns to its left and right should be checked to make sure formulas contained in them reference the proper columns. (For example, make sure the formula calculating the flow rate uses the flow rate from the column to the immediate left, which represents the upstream reach.)

7.1. SPREADSHEET MODEL PARAMETERS

The spreadsheet model contains the same parameters and uses the same calculations as the FORTRAN implementation. Section 3 describes how input values can be determined, and Sect. 5 describes the input used for the design conditions in the EIS. The variables included in the spreadsheets are as follows:

Row 1. Reach name (input). This is the name of the feature (dam, discharger, or tributary) that defines the upstream end of the reach. Note that the reach name is not the same as the name of the navigation pool, which is named for the dam at the downstream end of the pool.

Row 2. River mile (input). This is the river mile of the upstream end of the reach, measured downstream from Pittsburgh on the Ohio and upstream from Pittsburgh for the Allegheny and Monongahela.

Row 3. Reach length (calculated). The length of the reach in feet. This value is calculated from the river mile of the reach and that of the downstream reach, so it does not have to be modified when new reaches are added.

Row 4. Tributary flow (input). The flow in cubic feet per second of a tributary at the head of the reach. A value of zero is used when no tributary is present.

Row 5. Flow in reach (calculated, except for the first reach in the spreadsheet where it is input). The flow in cubic feet per second for the reach, which is calculated from the upstream reach flow plus the tributary flow (Sect. 2.2).

Row 6. Cross-sectional area (input). The average cross-sectional area of the river in the reach, in square feet (Sect. 2.2).

Row 7. Depth (input). Average depth of the reach, in feet.

Row 8. Velocity (calculated). The average velocity of the reach in feet per second. The value is calculated as the flow divided by the cross-sectional area (Sect. 2.2).

Row 9. Travel time (calculated). The average time it takes water to travel the length of the reach, in days. The value is calculated by dividing the length of the reach by the velocity (Sect. 2.2).

Row 10. Tributary DO (input). The dissolved oxygen concentration of a tributary, if one exists, in milligrams per liter.

Row 11. Tributary BOD (input). The concentration of ultimate BOD in a tributary, if one exists, in milligrams per liter.

Row 12. BOD loading (input). The point-source (ultimate) BOD loading at the head of the reach, if any. The value should be input as pounds per day of ultimate BOD that enters the river at this point. The spreadsheet converts pounds per day to milligrams per liter by dividing pounds per day by the flow in cubic feet per second, and then multiplying by a units conversion factor of 0.185; the values in the "Starting BOD" row are converted in this manner.

Row 13. Dam aeration coefficient (input). The coefficient β in the linear dam aeration model. A value of 1.0 should be used if no dam is present (Sect. 2.5).

Row 14. Dam aeration constant (input). The constant α in the dam aeration model, in milligrams per liter. A value of zero should be used if no dam is present (Sect. 2.5).

Row 15. Flow not aerated (input). The flow rate in cubic feet per second (between zero and the total river flow) which does not pass over the dam or through the gates. This input variable is used to specify how much of the water is used for generation instead of aeration when the reach starts with a dam with hydropower. A default value of zero should be used when the reach does not start with a dam with hydropower, though the value does not affect results when the dam aeration coefficient is 1.0 and the dam aeration constant is zero. When a hydropower project is being modeled, the flow not aerated should include lockage and turbine flows. Leakage should not be included as flow not aerated, since effects of leakage on dam aeration are intrinsically included in the aeration coefficients (Sect. 2.6).

The spreadsheet can be modified as follows to calculate the flow not aerated from the spill flow for any particular dam. Instead of a numeric value, a formula that calculates the flow not aerated as the total river flow minus the spill flow should be entered in the row "flow not aerated." For example, there is a reach that starts with a dam in column G of the spreadsheet. The total river flow is in row 10, and the required spill flow at the dam is 1000 ft^3/s. The formula to type in the row for "flow not aerated" in column G is (G10-1000).

Row 16. DO above dam (calculated, except in the first reach of a spreadsheet, where it is input). The DO at the head of the reach, in milligrams per liter, not including dam aeration if the reach starts at a dam. This value is calculated as the average, weighted by flow rate, of the DO at the end of the upstream reach and in the tributary, if there is a tributary (Sect. 2.6).

Row 17. Starting BOD (calculated, except in the first reach of a spreadsheet, where it is input). The BOD at the beginning of the reach, in milligrams per liter. This value is calculated as the average, weighted by flow rate, of BOD at the end of the upstream reach and in the tributary, if there is a tributary, plus the BOD added as a point-source loading (Sect. 2.7).

Row 18. Reach temperature (input). The temperature in the reach, in degrees Celsius (Sect. 2.3).

Row 19. DO saturation (calculated). The saturation concentration of DO in the reach. The value is calculated using the ASCE equation, which is a third-order polynomial function of temperature (Sect. 2.4).

Row 20. k_1 at 20°C (input). The BOD decay rate at 20°C, per day (Sect. 2.10).

Row 21. k_2 at 20°C (calculated or input). The stream reaeration rate at 20°C per day. The O'Connor and Dobbins (1958) equation is used to estimate k_2 as a function of depth and velocity (Sect. 2.11), unless the formula in the spreadsheet for this equation is overwritten with a value.

Row 22. $k_1(T)$ (calculated). The BOD decay rate adjusted to the stream temperature (Sect. 2.10).

Row 23. $k_2(T)$ (calculated). The stream reaeration rate adjusted to the stream temperature (Sect. 2.11).

Row 24. Initial deficit (calculated). The DO deficit at the upstream end of the reach, in milligrams per liter.

This value is calculated by (1) subtracting the DO above the dam from the DO saturation concentration to get the DO deficit above the dam and then (2) applying the dam aeration model (see Sect. 2.5). The dam aeration model is applied to the fraction of the flow which passes over the dam, and the concentration after mixing with unaerated water is calculated (Sect. 2.6).

Row 25. Final deficit (calculated). The DO deficit at the downstream end of the reach, in milligrams per liter. This value is calculated using the Streeter-Phelps equation (Sect. 2.8).

Row 26. Starting DO (calculated). The DO concentration at the upstream end of the reach, following dam aeration. The value is calculated by subtracting the initial deficit (Row 24) from the saturation concentration.

Row 27. Final DO (calculated). The DO concentration at the downstream end of the reach, in milligrams per liter. This value is calculated by subtracting the final deficit from the DO saturation concentration.

Row 28. Final BOD (calculated). The BOD concentration remaining at the downstream end of the reach, in milligrams per liter. This value is calculated using a first-order (exponential) decay equation for BOD (Sect. 2.9).

Row 29. Critical time, raw (calculated). The travel time from top of the reach to the point of the critical DO concentration (the minimum concentration, or DO sag point), in days. This value is obtained from an equation which is derived by differentiating the Streeter-Phelps equation with respect to time and setting it equal to zero (Sect. 2.12). This value may be greater than the travel time of the reach or may be negative if DO deficits decrease throughout the reach. The model can also give an error for this and subsequent variables when there is a negative DO deficit.

Row 30. Critical time, intermediate (calculated). The calculated travel time from the top of the reach to the point of the critical DO concentration, in days, corrected to equal zero if the raw critical time is negative (Sect. 2.12).

Row 31. Critical time, final (calculated). The travel time from the top of the reach to the point of the critical DO concentration, in days, corrected to equal the travel time of the reach if the raw critical time is greater than the travel time of the reach and to equal zero if the raw critical time is negative. This value is calculated from the intermediate critical time (Sect. 2.12).

Row 32. Critical deficit, raw (calculated). The DO deficit at the sag point, in milligrams per liter. This value is obtained from the differentiated Streeter-Phelps equation.

Row 33. Critical deficit, intermediate (calculated). The critical DO deficit, corrected to equal the deficit at the upstream end of the reach if the raw critical time is negative.

Row 34. Critical deficit, final (calculated). The critical (maximum) DO deficit, corrected to equal the DO deficit at the downstream end of the reach if the raw critical time is greater than the reach travel time. This value is the highest deficit that occurs in the reach, whether it occurs at the beginning, at the end, or within the reach.

Row 35. Critical DO concentration (calculated). The lowest DO concentration in the reach. This value is calculated by subtracting the final critical deficit from the DO saturation concentration.

Row 36. Critical distance, in river miles (calculated). The river mile at which the lowest DO concentration (highest deficit) in the reach occurs. This value is calculated by multiplying the reach velocity by the critical time and adding the product to the upstream river mile of the reach.

Row 36. DO index (calculated). The DO index is the integral of the curve of DO vs distance for the reach (Sect. 4). This parameter can be used as an indicator of impacts of changes in aeration or discharge on DO, since it combines both changes in DO concentration and the distance affected. The index is evaluated using an analytical integral of the DO deficit (Streeter-Phelps) equation. The integral is

$$\text{DO index} = V \left\{ C_s t + \frac{k_1 L_0}{k_2 - k_1} \left[\frac{1}{k_1} \exp(-k_1 t) - \frac{1}{k_2} \exp(-k_2 t) - \frac{1}{k_1} + \frac{1}{k_2} \right] - \frac{D_0}{k_2} \left[1 - \exp(-k_2 t) \right] \right\}.$$

7.2. USE OF THE SPREADSHEET MODEL

Spreadsheet models should be retrieved into 1-2-3 like any other spreadsheet. Input parameter values are changed simply by entering the new value into the proper cell (where the column represents the proper reach and the row is for the parameter to be changed). Values should be entered only for the parameters that are referred to as input (not as calculated) in Sect. 7.1, except that the initial flow rate, DO concentration, and BOD concentration must be entered for the first reach.

Generally, new values should not be entered into cells containing formulas, because such cells represent parameters calculated from other values. However, formulas are occasionally used in cells for input parameters. For example, the row labeled "flow not aerated" (Row 15) contains input variables, not calculated values. A simple formula can be used to determine the value of the flow not aerated from the total river flow (No. 14 in Sect. 7.1). For example, when the flow not aerated is calculated as the total river flow minus 1000 ft^3/s, a hydropower plant with a spill flow of 1000 ft^3/s is simulated. (All other flow is used for generation and lockage and therefore is not aerated.)

There are no cells in the spreadsheet that are protected from accidental overwriting, so the user must be careful not to enter values into incorrect cells. Lotus 1-2-3 has a facility for protecting cells but it makes use of the spreadsheets cumbersome.

No value (number, label, or formula) should ever be entered in the home cell (row 1, column 1). Doing so prevents the macro that graphs the model results from working.

After new parameter values are entered into a spreadsheet, the F9 key must be pressed to recalculate the spreadsheet, since the manual recalculation option is used. Until this key is pressed, the spreadsheet will not calculate the model results using the new parameter values.

The spreadsheet sometimes leaves an error message in cells calculating the critical time and distance. In some cases, the calculation of critical distance results in an attempt to compute the logarithm of a negative number, resulting in the error. The error message can be ignored.

After the spreadsheet has been recalculated, the model results can be read directly from the rows "Starting DO," "Final DO," "Critical DO," and "Critical distance."

7.3. INITIAL CONDITIONS FOR THE OHIO RIVER MODEL

There are separate spreadsheets for the Allegheny, Monongahela, and Ohio rivers. To get the proper initial conditions (flow, DO concentration, and BOD concentration) at the start of the Ohio River, the Allegheny and Monongahela river models must be executed first. No facility has been developed to automatically determine initial conditions for the Ohio from results of the Allegheny and Monongahela river models. The initial flow in the Ohio should be entered as the sum of Allegheny and Monongahela river flows, and the DO and BOD concentrations should be manually calculated as the flow-weighted average of the concentrations at the ends of the Allegheny and Monongahela rivers. For example, the starting DO concentration in the Ohio River (C_{OR}) is calculated as

$$C_{OR} = \frac{C_{AR}Q_{AR} + C_{MR}Q_{MR}}{Q_{AR} + Q_{MR}} ,$$

where C_{AR} and Q_{AR} are the concentration and flow in the Allegheny River, and C_{MR} and Q_{MR} are the flow and concentration in the Monongahela River. The starting BOD concentration in the Ohio is calculated in the same way.

7.4. GRAPHING RESULTS

The spreadsheets have been programmed to graph the results using a macro (a series of 1-2-3 commands that are written into the spreadsheet and can be executed automatically). The macro works by (1) copying the starting river mile of each reach into one row of a new table, (2) copying the starting DO concentration of each reach into the second row of the table, (3) appending the downstream river mile of each reach to the end of the first row of the table, (4) appending the DO concentration at the end of each reach to the end of the second row of the table, and (5) sorting (by river mile) the river mile-DO concentration data pairs in the first table into a second table, from which the graph is drawn. When the macro finishes executing, it is in the 1-2-3 graph facility. The first few times the macro is used, the X and Y ranges should be checked. The macro is not foolproof, and sometimes changes in input data can create results that must be graphed differently. The graph should be checked against the spreadsheet to make sure the macro worked properly. The graph can spreadsheet to make sure the macro worked properly. The graph can then be saved and printed with the Lotus PRINTGRAPH program. The critical DO concentrations are not graphed.

8. SENSITIVITY AND UNCERTAINTY OF THE MODEL

8.1. INTRODUCTION

The sensitivity and uncertainty of the Ohio River basin DO model, with the parameters used for the EIS, were analyzed. The sensitivity analysis investigates which parameters the model results are most sensitive to (i.e., which parameters, when varied, cause the greatest change in the modeled DO concentrations). The sensitivity analysis identifies processes (such as dam aeration, water surface aeration, and BOD decay) that have the greatest effect on DO concentrations at different locations. The uncertainty analysis is an investigation of variability in the results predicted by the model. This analysis is performed by including the estimated uncertainty in the model parameters into the model results to determine the uncertainty in the results. The uncertainty analysis essentially creates a stochastic DO model by treating model parameters as means of probability distributions instead of as constants.

8.2. SENSITIVITY ANALYSIS

8.2.1. Methods

The sensitivity analysis was performed using the Gradient Enhanced Software System (GRESS), developed at ORNL (Oblow 1983a, 1983b). GRESS enhances FORTRAN code by giving it the ability to determine partial derivatives of any selected output variable with respect to any selected input variable. GRESS also calculates a normalized sensitivity index that can be used to compare the model sensitivity among parameters having different units. (The sensitivity index of output variable A with respect to parameter B is equal to the partial derivative of A with respect to B times the value of B and divided by the value of A.) GRESS was used to determine the partial derivatives and sensitivity indexes of the critical (lowest) DO concentration in each reach with respect to the following variables:

1. the initial DO concentrations in the Allegheny and Monongahela rivers,
2. the initial BOD concentrations in the Allegheny and Monongahela rivers,
3. the initial flows in the Allegheny and Monongahela rivers,
4. k_1 in the Allegheny and Monongahela rivers,
5. k_2 in each reach,
6. the tributary flow in each reach,
7. the tributary DO concentration in each reach,
8. the tributary BOD concentration in each reach,
9. the point-source BOD loading in each reach,
10. the dam aeration constant in each reach with a dam,
11. the dam aeration coefficient in each reach with a dam,
12. the aeration rate (the increase in DO concentration in the spill flow at a dam) in each reach with a dam,

13. the flow rate used for generation (flow not aerated) in each reach with a dam, and

14. the water temperature in each reach.

The GRESS sensitivity analyses were conducted on the model with the parameters used for the design conditions (Sect. 5) with the spill flows recommended for Alternative 3 in the EIS, the scenario upon which the staff recommendations in the EIS were based. The GRESS analyses were also conducted on the model with the parameters for the design conditions with none of the proposed new hydropower projects in operation (but with existing and licensed projects in operation). Each of these analyses produces over 27,700 partial derivatives as output; a small fraction of these values were analyzed graphically to develop an overall understanding of model sensitivities at important locations along the rivers.

8.2.2. <u>Results</u>

The GRESS sensitivity analysis shows that DO concentrations are generally most sensitive to water temperature (for example, see the values in Table 7). This result is not surprising because of the direct dependency of DO saturation and the rate constants k_1 and k_2 on temperature. It should be noted that the values in Table 7 for sensitivity to water temperature are related to the water temperature in the same reach that the output was calculated for; the sensitivity to changes in water temperature in the upstream reaches is not included. The sensitivity analysis also shows that model results are highly sensitive to the flow rate in most reaches (compare values in Table 7 to sensitivity indexes in Figs. 12-19). This result means that significant changes in predicted DO concentrations can be expected when different water temperatures and flows are modeled. The following analyses emphasize the sensitivity of the model to parameters other than temperature and flow.

The sensitivity to initial conditions (starting DO and BOD concentrations in the Allegheny and Monongahela rivers) were compared to sensitivities to the rate coefficients k_1 and k_2 to determine the extent (over distance downstream) over which the assumed initial conditions are important. The sensitivities to the rate coefficients k_1 and k_2 were used for comparison to the sensitivity to initial conditions because they represent BOD decay and water surface aeration, which control DO concentrations when initial conditions and dam aeration are not important, and because they are relatively constant throughout the rivers. Figures 12 and 13 show the results of these analyses. In the Allegheny, the model is not particularly sensitive to the initial BOD concentration. The predicted DO concentrations are more sensitive to the initial DO concentration than to k_1 and k_2 from Allegheny dam 9 to about Allegheny dam 5. This result is not surprising since the licensed hydropower plants at Allegheny dams 9, 8, 6, and 5, combined with the low aeration efficiency of dam 7, provide little dam aeration in these reaches. If dam aeration were

Table 7. Sensitivities to flow and temperature at critical locations under design conditions and Alternative 3 spill flows

Location	$\delta C/\delta Q$[a] (mg/L)/cfs	$\delta C/\delta T$[b] (mg/L)/°C	Sensitivity index for Q[c]	Sensitivity index for T[d]
Allegheny RM 30	0.00032	-0.015	0.30	0.066
Allegheny RM 0	0.000028	-0.145	0.02	0.50
Monongahela RM 0	0.00011	-0.04	0.029	0.17
Monongahela RM 65	0.00033	-0.132	0.089	0.54
Ohio RM 54[e]		-0.084		0.08
Ohio RM 100		-0.052		0.21
Ohio RM 250		-0.022		0.11

[a]Partial derivative of the critical dissolved oxygen concentration with respect to river flow.

[b]Partial derivative of the critical dissolved oxygen concentration with respect to the water temperature in the same reach.

[c]GRESS sensitivity index for flow, which can be compared to values in Figs. 12-19.

[d]GRESS sensitivity index for the water temperature in the same reach, which can be compared to values in Figs. 12-19.

[e]The sensitivity of Ohio River dissolved oxygen concentrations to river flow is not estimated because it is complicated by the effects of many tributary inflows.

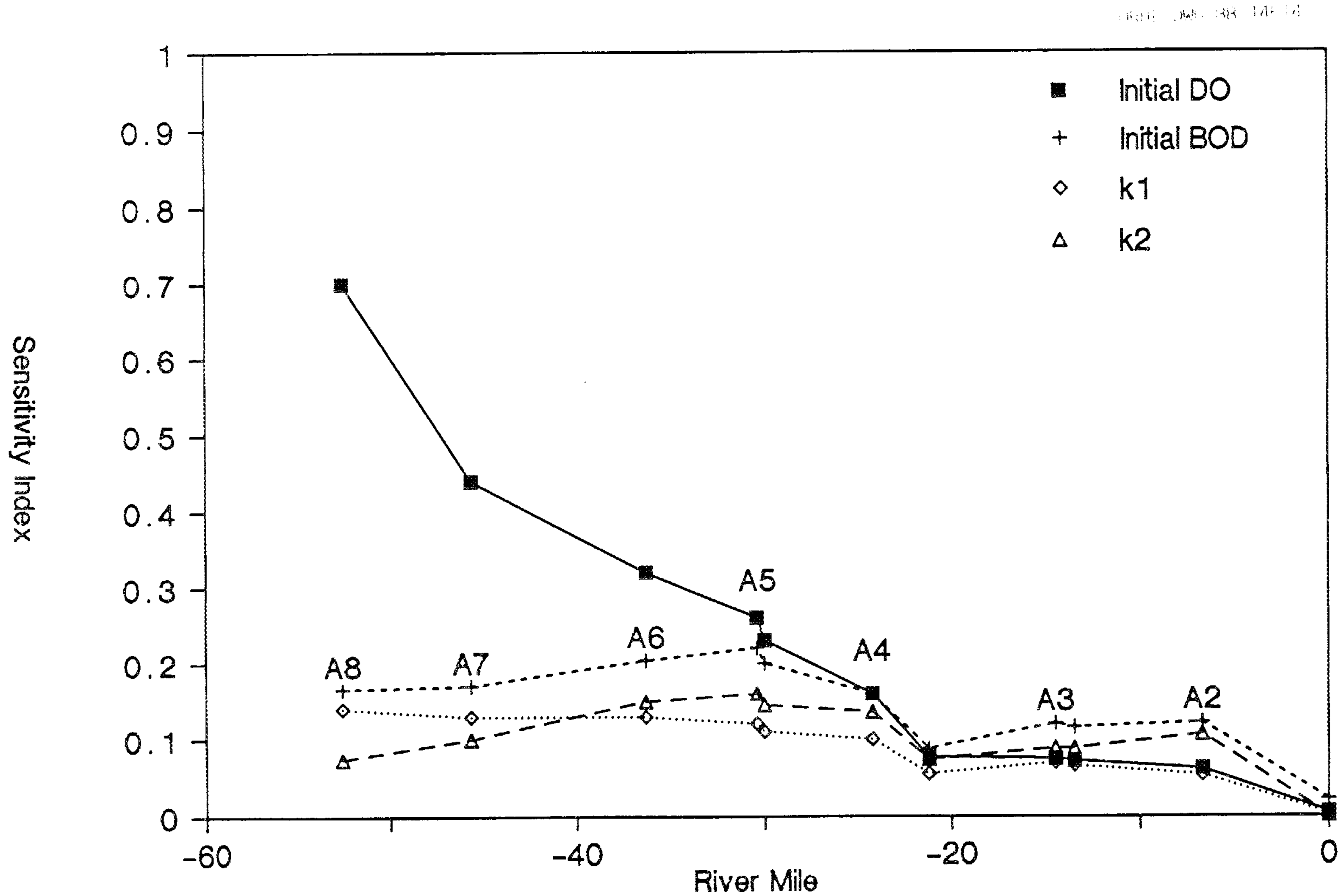

Fig. 12. Sensitivities of Allegheny River critical DO concentrations to initial conditions, under design conditions with moderate flows and Alternative 3 hydropower development.

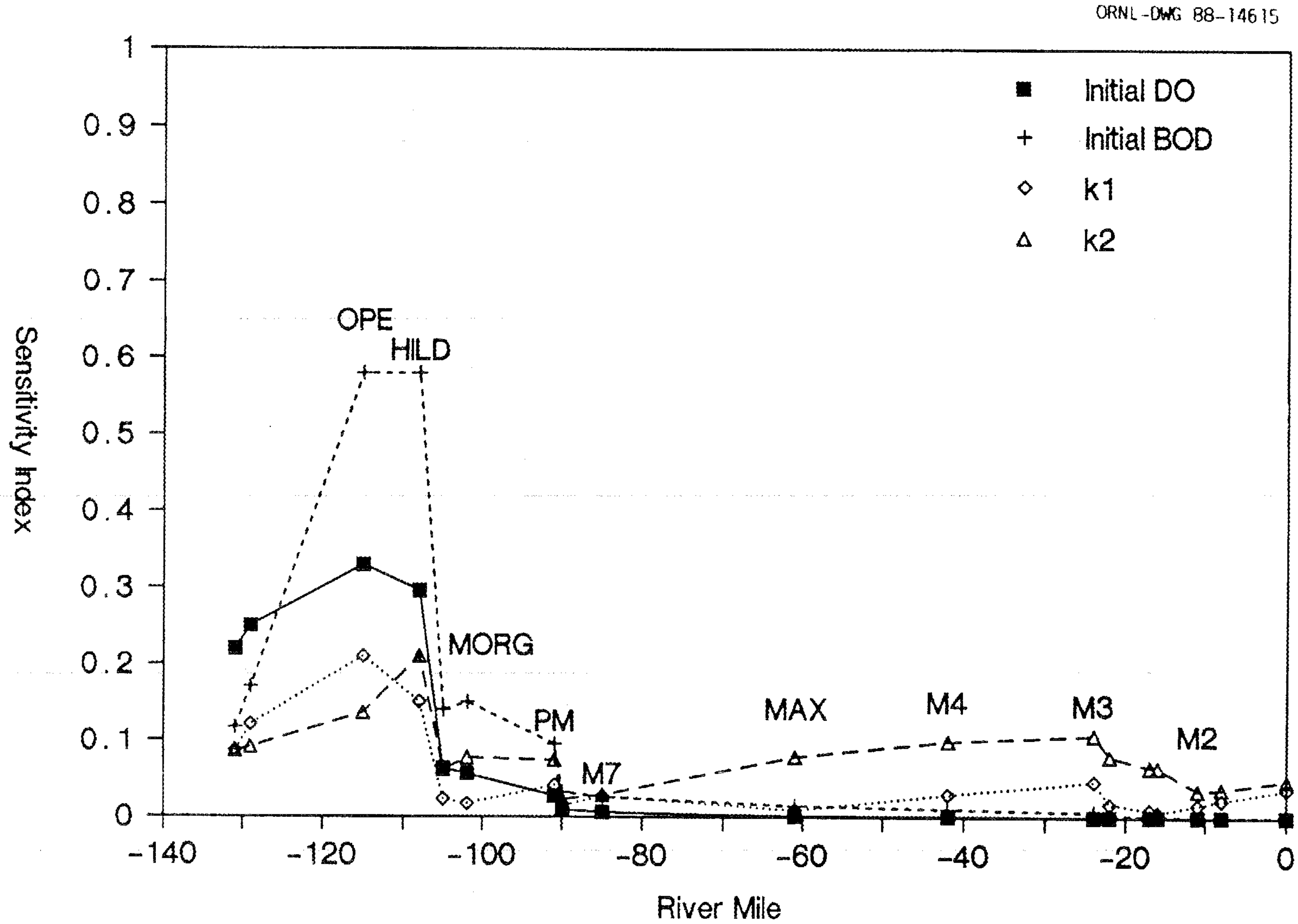

Fig. 13. Sensitivities of Monongahela River critical DO concentrations to initial conditions, under design conditions with moderate flows and Alternative 3 hydropower development.

ORNL-DWG 88-14616

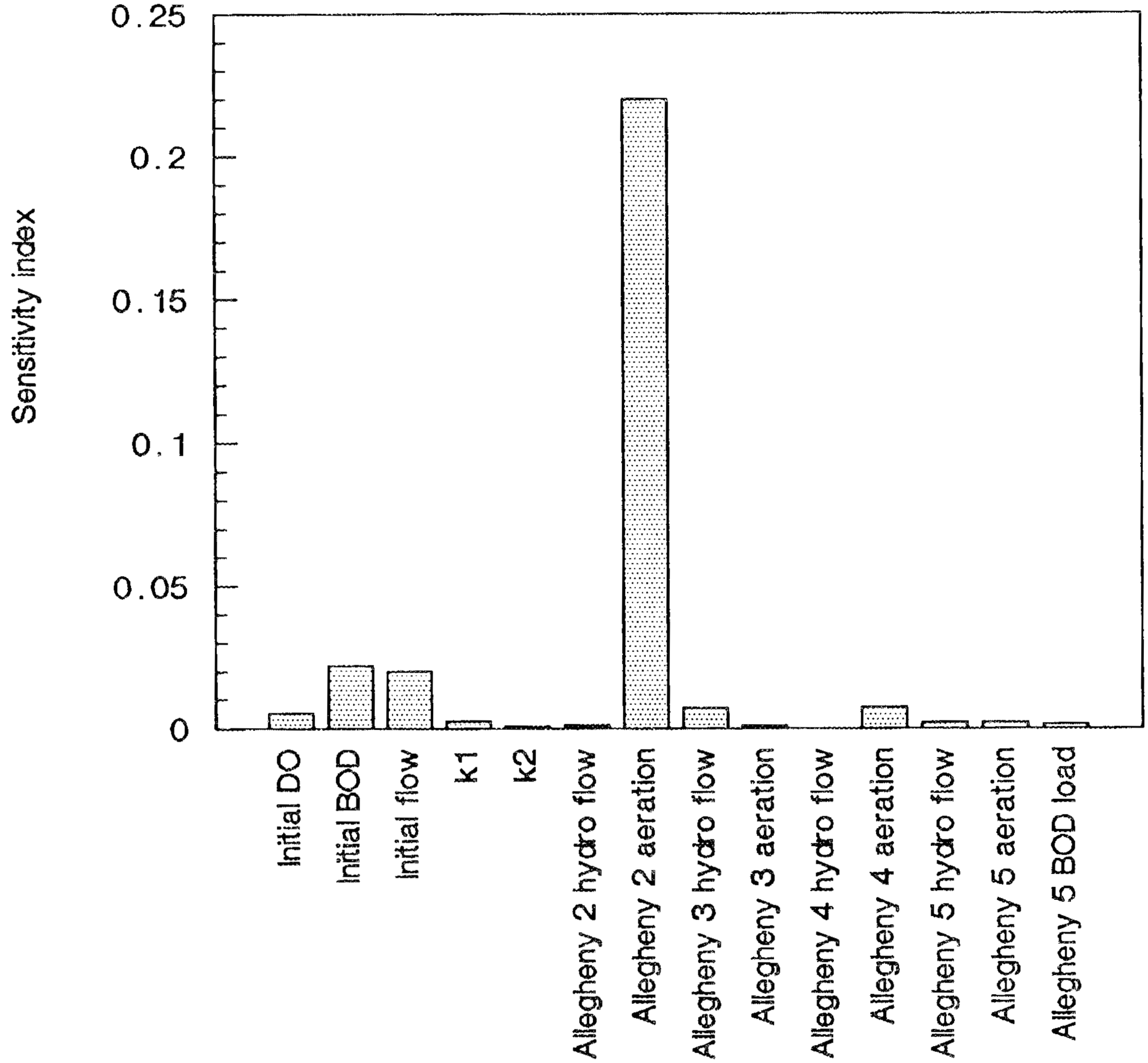

Fig. 14. Sensitivities of the critical DO concentration at Allegheny river mile 0, under design conditions with moderate flows and Alternative 3 hydropower development.

ORNL-DWG 88-14617

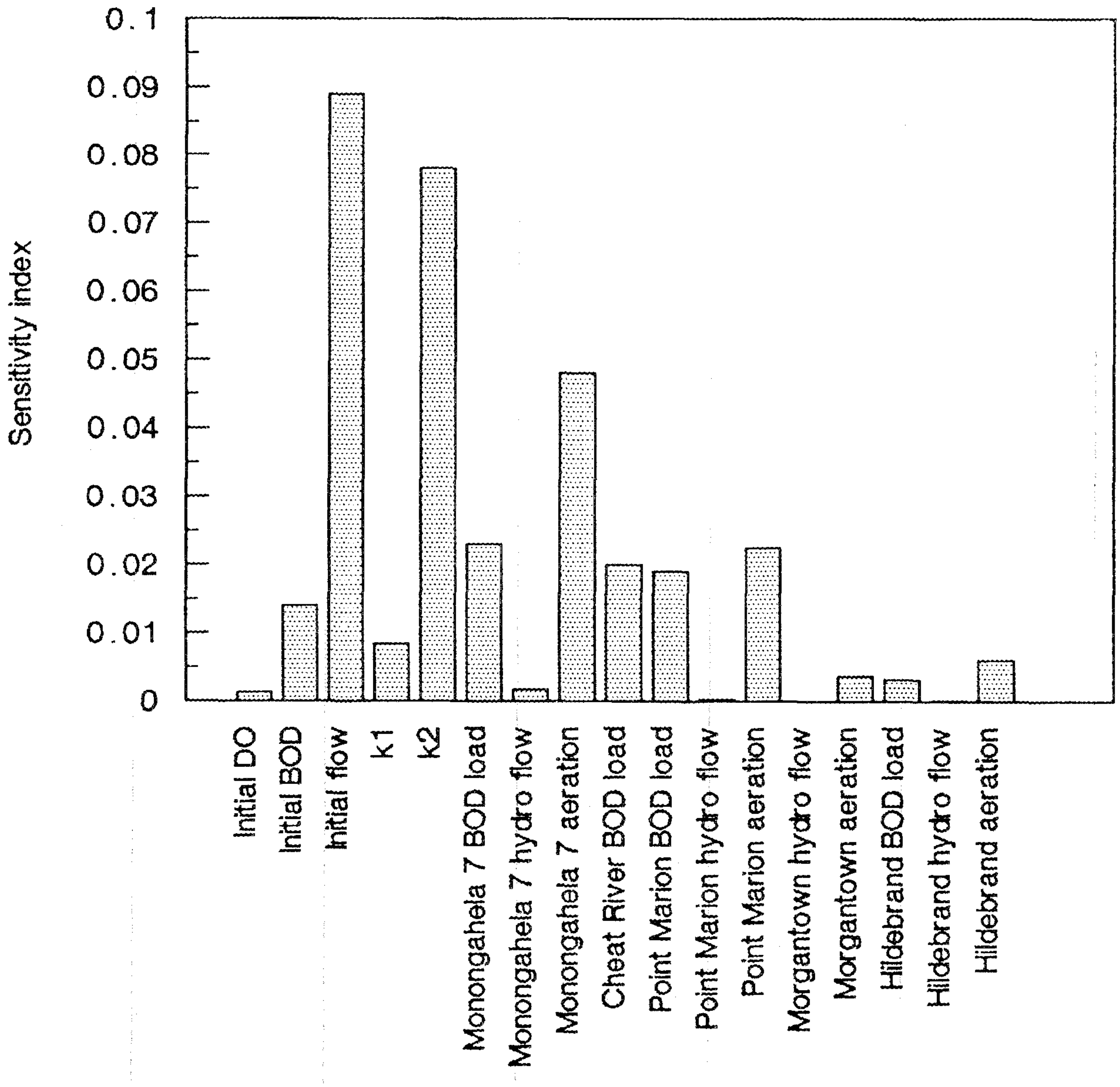

Fig. 15. Sensitivities of the critical DO concentration at Monongahela river mile 65, under design conditions with moderate flows and Alternative 3 hydropower development.

ORNL-DWG 88-14618

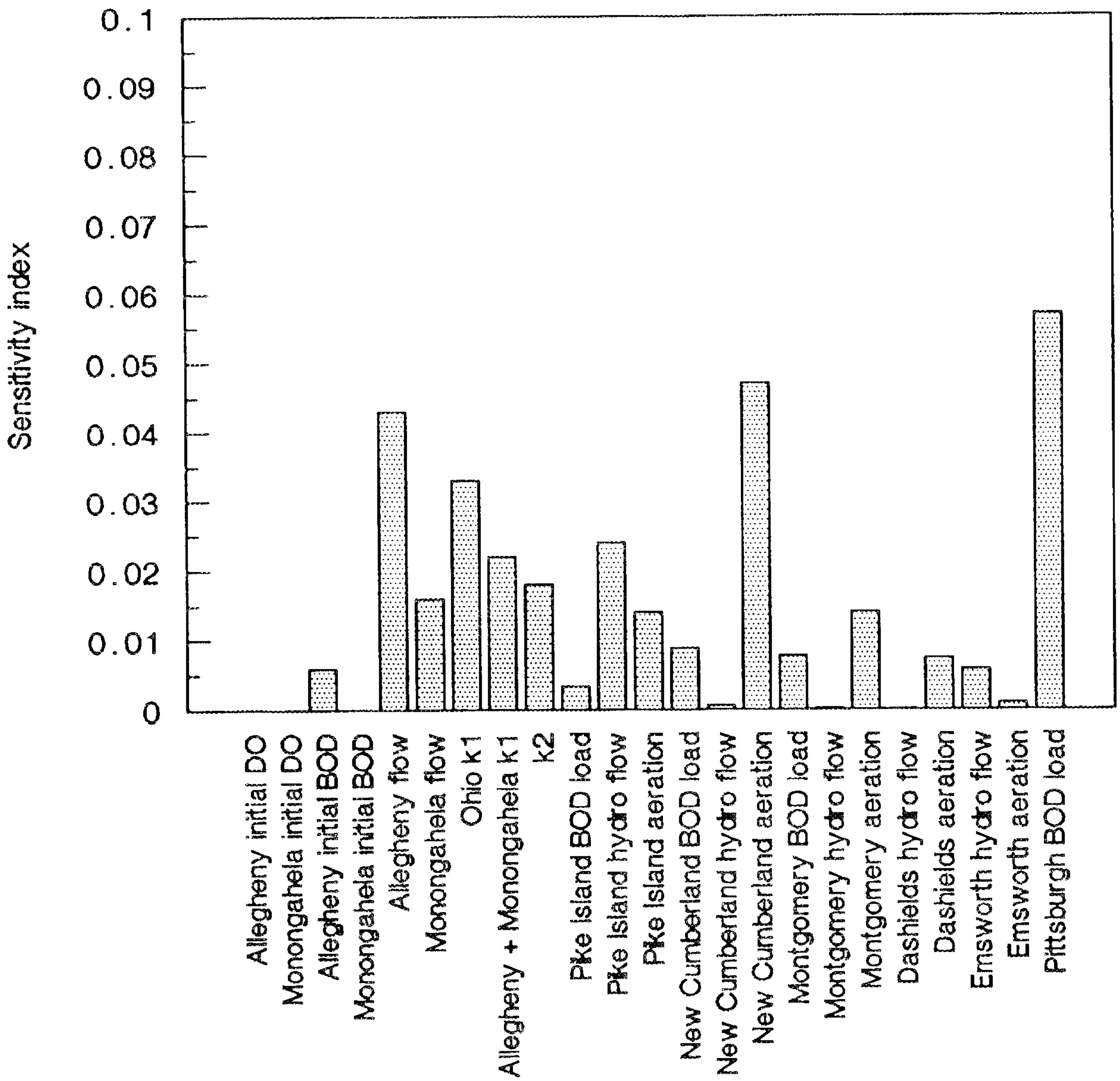

Fig. 16. Sensitivities of the critical DO concentration at Ohio river mile 100, under design conditions with moderate flow and Alternative 3 hydropower development

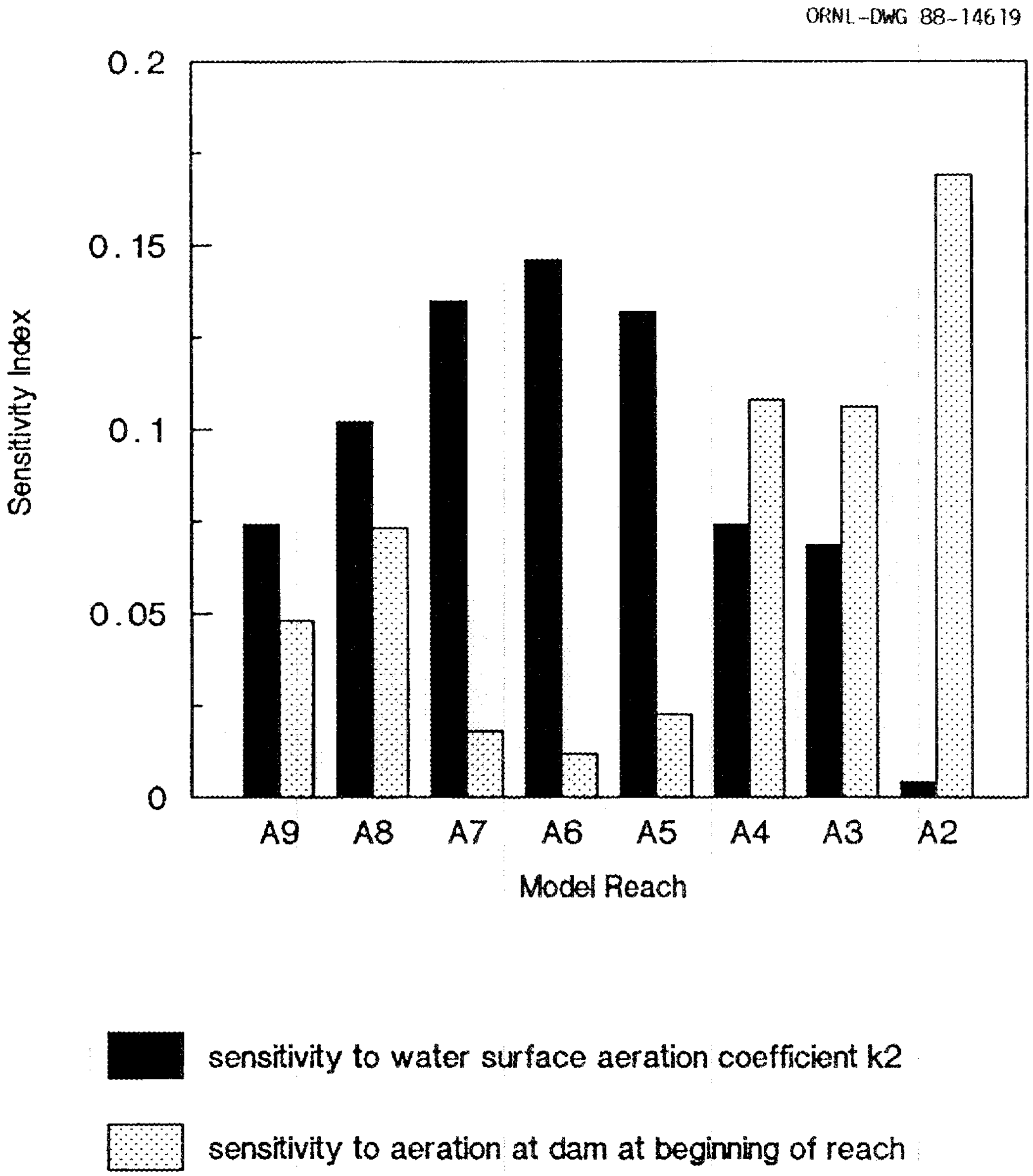

Fig. 17. Sensitivities of Allegheny River critical DO concentrations to k_2 and dam aeration, under design conditions with moderate flows and no additional hydropower development

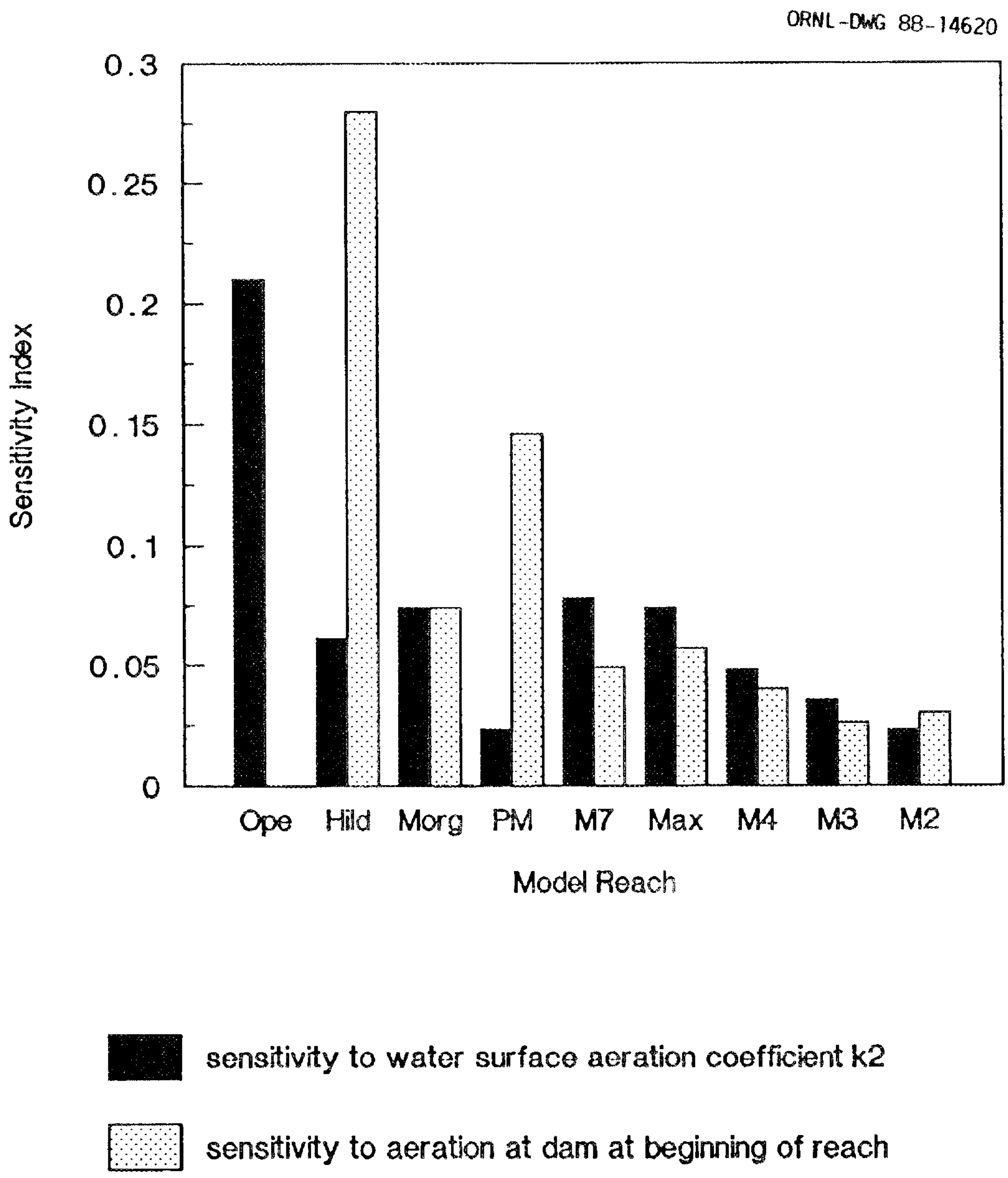

Fig. 18. Sensitivities of Monongahela River critical DO concentrations to k_2 and dam aeration, under design conditions with moderate flows and no additional hydropower development

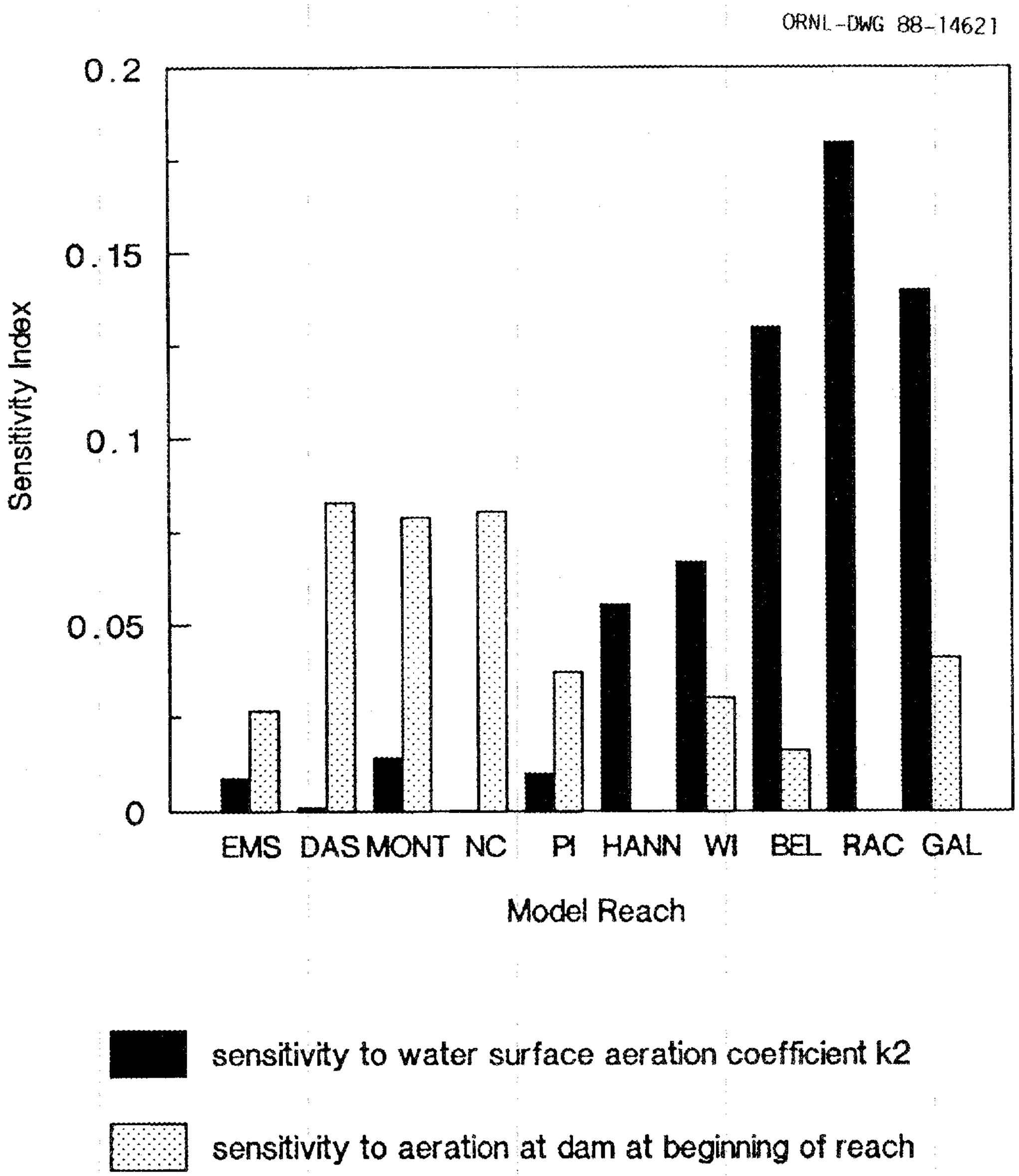

Fig. 19. Sensitivities of Ohio River critical DO concentrations to k_2 and dam aeration, under design conditions with moderate flows and no additional hydropower development.

higher, the effects of initial DO concentrations would be overwhelmed by the effects of dam aeration. This result indicates that the DO concentration at Allegheny dam 9 will have a strong influence on DO concentrations as far downstream as dam 5 when all the licensed hydropower projects are in operation.

The predicted DO concentrations in the Monongahela River are relatively sensitive to initial DO and BOD concentrations as far downstream as Hildebrand Dam. Hildebrand is the first efficient aerator on the river, and apparently DO concentrations below Hildebrand are controlled more by dam aeration, water surface aeration, and BOD loads than by assumed initial conditions. This result means that predicted DO concentrations in the Monongahela downstream of Hildebrand are insensitive to assumed conditions at Tygart Dam.

The sensitivities of predicted DO concentrations to a number of parameters were determined for critical locations on each river. The critical locations are those where the proposed hydropower would reduce DO concentrations the most, according to model analyses presented in the EIS. The critical locations are at RM 0 on the Allegheny, at RM 65 (the sag point below Monongahela dam 7) on the Monongahela, and at RM 100 on the Ohio.

Figure 14 shows the sensitivity of predicted DO concentrations at Allegheny RM 0 to initial conditions, the water surface aeration rate k_2, the BOD decay rate k_1, the flow rates used for generation (equal to the sensitivity to the spill flow rate), and the dam aeration rates (the increase in DO concentration, in milligrams per liter, that occurs in the spill flow) at the first four dams upstream. The figure shows that DO concentrations at Allegheny RM 0 are highly sensitive to aeration at Allegheny dam 2 under the conditions simulated for Alternative 3. Under this alternative, dam 2 has a high spill flow, which controls DO concentrations because this dam is a very efficient aerator. The DO concentrations at Allegheny RM 0 are relatively insensitive to flow, though DO concentrations upstream of dam 2 are sensitive to flow.

The sensitivity of predicted DO concentrations at Monongahela RM 65 is shown in Fig. 15. The DO concentrations at this location are most sensitive to the flow rate, the water surface aeration rate coefficient k_2, and the aeration rate at Monongahela dam 7 (where no hydropower is proposed). Other parameters of importance to DO concentrations are the BOD loadings at several upstream reaches.

The sensitivity of predicted DO concentrations at Ohio RM 100 is shown in Fig. 16. This figure shows that DO concentrations are relatively sensitive to flow, BOD decay rate k_1, and aeration at the dams upstream of RM 100. The sensitivity to the value of k_1 used in the Allegheny and Monongahela rivers indicates that DO concentrations in these rivers still affect DO concentrations at Ohio RM 100.

Figure 17 compares the relative sensitivity of the modeled critical DO concentrations in each reach of the Allegheny River that starts with a dam to the surface aeration rate coefficient k_2

and to the amount of aeration (the milligram-per-liter increase in DO in the spill flow) taking place at the dam. The sensitivity indexes are for conditions without the proposed new hydropower projects, but with the licensed projects at dam 9, 8, 6, and 5. These sensitivity indexes indicate the relative importance of surface aeration vs dam aeration in these reaches. The figure shows that below Allegheny dams 7, 6, and 5, water surface aeration is more important for maintaining DO concentrations; this is expected because dam 7 is a poor aerator and because of the licensed projects with low spill flows at dams 5 and 6. However, below dams 4, 3, and 2, the model becomes much more sensitive to dam aeration. This indicates that below dam 4 dam aeration is important for maintaining DO concentrations in the Allegheny.

Figure 18 shows the relative sensitivity of the model to k_2 and dam aeration in the Monongahela River, without the proposed new hydropower. In the reach below Opekiska Dam, which provides negligible aeration, the model is not sensitive to dam aeration. Below Hildebrand and Point Marion dams, the model is more sensitive to dam aeration; and, for the rest of the river, the model seems to be about equally sensitive to water surface aeration and dam aeration. These results indicate that dam aeration is especially important for maintaining DO concentrations below Hildebrand and Point Marion dams and remains of importance in the reaches further down the Monongahela River.

The relative sensitivity of the model to k_2 and dam aeration in the Ohio River, without the proposed new hydropower, is shown in Fig. 19. The figure shows that predicted DO concentrations below the first five dams on the Ohio River are more sensitive to dam aeration than to water surface aeration. Below about RM 100, the model becomes much more sensitive to water surface aeration. This indicates that aeration at the first five dams of the Ohio is more important for maintaining DO concentrations than is aeration at the rest of the Ohio River dams in the study. This result is expected because of the more efficient aeration at the upper five dams.

8.2.3. Conclusions

In general, the DO model is most sensitive to water temperature and flow rate. The values of these parameters should be selected carefully in future modeling studies. The effects of variation in these parameters should be at least qualitatively investigated in any new studies, since they strongly influence predicted DO concentrations.

From Allegheny dam 9 downstream to dam 5, the modeled DO concentrations are sensitive to the initial DO concentration in the Allegheny, which is an input parameter. This starting DO concentration should be selected carefully, and the effects of variation in it should be investigated in any additional modeling studies. The model is not especially sensitive to the initial BOD concentration in the Allegheny, nor to the initial DO and BOD concentrations in the Monongahela.

The DO concentrations at RM 0 of the Allegheny River and in the upper reaches of the Ohio River are very sensitive to aeration at Allegheny dam 2 when this dam is spilling water. This dam is very important for maintenance of DO concentrations in these reaches.

In the upper 100 river miles of the Ohio River, dam aeration is important for maintaining DO concentrations. The model is sensitive to the decay rate, k_1, of BOD below Pittsburgh; consequently, obtaining measured values of this parameter would be useful to improve the model. Processes controlling DO in the Allegheny and Monongahela rivers have an important effect on DO in the Ohio River at least as far downstream as RM 100.

There are reaches in each river where dam aeration is and is not relatively important for maintaining DO concentrations (i.e., where DO concentrations are and are not sensitive to dam aeration). The reaches where the model is most sensitive to dam aeration are below Allegheny dam 4, below Hildebrand and Point Marion dams, and below the first five dams on the Ohio River. These reaches are generally where the most dam aeration occurs, so it appears that the model is more sensitive to dam aeration where the dam aeration rate is high. This fact implies that dam aeration has a greater than linear effect on critical DO concentrations; that is, as dam aeration increases, the DO concentrations rise at an increasing rate.

It should be noted that the sensitivities determined in this analysis can change when the model parameters change. The sensitivities of the model to various parameters could change significantly when different scenarios or conditions are modeled. The results presented here describe the sensitivities of the model as it represents the design conditions and recommended spill flows in the EIS.

8.3. UNCERTAINTY ANALYSIS

8.3.1. Methods

The uncertainty analysis incorporates the estimated uncertainty in model parameters into an estimated uncertainty in the model results and provides confidence bounds for the model's predictions of DO concentrations. This method does not address uncertainties in how the model is formulated, but assumes that the structure of the model (i.e., the equations used) is correct and addresses the uncertainty in the values of the model parameters. The model parameters for the design conditions used in the EIS were determined by using the following steps (Sect. 5):

1. River flows, water temperatures, and the initial Allegheny River DO concentration were selected to represent conditions when DO concentrations are expected to be low. The values were selected after examining the range of measured historic values for these parameters. The initial DO concentration on the Monongahela River, at the outlet from Tygart Dam, was assumed to be at saturation due to aeration at the dam.

2. Dam aeration parameters (α and β) were estimated from field data. The k_2 values were estimated using the O'Connor-Dobbins equation. Tributary DO and BOD concentrations were estimated.

3. The values for BOD loadings, k_1, and, in one case, tributary DO concentrations were determined by calibrating the model to measured data.

The uncertainty analysis was performed by estimating the uncertainty in all the input parameters that were either estimated or determined from calibration. No uncertainty was assigned to the parameters (flow, temperature, and initial DO concentrations) that were selected as design conditions.

The uncertainty analysis was performed for the design conditions used in the EIS (Sect. 5) with the proposed hydropower plants operating with the spill flows recommended under Alternatives 3 and 4 of the EIS (i.e., the parameters in Table 5), since this is the model run on which the recommendations in the EIS were based. The analysis was also performed for the model with the assumption that none of the proposed new hydropower projects were in operation. The software used for the uncertainty analysis is the PRISM system developed at ORNL (Gardner et al. 1983, Gardner 1984).

The expected uncertainty in model parameters is represented by a frequency distribution that actual values of the parameter are expected to follow. The analysis therefore requires a description of the frequency distribution each parameter follows and a description of any important correlations between parameters. Each distribution is described by (1) the type of frequency distribution, such as normal (Gaussian), uniform, or lognormal; (2) a mean value and a variance for normal and lognormal distributions; and (3) minimum and maximum values for uniform distributions. PRISM allows the use of bivariate distributions that describe the joint frequency distribution of two parameters whose values are correlated. The frequency distributions for model parameters were determined as follows.

The uncertainty in the dam aeration coefficients (β's) and constants (α's) was obtained from the linear regression analyses that were used to estimate these parameters. For each dam, a bivariate normal distribution was assigned to describe the joint frequency distribution of α and β. Regression analysis for the linear dam aeration model (Sect. 2.5) using field data for each dam provided a full description of the bivariate normal distribution of α and β. The least-squares regression estimates of α and β (the values used in the model; Table 5) are the means, and the variance-covariance matrix of the parameters provided by the SAS statistical program complete the description of the bivariate normal distribution.

The uncertainty in the k_2 estimates from the O'Connor-Dobbins equation was estimated from measured and calculated values of k_2

in the Ohio River presented by O'Connor and Dobbins (1958). The equation for k_2 is

$$k_2 = Z(V^{0.5})/\text{depth}^{1.5} \quad ,$$

where Z is a constant with a value of 12.9. The uncertainty in k_2 was assigned to the constant Z. Values of Z that reproduced the measured k_2 values for 22 field measurements were calculated. These values of Z were approximately lognormally distributed, with the associated normal distribution having a mean of 2.76 and a standard deviation of 0.633. This lognormal distribution was assigned as the uncertainty in k_2.

Uncertainties in tributary DO and BOD concentrations were assumed to be uniformly distributed within a range of $\pm$ 2 mg/L of the mean (the mean being the value used in the model).

The uncertainty in the point-source BOD loadings were assumed to be normally distributed with a standard deviation of 25% of the value used in the model.

The uncertainty in k_1 was estimated from data published in USEPA (1985, p. 147). This document presents values of k_1 that include sediment oxygen demand (as does the k_1 used in the Ohio River model), from a variety of rivers. The measured values of k_1 in rivers with approximately the same depths as those in this study were approximately uniformly distributed over a range of 0.08 to 0.5. A uniform distribution with this range was used for k_1.

After frequency distributions were assigned to the parameters that reflected uncertainty, the model was executed 2000 times. A Latin-hypercube method (Rose and Schwartzman 1981) was used to systematically assign parameter values for each execution that, over the 2000 executions, fit the frequency distributions assigned to each parameter. The critical (lowest) DO concentration in each reach of the model was stored for each of the 2000 executions, and statistics were obtained on these results. The mean, maximum, minimum, and standard deviation of the 2000 values of critical DO concentration for each reach were determined.

8.3.2. Results

The mean critical DO concentrations and the 95% confidence interval (CI) for each reach of the Allegheny, Monongahela, and Ohio rivers for the model with the proposed hydropower projects are plotted in Figs. 20, 21, and 22. Assuming that the structure of the model is correct (i.e., the uncertainty lies in the parameter values) and that the critical DO concentrations generated in the uncertainty analysis are normally distributed for each reach, there is a 95% probability that true value of the critical DO lies within these CIs. (The 95% CI is equal to the mean ± 1.96 times the standard deviation of the 2000 critical DO values for each reach.) In most cases the 95% CI calculated in this way is close to the observed minimum and maximum DO concentrations generated by the uncertainty analysis.

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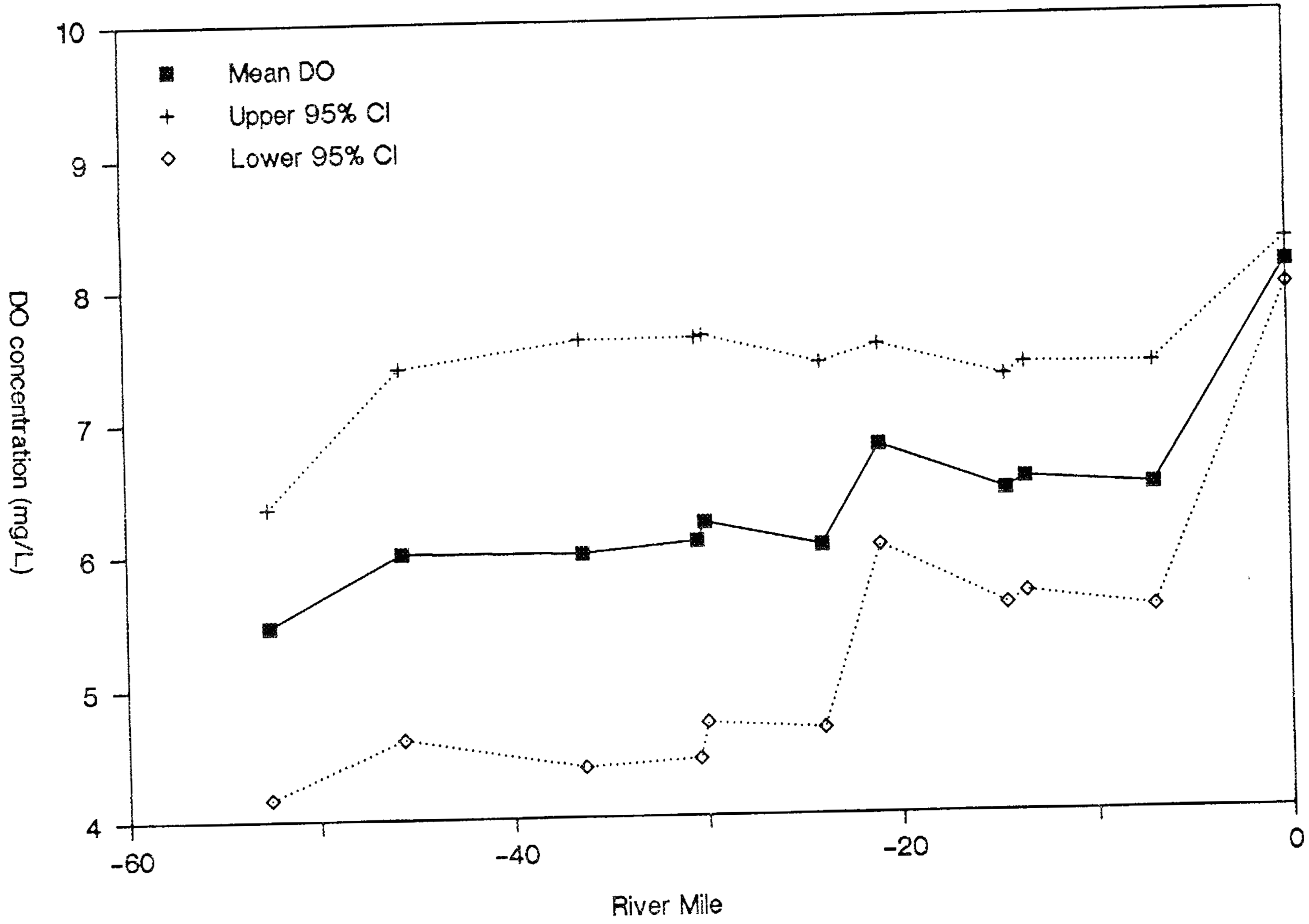

Fig. 20. Uncertainty analysis [95% confidence interval (CI)] for the Allegheny River, under design conditions with moderate flows and Alternative 3 hydropower development.

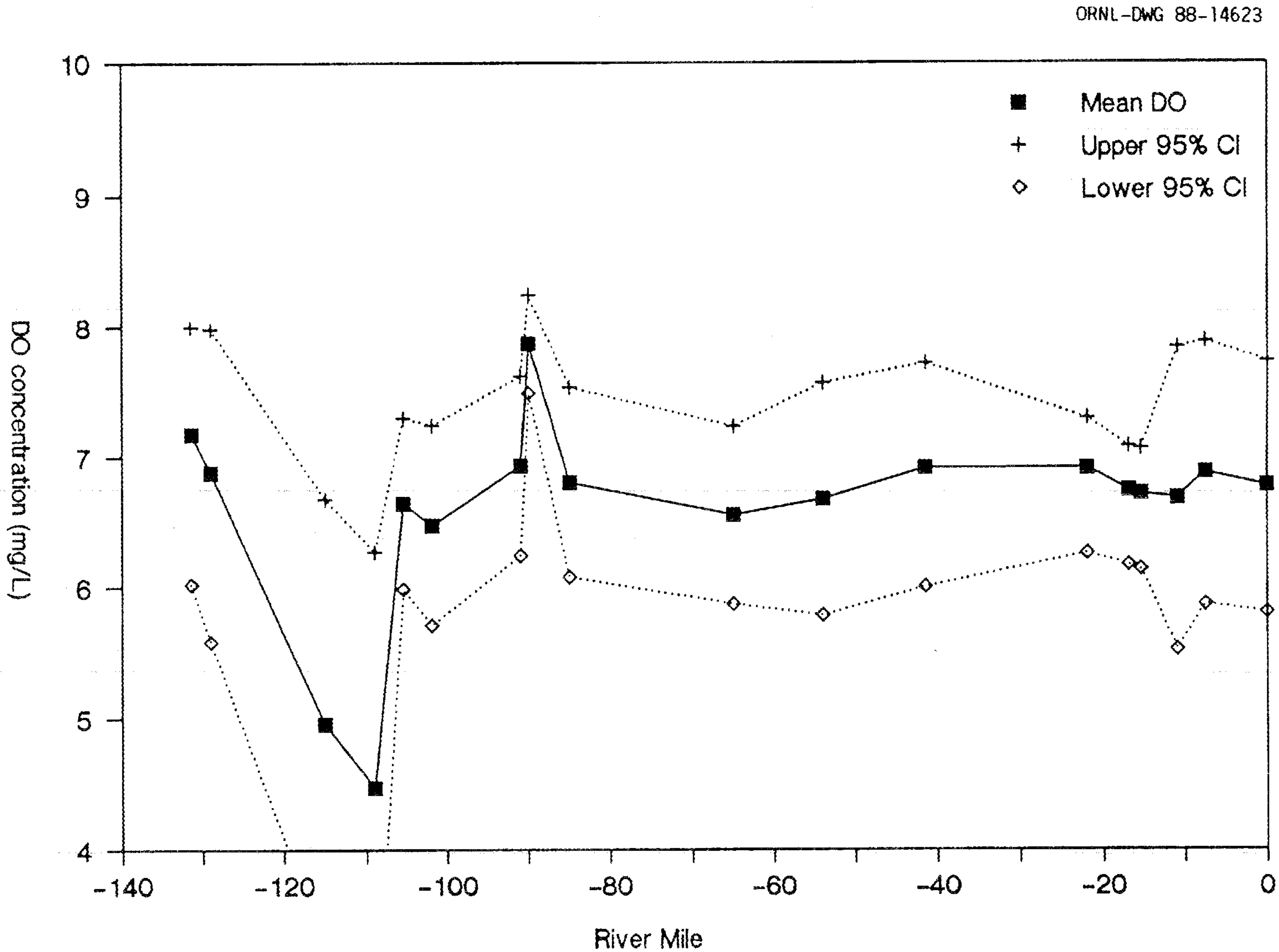

Fig. 21. Uncertainty analysis [95% confidence interval (CI)] for the Monongahela River, under design conditions with moderate flows and Alternative 3 hydropower development.

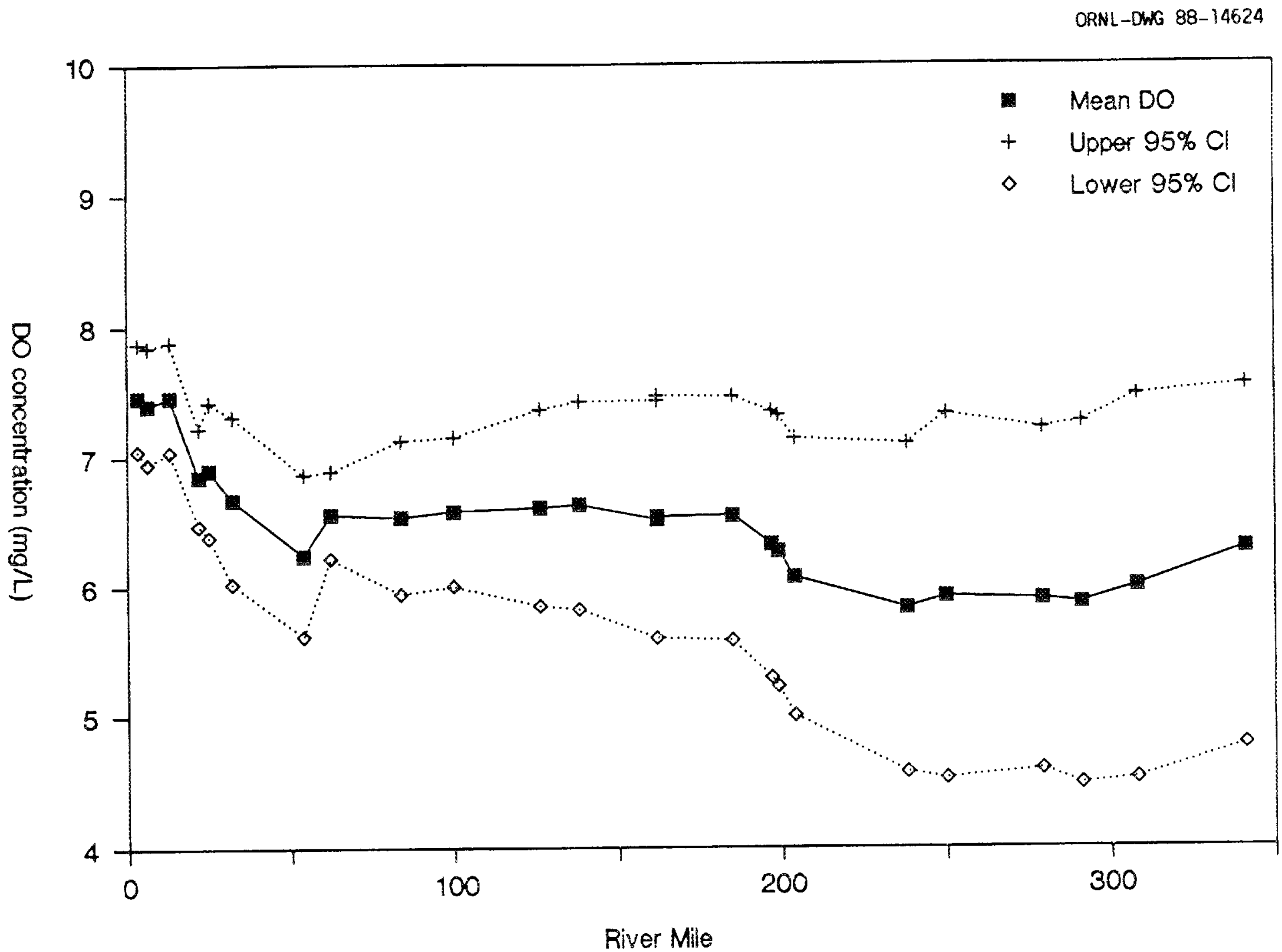

Fig. 22. Uncertainty analysis [95% confidence interval (CI)] for the Ohio River, under design conditions with moderate flows and Alternative 3 hydropower development.

There is relatively high uncertainty (95% CI within about 1.5 mg/L of the mean) in the Allegheny River model results from dam 9 as far downstream as the dam 4 reach (Fig. 20). The uncertainty decreases until RM 0, where the value is very small.

There is also relatively high uncertainty in the Monongahela River model results from Tygart Dam to the Hildebrand Dam reach, as Fig. 21 indicates. For the rest of the Monongahela, the uncertainty is relatively low, with the 95% CI within about 1 mg/L of the mean.

The model uncertainty on the Ohio River is low until it gradually increases below RM 100 (Fig. 22). In the reach between RM 0 and RM 100 where dam aeration is especially important, the 95% CI is within about 0.5 mg/L of the mean. At the reach below Gallipolis Dam, the 95% CI has expanded to about 1.5 mg/L from the mean.

Figures 23, 24, and 25 show the uncertainty analysis results for the Allegheny, Monongahela, and Ohio rivers without the proposed new hydropower development. Also shown on these three figures are the range of measured DO concentrations (the mean and the mean $\pm$ 1.96 standard deviations) at the ORSANCO water quality monitoring stations. The ORSANCO data were collected in the months of July, August, and September between 1980 and 1988, when the water temperature was between 26 and 30^{o}C.

The DO model uncertainties without the proposed new hydropower projects are similar to those for the model with Alternative 3 spill flows. At the ORSANCO monitoring stations on

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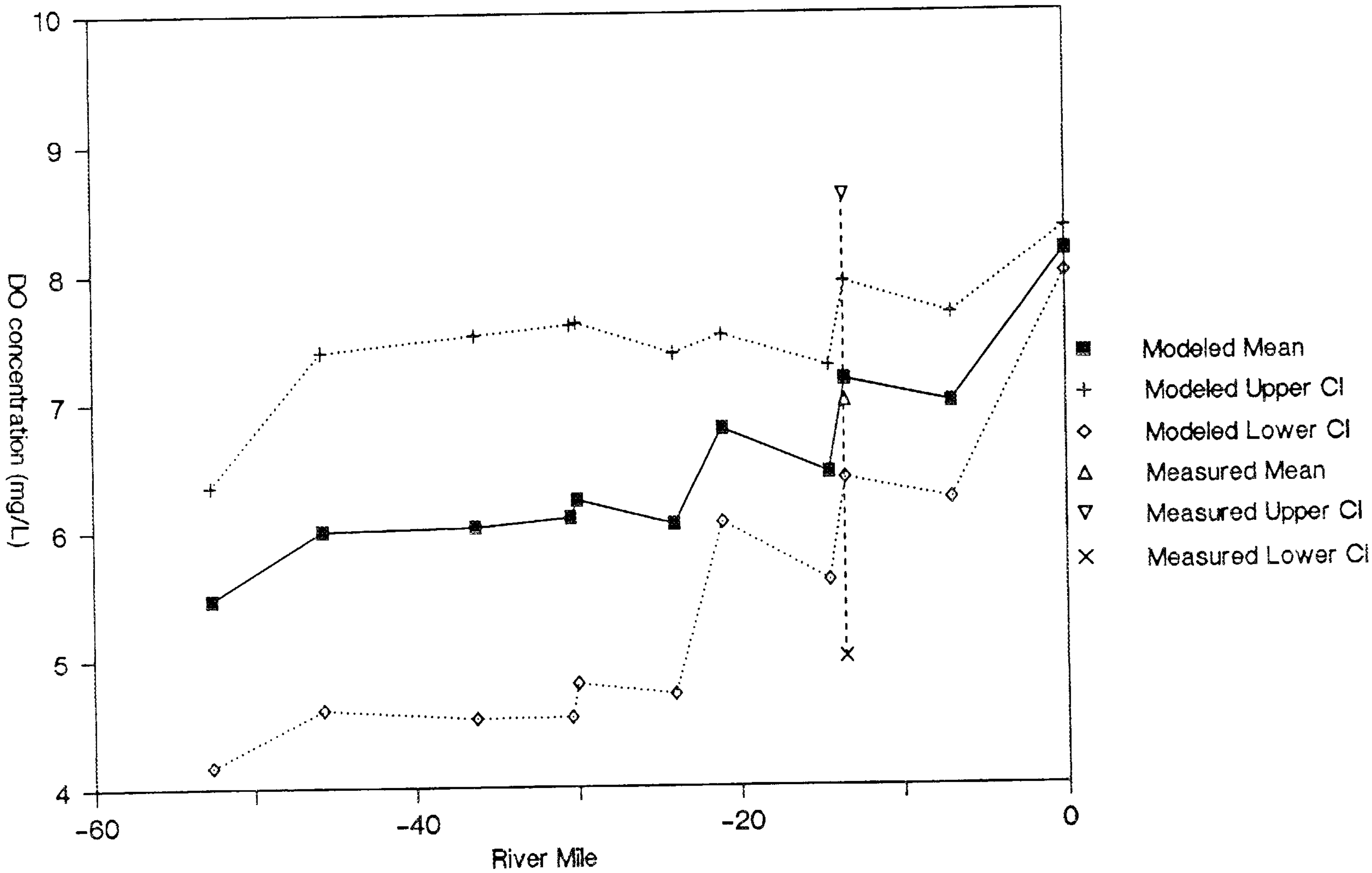

Fig. 23. Uncertainty analysis [95% confidence interval (CI)] for the Allegheny River, under design conditions with moderate flows and no additional hydropower development.

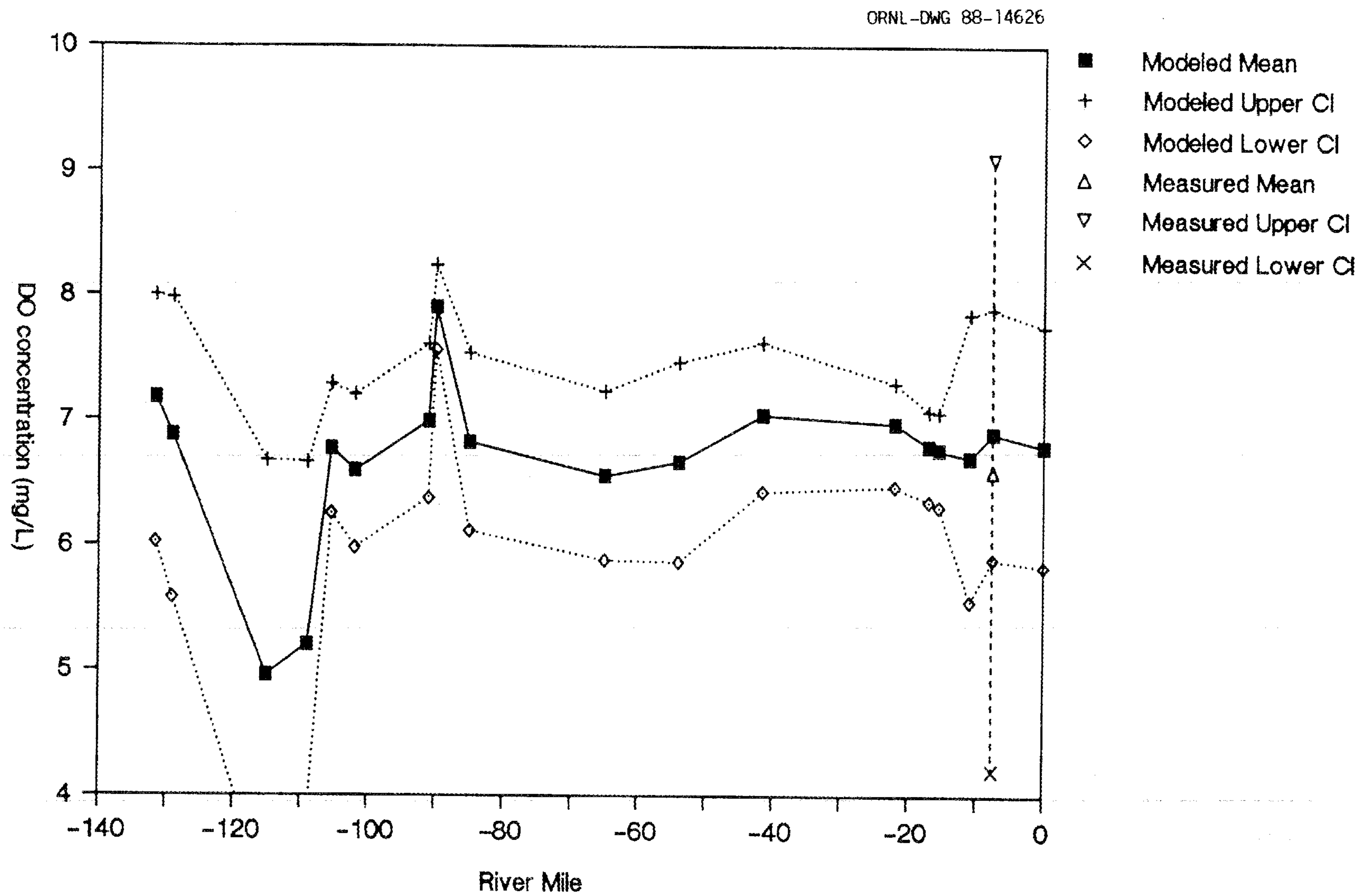

Fig. 24. Uncertainty analysis [95% confidence interval (CI)] for the Monongahela River, under design conditions with moderate flows and no additional hydropower development.

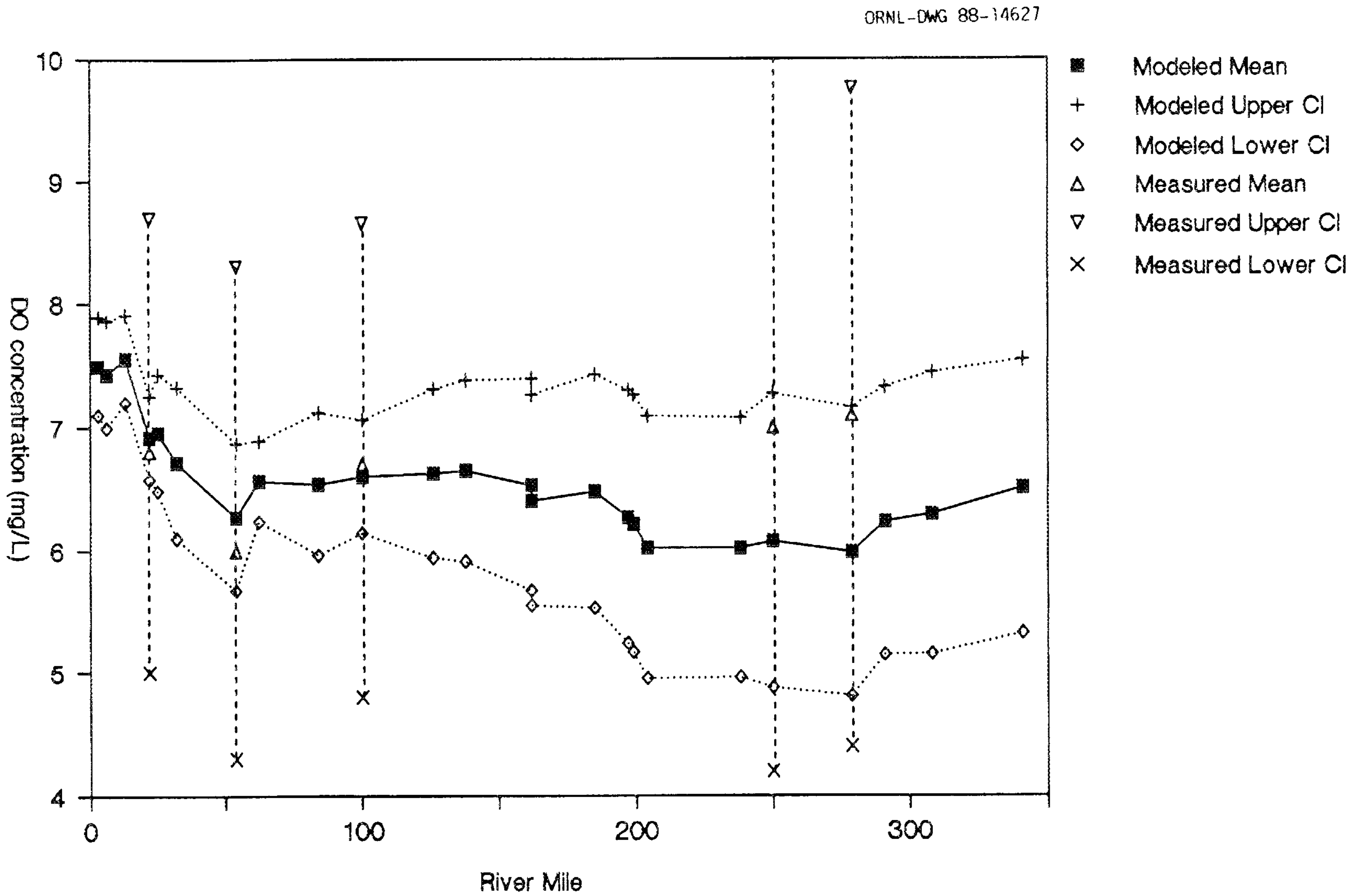

Fig. 25. Uncertainty analysis [95% confidence interval (CI)] for the Ohio River, under design conditions with moderate flows and no additional hydropower development.

the Allegheny and Monongahela rivers and at the first three stations on the Ohio River, the mean measured DO concentration is very close to the mean concentration modeled in the uncertainty analysis. The similarity between the modeled and measured mean concentrations indicates that the parameter frequency distributions used in the uncertainty analysis accurately model actual DO concentrations. There is much more variability in the measured data than there is uncertainty in the model. The variability in the measured data is probably caused by variability in the flow rate, which was constant in the uncertainty analysis, and other processes such as primary productivity that are not incorporated in the model.

In all three rivers, the uncertainty in the model is lowest in the reaches that are most influenced by dam aeration. The clearest example of this is the Allegheny dam 2 reach, where the DO concentration is highly controlled by the aeration at dam 2 (Sect. 8.2.2). Even though the aeration parameters for dam 2 have more uncertainty than those for most other dams, the resulting uncertainty in model results is essentially negligible. In contrast, below Ohio RM 200 where dam aeration has very little effect on DO concentrations, the uncertainty is relatively high. Below Ohio RM 200, DO concentrations are controlled more by the rate coefficients k_1 and k_2 than in the upper end of the river, and uncertainties in the values of these coefficients increase the uncertainty in the model.

8.3.3. Conclusions

The 95% CIs in the Ohio River basin DO model range from less than ± 5% of the mean to about ± 25% of the mean. The uncertainty analysis shows that the dam aeration models give stability to the model results, since the uncertainty is much lower in reaches where DO concentrations are dominated by dam aeration. There is apparently less uncertainty in the linear regression dam aeration parameters (Sect. 2.5) than in the other parameters controlling DO concentrations, since the dam aeration parameters were determined empirically from relatively good data. This conclusion is important because the purpose of the model is to evaluate impacts of changes in dam aeration and to select spill flows that provide adequate DO concentrations. The uncertainty in the model is lowest in the reaches where the decisions based on the model are most important.

9. CONCLUSIONS

The water quality model developed for the upper Ohio River basin hydropower EIS is a simple tool for the assessment of impacts of hydropower development on DO concentrations. The model assumes that the decay of BOD from all sources can be modeled by using a single rate constant per reach, that river conditions are steady, and that channel cross sections are constant with respect to flow rate. These assumptions are reasonable when the model is used for its intended objective of simulating overall (not instantaneous) changes in DO resulting from changes in dam aeration during low flows and high temperatures.

The model should not be used to assess the impacts of changes in other parameters affecting DO concentration, such as wastewater discharges, for which it was not designed. The hydraulic assumptions of the model are not valid at high flow rates, when pool elevations change. The model should not be expected to accurately simulate actual instantaneous conditions in the upper Ohio River basin because actual flows, temperatures, and BOD loads are unsteady, especially over the long travel times through the system. However, the dam aeration models developed for this DO model could easily be included in water quality models that simulate unsteady conditions.

The model has been implemented as a FORTRAN code and as electronic spreadsheets, both of which execute on personal computers. The FORTRAN code has the advantages of being less susceptible to user-induced errors and not requiring prior knowledge of Lotus 1-2-3. The spreadsheet implementation is more easily modified to incorporate new parameters and produces graphic output more easily. Both implementations can easily be modified to include more reaches. The model should be readily usable by FERC for additional analyses of hydropower impacts in the upper Ohio River basin and should be adaptable to other large river systems.

The model results are relatively sensitive to water temperature, flow rates, and the initial DO concentration in the Allegheny River. These parameters especially should be selected with care, and the effects of their variation on results should be investigated in any modeling studies. The uncertainty in the model results is relatively low, especially in the reaches where dam aeration is important, indicating that the model is valid for its intended purpose of simulating changes in DO concentration resulting from changes in aeration at navigation dams.

10. REFERENCES

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APPENDIX A

FORTRAN Model Listing

```
C
C     PROGRAM TO PRODUCE REACH CALCULATIONS MADE WITH 1.2.3 PROGRAM
C         PROGRAMMER  -  B. D. HOLCOMB
C         PROGRAM LAST REVISED  -   6/13/88
C
C     QTYPE     FLAG TO IDENTIFY REACH FLOW CALLED 'QGEN' IN THE
C               READ STATEMENT.  IF QTYPE IS ZERO, QGEN IS THE
C               SPILL, ELSE QGEN IS AS LABELED.
C     NRAGY     NUMBER OF ALLEGHENY RIVER REACHES
C     NRMON     NUMBER OF MONONGAHELA RIVER REACHES
C     NROHIO    NUMBER OF OHIO RIVER REACHES
C     IDOAGY    INITIAL DO IN ALLEGHENY
C     IDOMON    INITIAL DO IN MONONGAHELA
C     ILAGY     INITIAL BOD IN ALLEGHENY
C     ILMON     INITIAL BOD IN MONONGAHELA
C     IQAGY     INITIAL FLOW IN ALLEGHENY
C     IQMON     INITIAL FLOW IN MONONGAHELA
C
C
C     INPUT FOR EACH REACH
C
C
C     RNAME     REACH NAME (CHARACTER)
C     RM        RIVER MILE OF START OF REACH
C     XSEC      CROSS-SECTIONAL AREA, SQUARE FEET
C     DEPTH     DEPTH, FEET
C     TRIBQ     TRIBUTARY INFLOW AT START OF REACH
C     TRIBDO    DO IN TRIBUTARY
C     TRIBL     BOD IN TRIBUTARY
C     LLOAD     BOD LOAD AT START OF REACH, POUNDS PER DAY
C     DAMCOEF   DAM AERATION COEFFICIENT
C     DAMCNST   DAM AERATION CONSTANT
C     QGEN      FLOW USED FOR GENERATION + LOCKAGE AT DAM
C     T         WATER TEMPERATURE
C     K1        BOD RATE COEFFICIENT
C     K2        Aeration rate coefficient.  Use calculated value if
C               input value is zero.
C
C     SYMBOLS
C
C
C     BOD
C     DO        DISSOLVED OXYGEN CONCENTRATION, MG/L
C     D         DISSOLVED OXYGEN DEFICIT, MG/L
C     L         BOD CONCENTRATION, MG/L
C     Q         FLOW
C     T         TEMPERATURE
C
      CHARACTER*6 REACH(30), RNAME, RNAMN, CONF
C
      REAL*4  IDOAGY, IDOMON, ILAGY, ILMON, IQAGY, IQMON, LLOAD
      REAL*4  K1, K2, K1T, K2T, K2MK1, K2SK1, LO, LT
```

```
      REAL*4 K1TC, K2TC, ENDDO(3), ENDBOD(3), ENDFLO(3)
      REAL*4 TAB(35,30), RIQ(3), RIL(3), RIDO(3)
C
      INTEGER*4 NLIM(3), QTYPE
C
      DATA CONF / 'CONF  ' /
C
C
      NRT = 35
      NM = 31
C
C     COEFFICIENT FOR CONVERTING FT/SEC TO MPH
      C1 = 3600./5280.
C
      OPEN (UNIT=8,FILE='ORMDL.DAT',STATUS='OLD')
C
C     OPEN FILES FOR INDIVIDUAL RIVER DATA
C
      OPEN (UNIT=10,FILE='ALLEGHNY.OUT',STATUS='UNKNOWN')
      OPEN (UNIT=11,FILE='MONONGLA.OUT',STATUS='UNKNOWN')
      OPEN (UNIT=12,FILE='OHIO.OUT',STATUS='UNKNOWN')
C
      READ (8,901,END=800) QTYPE, NRAGY, NRMON, NROHIO
C
      NLIM(1) = NRAGY
      NLIM(2) = NRMON
      NLIM(3) = NROHIO
C
C     WRITE (6,*) NRAGY,NRMON, NROHIO
      READ (8,902) IDOAGY, IDOMON, ILAGY, ILMON, IQAGY, IQMON
C
      RIQ(1) = IQAGY
      RIQ(2) = IQMON
      RIQ(3) = 0.
      RIL(1) = ILAGY
      RIL(2) = ILMON
      RIL(3) = 0.
      RIDO(1) = IDOAGY
      RIDO(2) = IDOMON
      RIDO(3) = 0.
C
C     WRITE (6,*) IDOAGY, IDOMON, ILAGY, ILMON, IQAGY, IQMON
  901 FORMAT(8X,1I6)
  902 FORMAT(8X,1F6.0)
C
      READ (8,903)
  903 FORMAT(4X)
      READ (8,903)
      READ (8,903)
      READ (8,903)
C
C
```

```
C
      DO 500 NRIV=1,3
C
      NR = 0
      RFLOW = RIQ(NRIV)
C
      IF(NRIV.EQ.3) THEN
         RFLOW = ENDFLO(1) + ENDFLO(2)
         RIL(NRIV) = (ENDBOD(1)*ENDFLO(1) + ENDBOD(2)*ENDFLO(2))/RFLOW
         RIDO(NRIV) = (ENDDO(1)*ENDFLO(1) + ENDDO(2)*ENDFLO(2))/RFLOW
C     *******    PATCH    *********
C        RFLOW = 12680.
C        RIQ(3) = 12680.
C        RIL(3) = 0.64
C        RIDO(3) = 6.50
C     ******************************
      ENDIF
C
      FBOD = RIL(NRIV)
      FDO = RIDO(NRIV)
      FQ = RIQ(NRIV)
      NNN = NLIM(NRIV) + 1
      DO 300 NREC=1,NNN
C
      IF(NREC.NE.NNN) THEN
   50 READ (8,900,END=800) RNAME, RM, TRIBQ, XSEC, DEPTH, TRIBDO,
     X   TRIBL, LLOAD, DAMCOF, DAMCST, QGEN, T, K1, K2
  900 FORMAT(1A6,1F5.1,2F7.0,1F4.0,2F5.0,1F7.0,2F6.2,1F7.0,
     X  1F4.0,1F5.3,1F6.3)
C     WRITE (6,900) RNAME, RM, TRIBQ, XSE , DEPTH, TRIBDO,
C    X   TRIBL, LLOAD, DAMCOF, DAMCST, QGEN, T, K1
C
      ELSE
C
C SETUP CONFLUENCE VECTOR
C
         IF(NRIV.EQ.3) GO TO 300
         RM = 0.
         TRIBQ = 0.
         TRIBDO = 0.
         TRIBL = 0.
         DAMCOF = 1.
         DAMCST = 0.
         QGEN = 0.
         LLOAD = 0.
         RNAME = CONF
      ENDIF
C
      NR = NR + 1
      TSQ = T*T
C
C
```

```
      REACH(NR) = RNAME
      TAB(1,NR) = RM
      TAB(3,NR) = TRIBQ
      TAB(9,NR) = TRIBDO
      TAB(10,NR) = TRIBL
      TAB(11,NR) = LLOAD
      TAB(12,NR) = DAMCOF
      TAB(13,NR) = DAMCST
C
C     CALCULATIONS FOR EACH REACH (DAMS ARE ASSUMED TO BE AT START
C         OF REACH)
C
C     REACH LENGTH IN FEET: CALCULATE FROM RIVER MILE OF REACH AND
C     DOWNSTREAM REACH.  RIVER MILES ARE DISTANCE FROM CONFLUENCE
C     OF ALLEGHENY AND MONONGAHELA.
C
C     GET NEXT RECORD TO DETERMINE REACH LENGTH
      IF(NREC.LT.NNN-1) THEN
         READ (8,900) RNAMN, RNEXT
         BACKSPACE 8
      ELSE
         RNEXT = 0.
      ENDIF
C
C     FLOW:  ADD TRIBUTARY FLOW IN UPSTREAM REACH (CU FT/SEC)
         RFLOW = RFLOW + TRIBQ
      IF(QTYPE.EQ.0 .AND. NNN.NE.NREC) THEN
          QSPILL = QGEN
          QGEN = RFLOW - QSPILL
      ELSE
          QSPILL = RFLOW - QGEN
      ENDIF
C
C
C
C     GET REACH LENGTH (FEET)
      RLEN = ABS((RM - RNEXT))*5280.
      TAB(2,NR) = RLEN
C
C     CALCULATE VELOCITY:  FLOW DIVIDED BY XSEC (FT/SEC)
      RVEL = RFLOW / XSEC
      RVMPH = C1*RVEL
      RVMPD = RVMPH*24.
      TAB(4,NR) = RFLOW
      TAB(5,NR) = XSEC
      TAB(6,NR) = DEPTH
      TAB(7,NR) = RVEL
C
```

```
C      TRAVEL TIME, DAYS:  REACH LENGTH DIVIDED BY VELOCITY
       TTSECS = RLEN/RVEL
       TTDAYS = TTSECS/86400.
       TAB(8,NR) = TTDAYS
       TTOR = TTDAYS
C
C      DO SATURATION CONCENTRATION:
       TERM = TSQ*(0.00791-0.77774E-04*T)
       DOSAT = 14.652 - 0.41022*T + TERM
C
C      DO ABOVE DAM:  DO MASS BALANCE ON DO IN TRIBUTARY AND DO FROM
C      DOWNSTREAM END OF PREVIOUS REACH.
C
C      DO ABOVE DAM
       DOADAM = ((TRIBQ*TRIBDO) + (FQ*FDO)) / RFLOW
C
C      GET DO DEFICIT ABOVE DAM
       DODAD = DOSAT - DOADAM
C
C      DO DEFICIT AFTER AERATION
       DODAA = DODAD*DAMCOF - DAMCST
C
C      DO DEFICIT BELOW DAM
C
       DOBDAM = (DODAD*QGEN + DODAA*(QSPILL)) / RFLOW
C
C      GET STARTING BOD
       LO = (TRIBQ*TRIBL + FQ*FBOD) / RFLOW
C      ADD BOD FROM POINT SOURCE LOAD LLOAD:
       LO = LO + 0.185*LLOAD/RFLOW
       TAB(14,NR) = QGEN
       TAB(15,NR) = DOADAM
       TAB(16,NR) = LO
       TAB(17,NR) = T
       TAB(18,NR) = DOSAT
C
C      FIND K2 (REAERATION RATE COEFFICIENT)
C      Calculate from OConnor Dobbins Eq. if not input.
C
       IF (K2.EQ.0) K2 = 12.9*SQRT(RVEL)/(DEPTH**1.5)
C
C      TEMPERATURE-CORRECTED RATE COEFFICIENTS K1 AND K2
       K1TC = K1*1.047**(T-20)
       K2TC = K2*1.024**(T-20)
       K2MK1 = K2TC - K1TC
       K1T = K1TC*TTDAYS
       K2T = K2TC*TTDAYS
       K2SK1 = K2TC/K1TC
       TAB(19,NR) = K1
       TAB(20,NR) = K2
       TAB(21,NR) = K1TC
       TAB(22,NR) = K2TC
```

```
C
C     DO DEFICIT AT HEAD OF REACH:
      DODHR = DOBDAM
C
C     DO DEFICIT AT END OF REACH:
      DT = (K1TC*LO)/(K2MK1)*(EXP(-K1T) - EXP(-K2T))
      DT = DT + DODHR*(EXP(-K2T))
C
C     DO CONCENTRATION AT END OF REACH:
      DOEOR = DOSAT - DT
C
C     BOD AT END OF REACH
      LT = LO*EXP(-K1T)
C
C     CRITICAL TIME  -  TRAVEL TIME FROM BEGINNING OF REACH TO
C     MAXIMUM DO DEFICIT
      TCRIT = 0.
      ALF = K2SK1*(1.-(K2MK1*DODHR)/(K1TC*LO))
      IF(ALF.GE.0.) THEN
         TCRIT = (1./K2MK1)*LOG(ALF)
      ENDIF
C
C     CHECK TCRIT FOR NEGATIVE VALUE
      IF(TCRIT.LT.0.) TCRIT = 0.
C     SET TCRIT TO THE TRAVEL TIME OF THE REACH IF IT EXCEEDS
C     THE TRAVEL TIME OF THE REACH
      IF(TCRIT.GT.TTOR) TCRIT = TTOR
C
C     CALCULATE CRITICAL DISTANCE, IN RIVER MILES  - LOCATION OF
C     HIGHEST DO DEFICIT
      DCRIT = TCRIT*RVMPD
C     CHANGE MILES TO CORESPONDING RIVER MILE
      IF(NRIV.LE.2) DCRIT = RM - DCRIT
      IF(NRIV.EQ.3) DCRIT = RM + DCRIT
C
C
      TAB(23,NR) = DODHR
      TAB(24,NR) = DT
      TAB(25,NR) = DOSAT - DODHR
      TAB(26,NR) = DOEOR
      TAB(27,NR) = LT
      TAB(28,NR) = TCRIT
C
C     GET CRITICAL DEFICIT
      K1T = K1TC*TCRIT
      K2T = K2TC*TCRIT
      DEFCR = (K1TC*LO)/(K2MK1)*(EXP(-K1T) - EXP(-K2T))
      DEFCR = DEFCR + DODHR*(EXP(-K2T))
      TAB(29,NR) = DEFCR
      TAB(30,NR) = DOSAT - DEFCR
```

```
C     IF LOG TERM OF CRITICAL TIME CALCULATION IS NEGATIVE
C      THEN SET CRITICAL DO TO THE MINIMUM OF THE DO VALUES
C      AT THE ENDS OF THE REACH.
      IF(ALF.LT.0.) TAB(30,NR) = MIN(TAB(25,NR),TAB(26,NR))
      TAB(31,NR) = DCRIT
      FDO = DOEOR
      FBOD = LT
      FQ = RFLOW
C
      IF(NREC.EQ.NNN-1) THEN
         ENDDO(NRIV) = FDO
         ENDBOD(NRIV) = FBOD
         ENDFLO(NRIV) = FQ
      ENDIF
C
C     GET NEXT RECORD
  300 CONTINUE
C
      RIQ(3) = RIQ(3) + RFLOW
C
        CALL TPRINT(TAB,REACH,NM,NR,NRIV)
C
C
C     WRITE SUMMARY INFORMATION FOR EACH REACH
      IOD = 9 + NRIV
      NRM1 = NR - 1
      DO 350 J=1,NRM1
C     WRITE (IOD,904) J, REACH(J)
      WRITE (IOD,905) TAB(1,J), TAB(25,J)
      WRITE (IOD,905) TAB(31,J), TAB(30,J)
      WRITE (IOD,905) TAB(1,J+1), TAB(26,J)
  350 CONTINUE
C
C
  500 CONTINUE
  904 FORMAT(' REACH NO.',1I4,4X,1A6)
  905 FORMAT(2F12.3)
C
  800 STOP
      END
      SUBROUTINE TPRINT(TAB,REACH,NR,NC,NRIV)
      REAL*4 TAB(35,30)
C
      CHARACTER*6 REACH(30)
      CHARACTER*18 LABEL(32)
      CHARACTER*11 RIVNAM(3)
C
```

```
      DATA (LABEL(I),I=1,31) /
     1              'RIVER MILE         ','REACH LENGTH, FT  ',
     2              'TRIB FLOW          ','FLOW, CFS         ',
     3              'X-SECT. AREA       ','DEPTH, FT         ',
     4              'VELOCITY           ','TRAVEL TIME, DAYS ',
     5              'TRIB DO            ','TRIB BOD          ',
     6              'BOD LOADING,#/DAY  ','DAM AER COEF      ',
     7              'DAM AER CONSTANT   ','FLOW NOT AERATED  ',
     8              'DO ABOVE DAM       ','STARTING BOD      ',
     9              'REACH TEMP.        ','DO SATURATION     ',
     1              'K1 (20 DEG)        ','K2 (20 DEG)       ',
     2              'K1 (T)             ','K2 (T)            ',
     3              'INITIAL DEFICIT    ','FINAL DEFICIT     ',
     4              'STARTING DO        ','FINAL DO          ',
     5              'FINAL BOD          ','CRITICAL TIME     ',
     6              'CRIT. DEFICIT      ','CRITICAL DO       ',
     7              'CRIT. DISTANCE, RM'/
C
      DATA (RIVNAM(I),I=1,3) / '  ALLEGHENY','MONONGAHELA',
     1                         '       OHIO'/
C
      NCOLS = 6
      NFULLB = NC/NCOLS
      IF(MOD(NC,NCOLS).NE.0) NFULLB = NFULLB + 1
      NSKIP = MAX(1,60/(NR+4))
      WRITE (6,901) RIVNAM(NRIV)
C
      DO 200 M=1,NFULLB
      NC1 = NCOLS*(M-1) + 1
      NC2 = NCOLS*M
      IF(M.EQ.NFULLB) NC2 = NC
      WRITE (6,904) (REACH(J),J=NC1,NC2)
      DO 100 I=1,NR
C
      WRITE (6,903) LABEL(I), (TAB(I,J),J=NC1,NC2)
  100 CONTINUE
C
      IF(NC2.EQ.NC) GO TO 800
      IF(M.EQ.NSKIP*(M/NSKIP))  THEN
         WRITE (6,901) RIVNAM(NRIV)
      ENDIF
C
  200 CONTINUE
  901 FORMAT('1   ',8X,1A11,' RIVER ')
  903 FORMAT(1X,1A18,6F10.2)
  904 FORMAT('0REACH',14X,6A10)
  800 RETURN
      END
```

APPENDIX B

Sample FORTRAN Model Output

ALLEGHENY RIVER

REACH	All 9	All 8	All 7	All 6	All 5	Kiski
RIVER MILE	62.20	52.60	45.70	36.30	30.40	30.00
REACH LENGTH, FT	50688.01	36431.99	49632.01	31152.00	2112.00	30624.00
TRIB FLOW	0.00	0.00	0.00	0.00	0.00	1690.00
FLOW, CFS	5850.00	5850.00	5850.00	5850.00	5850.00	7540.00
X-SECT. AREA	13700.00	10100.00	11200.00	13000.00	12300.00	12300.00
DEPTH, FT	15.00	11.00	11.00	15.00	14.00	14.00
VELOCITY	0.43	0.58	0.52	0.45	0.48	0.61
TRAVEL TIME, DAYS	1.37	0.73	1.10	0.80	0.05	0.58
TRIB DO	0.00	0.00	0.00	0.00	0.00	6.00
TRIB BOD	0.00	0.00	0.00	0.00	0.00	5.00
BOD LOADING,#/DAY	0.00	4000.00	4000.00	4000.00	4000.00	0.00
DAM AER COEF	0.58	0.61	0.90	0.69	0.57	1.00
DAM AER CONSTANT	0.00	0.62	0.00	0.00	0.00	0.00
FLOW NOT AERATED	3600.00	3600.00	5450.00	4850.00	4680.00	0.00
DO ABOVE DAM	6.00	6.13	6.37	6.12	5.99	6.11
STARTING BOD	4.00	3.49	3.01	2.35	2.01	2.67
REACH TEMP.	25.00	26.00	27.00	27.00	27.00	27.00
DO SATURATION	8.13	7.97	7.81	7.81	7.81	7.81
K1 (20 DEG)	0.10	0.20	0.20	0.20	0.10	0.10
K2 (20 DEG)	0.15	0.27	0.26	0.15	0.17	0.19
K1 (T)	0.13	0.26	0.28	0.28	0.14	0.14
K2 (T)	0.16	0.31	0.30	0.18	0.20	0.23
INITIAL DEFICIT	1.78	1.32	1.43	1.60	1.67	1.70
FINAL DEFICIT	1.99	1.60	1.69	1.82	1.66	1.68
STARTING DO	6.34	6.65	6.38	6.21	6.14	6.11
FINAL DO	6.13	6.37	6.12	5.99	6.15	6.13
FINAL BOD	3.37	2.88	2.22	1.88	1.99	2.46
CRITICAL TIME	1.37	0.73	1.10	0.80	0.00	0.00
CRIT. DEFICIT	1.99	1.60	1.69	1.82	1.67	1.70
CRITICAL DO	6.13	6.37	6.12	5.99	6.14	6.11
CRIT. DISTANCE, RM	52.60	45.70	36.30	30.40	30.40	30.00

ALLEGHENY RIVER

REACH	All 4	AVJt	All 3	AVJt	All 2	CONF
RIVER MILE	24.20	21.20	14.50	13.50	6.70	0.00
REACH LENGTH, FT	15840.00	35376.00	5280.00	35904.00	35376.00	0.00
TRIB FLOW	0.00	0.00	0.00	0.00	0.00	0.00
FLOW, CFS	7540.00	7540.00	7540.00	7540.00	7540.00	7540.00
X-SECT. AREA	12300.00	18600.00	15900.00	15900.00	13700.00	13700.00
DEPTH, FT	14.00	26.00	15.00	15.00	15.00	15.00
VELOCITY	0.61	0.41	0.47	0.47	0.55	0.55
TRAVEL TIME, DAYS	0.30	1.01	0.13	0.88	0.74	0.00
TRIB DO	0.00	0.00	0.00	0.00	0.00	0.00
TRIB BOD	0.00	0.00	0.00	0.00	0.00	0.00
BOD LOADING,#/DAY	0.00	1500.00	0.00	1000.00	0.00	0.00
DAM AER COEF	0.56	1.00	0.92	1.00	0.12	1.00
DAM AER CONSTANT	0.00	0.00	0.67	0.00	0.92	0.00
FLOW NOT AERATED	7140.00	0.00	7240.00	0.00	6640.00	0.00
DO ABOVE DAM	6.13	6.18	6.00	6.03	6.05	6.34
STARTING BOD	2.46	2.40	2.09	2.07	1.83	1.64
REACH TEMP.	27.00	27.00	28.00	28.00	28.00	28.00
DO SATURATION	7.81	7.81	7.66	7.66	7.66	7.66
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.19	0.06	0.15	0.15	0.16	0.16
K1 (T)	0.14	0.14	0.14	0.14	0.14	0.14
K2 (T)	0.23	0.07	0.18	0.18	0.20	0.20
INITIAL DEFICIT	1.64	1.63	1.63	1.63	1.33	1.32
FINAL DEFICIT	1.63	1.81	1.63	1.61	1.32	1.32
STARTING DO	6.17	6.18	6.03	6.03	6.33	6.34
FINAL DO	6.18	6.00	6.03	6.05	6.34	6.34
FINAL BOD	2.36	2.09	2.05	1.83	1.64	1.64
CRITICAL TIME	0.00	1.01	0.01	0.00	0.00	0.00
CRIT. DEFICIT	1.64	1.81	1.63	1.63	1.33	1.32
CRITICAL DO	6.17	6.00	6.03	6.03	6.33	6.34
CRIT. DISTANCE, RM	24.20	14.50	14.44	13.50	6.70	0.00

MONONGAHELA RIVER

REACH	T Dam	HdNav	W.Fk	Ope	Hild	C.Mrg
RIVER MILE	151.40	131.50	128.70	115.40	108.00	105.50
REACH LENGTH, FT	105071.97	14784.02	70223.98	39072.01	13200.00	18480.00
TRIB FLOW	0.00	0.00	40.00	0.00	0.00	0.00
FLOW, CFS	1750.00	1750.00	1790.00	1790.00	1790.00	1790.00
X-SECT. AREA	2900.00	5000.00	9000.00	8550.00	8600.00	8600.00
DEPTH, FT	6.00	15.00	18.00	19.00	17.00	17.00
VELOCITY	0.60	0.35	0.20	0.21	0.21	0.21
TRAVEL TIME, DAYS	2.02	0.49	4.09	2.16	0.73	1.03
TRIB DO	0.00	9.00	8.00	0.00	0.00	0.00
TRIB BOD	0.00	0.00	0.00	0.00	0.00	0.00
BOD LOADING, #/DAY	0.00	2000.00	4000.00	4000.00	4000.00	4000.00
DAM AER COEF	1.00	1.00	1.00	1.00	0.32	1.00
DAM AER CONSTANT	0.00	0.00	0.00	0.00	-0.10	0.00
FLOW NOT AERATED	0.00	0.00	0.00	1475.00	1475.00	0.00
DO ABOVE DAM	8.00	6.93	6.78	5.64	5.38	5.60
STARTING BOD	5.00	4.14	4.20	2.83	2.55	2.72
REACH TEMP.	24.00	26.50	26.50	26.00	26.00	26.00
DO SATURATION	8.29	7.89	7.89	7.97	7.97	7.97
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.00	0.13	0.08	0.07	0.08	0.08
K1 (T)	0.12	0.13	0.13	0.13	0.13	0.13
K2 (T)	0.01	0.15	0.09	0.08	0.10	0.10
INITIAL DEFICIT	0.29	0.95	1.11	2.32	2.29	2.36
FINAL DEFICIT	1.35	1.14	2.25	2.59	2.36	2.47
STARTING DO	8.00	6.93	6.78	5.64	5.67	5.60
FINAL DO	6.93	6.75	5.64	5.38	5.60	5.50
FINAL BOD	3.92	3.87	2.42	2.13	2.31	2.38
CRITICAL TIME	2.02	0.49	4.09	2.16	0.73	1.03
CRIT. DEFICIT	1.35	1.14	2.25	2.59	2.36	2.47
CRITICAL DO	6.93	6.75	5.64	5.38	5.60	5.50
CRIT. DISTANCE, RM	131.50	128.70	115.40	108.00	105.50	102.00

MONONGAHELA RIVER

REACH	Morg	PM	Cheat	Mon 7	Max	Mon 4
RIVER MILE	102.00	90.80	89.60	85.00	61.20	41.50
REACH LENGTH, FT	59135.98	6336.02	24287.99	125663.99	104016.01	93456.01
TRIB FLOW	0.00	0.00	730.00	0.00	105.00	80.00
FLOW, CFS	1790.00	1790.00	2520.00	2520.00	2625.00	2705.00
X-SECT. AREA	8400.00	4700.00	8600.00	10900.00	11300.00	7700.00
DEPTH, FT	17.00	10.00	14.00	16.00	16.00	10.00
VELOCITY	0.21	0.38	0.29	0.23	0.23	0.35
TRAVEL TIME, DAYS	3.21	0.19	0.96	6.29	5.18	3.08
TRIB DO	0.00	0.00	6.00	6.00	7.00	7.00
TRIB BOD	0.00	0.00	5.00	5.00	2.00	0.00
BOD LOADING,#/DAY	0.00	4000.00	4000.00	4000.00	5000.00	6000.00
DAM AER COEF	0.65	0.40	1.00	0.36	0.69	0.61
DAM AER CONSTANT	0.21	0.64	0.00	0.07	0.22	0.18
FLOW NOT AERATED	1475.00	1595.00	0.00	86.00	2625.00	2255.00
DO ABOVE DAM	5.50	5.58	5.90	5.81	6.32	6.40
STARTING BOD	2.38	1.96	3.10	3.01	1.64	1.19
REACH TEMP.	26.50	27.00	27.00	27.00	27.00	27.00
DO SATURATION	7.89	7.81	7.81	7.81	7.81	7.81
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.08	0.25	0.13	0.10	0.10	0.24
K1 (T)	0.13	0.14	0.14	0.14	0.14	0.14
K2 (T)	0.10	0.30	0.16	0.11	0.11	0.29
INITIAL DEFICIT	2.21	2.02	1.91	0.70	1.49	1.29
FINAL DEFICIT	2.31	1.96	2.00	1.52	1.43	0.80
STARTING DO	5.68	5.79	5.90	7.11	6.32	6.52
FINAL DO	5.58	5.85	5.81	6.29	6.38	7.01
FINAL BOD	1.54	1.91	2.71	1.26	0.80	0.78
CRITICAL TIME	2.47	0.00	0.96	6.29	1.82	0.00
CRIT. DEFICIT	2.32	2.02	2.00	1.52	1.54	1.29
CRITICAL DO	5.57	5.79	5.81	6.29	6.27	6.52
CRIT. DISTANCE, RM	93.40	90.80	85.00	61.20	54.28	41.50

MONONGAHELA RIVER

REACH	Mon 3	PA4472	P26913	Yough	Mon 2	PA4481
RIVER MILE	23.80	21.80	17.30	15.50	11.20	7.60
REACH LENGTH, FT	10560.00	23760.00	9504.00	22704.00	19008.00	40128.00
TRIB FLOW	0.00	0.00	0.00	3120.00	0.00	0.00
FLOW, CFS	2705.00	2705.00	2705.00	5825.00	5825.00	5825.00
X-SECT. AREA	7200.00	9450.00	7900.00	10600.00	8300.00	11800.00
DEPTH, FT	10.00	9.00	11.00	13.00	10.00	12.00
VELOCITY	0.38	0.29	0.34	0.55	0.70	0.49
TRAVEL TIME, DAYS	0.33	0.96	0.32	0.48	0.31	0.94
TRIB DO	7.00	0.00	0.00	7.00	0.00	0.00
TRIB BOD	0.00	0.00	0.00	2.00	0.00	0.00
BOD LOADING,#/DAY	5000.00	2000.00	2000.00	2000.00	2000.00	2000.00
DAM AER COEF	0.81	1.00	1.00	1.00	0.93	1.00
DAM AER CONSTANT	-0.14	0.00	0.00	0.00	0.20	0.00
FLOW NOT AERATED	80.00	0.00	0.00	0.00	100.00	0.00
DO ABOVE DAM	7.01	6.85	6.75	6.88	6.82	7.05
STARTING BOD	1.12	1.20	1.15	1.64	1.58	1.57
REACH TEMP.	32.00	32.00	31.00	30.00	29.00	29.00
DO SATURATION	7.08	7.08	7.22	7.36	7.51	7.51
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.20
K2 (20 DEG)	0.25	0.26	0.21	0.20	0.34	0.22
K1 (T)	0.17	0.17	0.17	0.16	0.15	0.30
K2 (T)	0.33	0.34	0.27	0.26	0.42	0.27
INITIAL DEFICIT	0.19	0.23	0.47	0.49	0.45	0.46
FINAL DEFICIT	0.23	0.32	0.48	0.54	0.46	0.70
STARTING DO	6.89	6.85	6.75	6.88	7.07	7.05
FINAL DO	6.85	6.75	6.74	6.82	7.05	6.81
FINAL BOD	1.06	1.01	1.09	1.52	1.51	1.18
CRITICAL TIME	0.33	0.96	0.32	0.48	0.31	0.94
CRIT. DEFICIT	0.23	0.32	0.48	0.54	0.46	0.70
CRITICAL DO	6.85	6.75	6.74	6.82	7.05	6.81
CRIT. DISTANCE, RM	21.80	17.30	15.50	11.20	7.60	0.00

MONONGAHELA RIVER

REACH	CONF
RIVER MILE	0.00
REACH LENGTH, FT	0.00
TRIB FLOW	0.00
FLOW, CFS	5825.00
X-SECT. AREA	11800.00
DEPTH, FT	12.00
VELOCITY	0.49
TRAVEL TIME, DAYS	0.00
TRIB DO	0.00
TRIB BOD	0.00
BOD LOADING,#/DAY	0.00
DAM AER COEF	1.00
DAM AER CONSTANT	0.00
FLOW NOT AERATED	0.00
DO ABOVE DAM	6.81
STARTING BOD	1.18
REACH TEMP.	29.00
DO SATURATION	7.51
K1 (20 DEG)	0.20
K2 (20 DEG)	0.22
K1 (T)	0.30
K2 (T)	0.27
INITIAL DEFICIT	0.70
FINAL DEFICIT	0.70
STARTING DO	6.81
FINAL DO	6.81
FINAL BOD	1.18
CRITICAL TIME	0.00
CRIT. DEFICIT	0.70
CRITICAL DO	6.81
CRIT. DISTANCE, RM	0.00

OHIO RIVER

REACH	Conf	ALCOS	Ems	Dash	LTV	Beavr
RIVER MILE	0.00	3.10	6.20	13.30	22.40	25.40
REACH LENGTH, FT	16368.00	16368.00	37488.00	48048.00	15840.00	33264.01
TRIB FLOW	0.00	0.00	0.00	0.00	0.00	2860.00
FLOW, CFS	13365.00	13365.00	13365.00	13365.00	13365.00	16225.00
X-SECT. AREA	20000.00	23000.00	17000.00	21000.00	30000.00	33000.00
DEPTH, FT	20.00	19.00	15.00	17.00	23.00	25.00
VELOCITY	0.67	0.58	0.79	0.64	0.45	0.49
TRAVEL TIME, DAYS	0.28	0.33	0.55	0.87	0.41	0.78
TRIB DO	5.90	0.00	0.00	0.00	0.00	6.00
TRIB BOD	0.74	0.00	0.00	0.00	0.00	2.00
BOD LOADING,#/DAY	0.00	193000.00	0.00	0.00	5000.00	0.00
DAM AER COEF	1.00	1.00	0.64	0.72	1.00	1.00
DAM AER CONSTANT	0.00	0.00	0.12	0.67	0.00	0.00
FLOW NOT AERATED	0.00	0.00	9470.00	12400.00	0.00	0.00
DO ABOVE DAM	6.54	6.49	6.31	6.21	5.88	5.76
STARTING BOD	1.44	4.06	3.87	3.58	3.23	2.87
REACH TEMP.	27.80	27.70	27.60	27.60	27.50	27.30
DO SATURATION	7.69	7.71	7.72	7.72	7.74	7.77
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.01	0.01	0.01	0.01	0.01	0.01
K1 (T)	0.14	0.14	0.14	0.14	0.14	0.14
K2 (T)	0.01	0.01	0.01	0.01	0.01	0.01
INITIAL DEFICIT	1.15	1.21	1.23	1.43	1.85	2.01
FINAL DEFICIT	1.20	1.39	1.51	1.84	2.03	2.29
STARTING DO	6.54	6.49	6.49	6.29	5.88	5.76
FINAL DO	6.49	6.31	6.21	5.88	5.71	5.48
FINAL BOD	1.39	3.87	3.58	3.16	3.05	2.57
CRITICAL TIME	0.28	0.33	0.55	0.87	0.41	0.78
CRIT. DEFICIT	1.20	1.39	1.51	1.84	2.03	2.29
CRITICAL DO	6.49	6.31	6.21	5.88	5.71	5.48
CRIT. DISTANCE, RM	3.10	6.20	13.30	22.40	25.40	31.70

OHIO RIVER

REACH	Mont	New C	Weirt	PikeI	RM100	Hann
RIVER MILE	31.70	54.40	62.50	84.20	100.00	126.40
REACH LENGTH, FT	119856.01	42767.99	114575.98	83424.02	139392.02	71807.99
TRIB FLOW	0.00	0.00	0.00	0.00	0.00	0.00
FLOW, CFS	16225.00	16225.00	16225.00	16225.00	16225.00	16225.00
X-SECT. AREA	29000.00	17000.00	30500.00	14000.00	30000.00	19000.00
DEPTH, FT	22.00	14.00	23.00	14.00	26.00	17.00
VELOCITY	0.56	0.95	0.53	1.16	0.54	0.85
TRAVEL TIME, DAYS	2.48	0.52	2.49	0.83	2.98	0.97
TRIB DO	0.00	0.00	5.00	0.00	0.00	0.00
TRIB BOD	0.00	0.00	10.00	0.00	0.00	0.00
BOD LOADING,#/DAY	20000.00	20000.00	20000.00	20000.00	20000.00	30000.00
DAM AER COEF	0.78	0.38	1.00	0.72	1.00	0.89
DAM AER CONSTANT	0.61	0.50	0.00	0.23	0.00	0.28
FLOW NOT AERATED	15210.00	16260.00	0.00	16260.00	0.00	16260.00
DO ABOVE DAM	5.48	4.78	4.63	4.00	3.81	3.29
STARTING BOD	2.80	2.20	2.26	1.78	1.80	1.50
REACH TEMP.	27.50	29.00	29.00	29.00	28.50	28.60
DO SATURATION	7.74	7.51	7.51	7.51	7.59	7.57
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.01	0.01	0.01	0.01	0.01	0.01
K1 (T)	0.14	0.15	0.15	0.15	0.15	0.15
K2 (T)	0.01	0.01	0.01	0.01	0.01	0.01
INITIAL DEFICIT	2.19	2.73	2.88	3.52	3.77	4.28
FINAL DEFICIT	2.95	2.88	3.51	3.70	4.29	4.44
STARTING DO	5.55	4.78	4.63	4.00	3.81	3.29
FINAL DO	4.78	4.63	4.00	3.81	3.29	3.13
FINAL BOD	1.97	2.03	1.55	1.57	1.16	1.30
CRITICAL TIME	2.48	0.52	2.49	0.83	2.98	0.97
CRIT. DEFICIT	2.95	2.88	3.51	3.70	4.29	4.44
CRITICAL DO	4.78	4.63	4.00	3.81	3.29	3.13
CRIT. DISTANCE, RM	54.40	62.50	84.20	100.00	126.40	140.00

OHIO RIVER

REACH	RM140	W I	Musk	L Kan	duPnt	HockR
RIVER MILE	140.00	161.70	172.00	184.60	196.80	199.30
REACH LENGTH, FT	114575.98	54384.02	66528.03	64415.98	13200.00	24287.95
TRIB FLOW	0.00	0.00	1660.00	0.00	0.00	520.00
FLOW, CFS	16225.00	16225.00	17885.00	17885.00	17885.00	18405.00
X-SECT. AREA	33500.00	13000.00	26000.00	33000.00	33000.00	42000.00
DEPTH, FT	23.00	12.00	19.00	27.00	27.00	33.00
VELOCITY	0.48	1.25	0.69	0.54	0.54	0.44
TRAVEL TIME, DAYS	2.74	0.50	1.12	1.38	0.28	0.64
TRIB DO	0.00	0.00	7.00	6.00	0.00	6.00
TRIB BOD	0.00	0.00	2.00	3.00	0.00	3.00
BOD LOADING,#/DAY	30000.00	30000.00	30000.00	30000.00	30000.00	30000.00
DAM AER COEF	1.00	0.97	1.00	1.00	1.00	1.00
DAM AER CONSTANT	0.00	0.17	0.00	0.00	0.00	0.00
FLOW NOT AERATED	0.00	16260.00	0.00	0.00	0.00	0.00
DO ABOVE DAM	3.13	2.71	3.04	2.83	2.57	2.61
STARTING BOD	1.64	1.43	1.70	1.75	1.74	2.01
REACH TEMP.	28.60	28.60	28.60	28.60	28.60	28.60
DO SATURATION	7.57	7.57	7.57	7.57	7.57	7.57
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.01	0.01	0.01	0.01	0.01	0.01
K1 (T)	0.15	0.15	0.15	0.15	0.15	0.15
K2 (T)	0.01	0.01	0.01	0.01	0.01	0.01
INITIAL DEFICIT	4.44	4.86	4.54	4.74	5.00	4.96
FINAL DEFICIT	4.86	4.94	4.74	5.00	5.06	5.11
STARTING DO	3.13	2.71	3.04	2.83	2.57	2.61
FINAL DO	2.71	2.63	2.83	2.57	2.51	2.46
FINAL BOD	1.09	1.33	1.44	1.43	1.67	1.82
CRITICAL TIME	2.74	0.50	1.12	1.38	0.28	0.64
CRIT. DEFICIT	4.86	4.94	4.74	5.00	5.06	5.11
CRITICAL DO	2.71	2.63	2.83	2.57	2.51	2.46
CRIT. DISTANCE, RM	161.70	172.00	184.60	196.80	199.30	203.90

OHIO RIVER

REACH	Bell	Racin	Kan R	Galli	Hntng	Grnup
RIVER MILE	203.90	237.50	265.70	279.20	308.30	341.00
REACH LENGTH, FT	177408.03	148896.06	71280.00	153647.87	172656.06	1800480.00
TRIB FLOW	0.00	0.00	5700.00	0.00	0.00	0.00
FLOW, CFS	18405.00	18405.00	24105.00	24105.00	24105.00	24105.00
X-SECT. AREA	31000.00	25000.00	38000.00	35000.00	35000.00	35000.00
DEPTH, FT	24.00	24.00	26.00	25.00	25.00	25.00
VELOCITY	0.59	0.74	0.63	0.69	0.69	0.69
TRAVEL TIME, DAYS	3.46	2.34	1.30	2.58	2.90	30.26
TRIB DO	0.00	0.00	6.00	0.00	2.00	0.00
TRIB BOD	0.00	0.00	3.00	0.00	50.00	0.00
BOD LOADING,#/DAY	30000.00	30000.00	0.00	20000.00	0.00	0.00
DAM AER COEF	0.89	1.00	1.00	0.84	1.00	1.00
DAM AER CONSTANT	0.00	0.00	0.00	0.08	0.00	0.00
FLOW NOT AERATED	18454.00	18454.00	0.00	23254.00	0.00	0.00
DO ABOVE DAM	2.46	1.79	2.54	2.33	2.04	1.86
STARTING BOD	2.13	1.57	1.56	1.44	0.98	0.64
REACH TEMP.	28.60	28.60	28.60	28.60	28.60	28.60
DO SATURATION	7.57	7.57	7.57	7.57	7.57	7.57
K1 (20 DEG)	0.10	0.10	0.10	0.10	0.10	0.10
K2 (20 DEG)	0.01	0.01	0.01	0.01	0.01	0.01
K1 (T)	0.15	0.15	0.15	0.15	0.15	0.15
K2 (T)	0.01	0.01	0.01	0.01	0.01	0.01
INITIAL DEFICIT	5.11	5.78	5.03	5.21	5.53	5.71
FINAL DEFICIT	5.78	6.11	5.24	5.53	5.71	4.75
STARTING DO	2.46	1.79	2.54	2.36	2.04	1.86
FINAL DO	1.79	1.46	2.33	2.04	1.86	2.82
FINAL BOD	1.27	1.11	1.28	0.98	0.64	0.01
CRITICAL TIME	3.46	2.34	1.30	2.58	2.90	3.46
CRIT. DEFICIT	5.78	6.11	5.24	5.53	5.71	5.77
CRITICAL DO	1.79	1.46	2.33	2.04	1.86	1.80
CRIT. DISTANCE, RM	237.50	265.70	279.20	308.30	341.00	379.94

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