Steady-state Dissolved Oxygen Model of the Willamette River, Oregon

River-Quality Assessment of the Willamette River Basin, Oregon

GEOLOGICAL SURVEY CIRCULAR 715-J

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By Stuart W. McKenzie, Walter G. Hines,
David A. Rickert, and Frank A. Rinella

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FOREWORD

The American public has identified the enhancement and protection of river quality as an important national goal, and recent laws have given this commitment considerable force. As a consequence, a considerable investment has been made in the past few years to improve the quality of the Nation's rivers. Further improvements will require substantial expenditures and the consumption of large amounts of energy. For these reasons, it is important that alternative plans for river-quality management be scientifically assessed in terms of their relative ability to produce environmental benefits. To aid this endeavor, this circular series presents a case history of an intensive river-quality assessment in the Willamette River basin, Oregon.

The series examines approaches to and results of critical aspects of river-quality assessment. The first several circulars describe approaches for providing technically sound, timely information for river-basin planning and management. Specific topics include practical approaches to mathematical modeling, analysis of river hydrology, analysis of earth resources–river quality relations, and development of data-collection programs for assessing specific problems. The later circulars describe the application of approaches to existing or potential river-quality problems in the Willamette River basin. Specific topics include maintenance of high-level dissolved oxygen in the river, effects of reservoir release patterns on downstream river quality, algal growth potential, distribution of toxic metals, and the significance of erosion potential to proposed future land and water uses.

Each circular is the product of a study devoted to developing resource information for general use. The circulars are written to be informative and useful to informed laymen, resource planners, and resource scientists. This design stems from the recognition that the ultimate success of river-quality assessment depends on the clarity and utility of approaches and results as well as their basic scientific validity.

Individual circulars will be published in an alphabetical sequence in the Geological Survey Circular 715 series entitled "River-Quality Assessment of the Willamette River Basin, Oregon."

J. S. Cragwall, Jr.
Chief Hydrologist

Cover: *Willamette River as it winds through Portland, Oregon. Photograph taken by Hugh Ackroyd.*

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SYMBOLS

(Definition of symbols and abbreviated terms used in this circular)

BOD—biochemical oxygen demand
BOD_{ult}—ultimate BOD
K_1—carbonaceous deoxygenation rate ($\log_e$), as measured in BOD bottle at 20°C
k_1—carbonaceous deoxygenation rate ($\log_{10}$), as measured in BOD bottle at 20°C
k_r—river carbonaceous deoxygenation rate ($\log_{10}$), corrected for temperature
K_n—nitrogenous deoxygenation rate ($\log_e$) in river, at 20°C
k_n—nitrogenous deoxygenation rate ($\log_{10}$) in river, at 20°C
K_2—reaeration coefficient ($\log_e$)
k_2—reaeration coefficient ($\log_{10}$)
Q—stream discharge
RM—river mile

CONVERSION FACTORS

Factors for converting English units to the International System of Units (SI) are given below to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the English units.

English	*Multiply by*	*Metric (SI)*
ft (feet)	3.048×10^{-1}	m (meters)
ft^2 (square feet)	9.290×10^{-2}	m^2 (square meters)
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
in^2 (square inches)	6.452	cm^2 (square centimeters)
lb (pounds)	4.536×10^{-1}	kg (kilograms)
mi (miles)	1.609	km (kilometers)
mi^2 (square miles)	2.590	km^2 (square kilometers)

STEADY-STATE DISSOLVED-OXYGEN MODEL OF THE WILLAMETTE RIVER, OREGON.

By Stuart W. McKenzie, Walter G. Hines, David A. Rickert and Frank A. Rinella

ABSTRACT

A steady-state dissolved-oxygen model, which is based on synoptic data collected during the summers of 1973 and 1974, has been formulated and tested for the Willamette River, Oregon. The model employs the accounting scheme of C. J. Velz in conjunction with a conceptually simple Lagrangian reference system. The model was calibrated and verified with separate data sets from the synoptic studies. Verification resulted in excellent agreement of model predictions with measured dissolved-oxygen data. Sensitivity analysis was used to examine the relative importance of the individual self-purification processes and model parameters. The verified model provides a planning and management tool for the critical summer low flow, high temperature conditions of the river.

INTRODUCTION

The summertime DO (dissolved-oxygen) regimen of the Willamette River, Oregon is presently dominated by basinwide secondary treatment, low-flow augmentation, nitrification, and a benthic-oxygen demand in Portland Harbor. The entire regimen and all sources and sinks of DO were recently described in detail in a companion report (Hines and others, 1977), which is hereafter referred to as Circular 715–I.

Using the information presented in 715–I as a basis, the present report describes a mathematical model that quantitatively simulates the low-flow DO regimen of the Willamette. Discussion focuses on the description, formulation, and testing of the model, referred to hereafter as the WIRQAS (Willamette Intensive River Quality Assessment Study) Model. The final goal of the model is the development of a practical management tool useful for assessing the impacts on river DO of planning and management alternatives. The impact assessment phase of the modeling effort will be subsequently described in Circular 715–K.

As used here, formulation and testing deal with four major elements of model development:

1. Configuration
2. Calibration
3. Verification (validation)
4. Sensitivity analysis

Before dealing with these elements, it is helpful to introduce the conceptual basis of the WIRQAS Model. In doing so it is convenient to consider first a general conceptual model of river self-purification processes. Then, as a means for specifying the configuration of the WIRQAS Model, the general model is modified for compatibility with the physical and biochemical characteristics of the Willamette River system.

Because of the technical detail of the following section, some readers may wish to proceed directly to the section entitled "Formulation of the WIRQAS DO Model."

CONCEPTUAL DEVELOPMENT OF THE STEADY-STATE DISSOLVED-OXYGEN MODEL

The understanding and explanation of the DO regimen of rivers involves the consideration of several complex physical, chemical, and biological processes. One approach for describing such a system is the development of a conceptual model. In other words, one seeks to formulate an integrated, rational set of concepts that satisfactorily describe the "real" system. Mathematics are used to provide an internally consistent, rigorous definition of the concepts and to allow a quantitative simulation.

Through more than 50 years of empirical observation and thought, a rich conceptual model of the river DO regimen has evolved. This general model incorporates a description of five self-purification processes (Circ. 715–I, Supp. A):

1. Carbonaceous deoxygenation
2. Nitrification
3. Benthic-oxygen demand
4. Plant photosynthesis and respiration
5. Atmospheric reaeration

For purposes of modeling, these processes can be considered as DO sources (producers) and sinks (consumers); the sources being photosynthesis and reaeration, the others being DO sinks.

Based on the need to quantitatively simulate the five self-purification processes, a number of mathematical DO models have been developed. One model, now in widespread use, was originally described by Bella and Dobbins (1968). Their model was based on the classic Streeter-Phelps (1925) equations for carbonaceous deoxygenation and atmospheric reaeration, plus terms for the other DO sources and sinks. The model also includes equations for simulating the transport characteristics of the river, including the inflow and outflow of water, DO, and oxygen-demanding materials. The mathematical framework of the Bella-Dobbins model is shown in equation 1:

$$\frac{\partial(AC)}{\partial t}+\frac{\partial(UAC)}{\partial x}=\frac{\partial}{\partial x}\left(AE\frac{\partial C}{\partial x}\right)+K_2A(C_s-C)$$
$$-K_1(AL)-K_n(AN)+A(P-R-B+D_b) \quad (1)$$

where

A = area of stream cross section perpendicular to flow,
C = average DO concentration in cross section,
U = average cross-sectional velocity in the longitudinal direction,
E = longitudinal dispersion coefficient,
K_2 = atmospheric reaeration rate ($\log_e$),
C_s = oxygen saturation in water at the prevailing temperature,
K_1 = carbonaceous deoxygenation rate ($\log_e$),
L = BOD_{ult} concentration (from carbonaceous material) in cross section,
K_n = nitrogenous deoxygenation rate ($\log_e$),
N = nitrogenous oxygen demand (a function of ammonium- and nitrite-ion concentration) in cross section,
P = oxygen added by photosynthesis per unit area,
R = oxygen consumed by aquatic plant respiration per unit area,
B = oxygen demand by benthal deposits per unit area,
D_b = oxygen added along the stream by inflows,
t = time, and
x = distance in the longitudinal direction.

In order to obtain values for L and N to use in equation 1 (L and N are constantly undergoing first-order decay along the course of the river in the x-direction), it is necessary to first solve equations 2 and 3:

$$\frac{\partial(AL)}{\partial t}=\frac{\partial\left(AE\frac{\partial L}{\partial x}\right)}{\partial x}+\frac{\partial(AUL)}{\partial x}-K_1(AL)+AL_a \quad (2)$$

$$\frac{\partial(AN)}{\partial t}=\frac{\partial\left(AE\frac{\partial N}{\partial x}\right)}{\partial x}+\frac{\partial(AUN)}{\partial x}-K_n(AN)+AN_a \quad (3)$$

where

L_a = rate of BOD_{ult} addition along the stream by inflows,
N_a = rate of addition of nitrogenous-oxygen demand along the stream by inflows,

and all other terms are as defined in equation 1.

The DO model described by equations 1–3 is based upon the idealized concept of a one-dimensional stream. That is, variations in velocity, concentrations, and process-rate coefficients are assumed to occur only in the longitudinal direction (x), and not in the horizontal or vertical directions. Equations 1–3 are derived using the laws of conservation of mass and momentum by performing a mass balance for a time interval, dt, on a stream segment of cross-sectional area, A, and length, dx (see fig. 1A). As dt and dx approach infinitesimally small values, the three partial differential equations that describe the temporal and spatial distribution of C, L, N, P, R, B, and D_b are obtained.

In many applications, the assumption of a one-dimensional stream is reasonable and scientifically sound. This is so because data-averaging techniques can be used to "smooth out" local and short-term nonhomogeneity in the vertical and horizontal dimensions.

The application of equations 1–3 to an actual river situation usually involves a fixed reference frame known as the Eulerian system (fig. 1A). With this system, the river is divided into short segments by establishing numerous cross-sectional planes normal to the direction of flow.

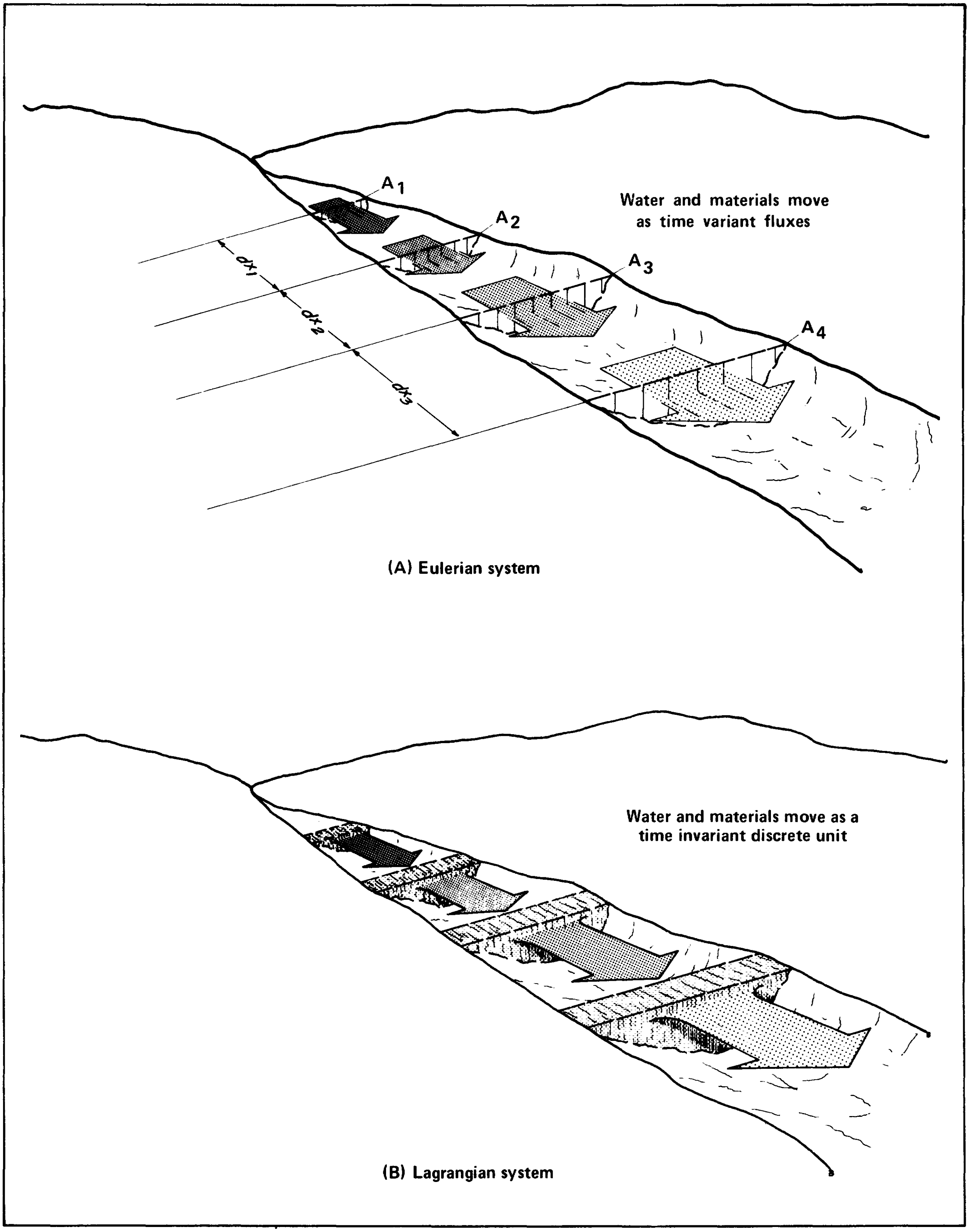

FIGURE 1.—Idealized concepts of water and materials transport used in river DO models. *A*, Eulerian system. *B*, Lagrangian system.

where

V= average velocity ≈ average time-of-travel

Q= streamflow

A= cross-sectional area

Consistent with the Velz-Lagrangian system, the WIRQAS Model was applied to the river between RM's 86.5 to 5.0 under conditions of summer low flow. As described elsewhere (Gleeson, 1972; Circular 715–I), no significant DO problems have occurred upstream of RM 86.5, nor have problems been noted at times other than during the summer. RM 5.0 is the approximate location of the lowest DO concentration in the Willamette during low-flow conditions. Below this point, mixing with Columbia River water (Circular 715–I, figs. 21 & 22) causes a rapid increase in DO concentrations.

HYDROLOGIC CHARACTERISTICS

A key consideration in the configuration of any DO model is the method by which the quantitative definition of streamflow, channel morphology, and water temperature is accomplished. These river characteristics determine the "immediate environment" (Hines and others, 1976) of the river within which the self-purification processes occur and are largely controlled.

STREAMFLOW

For the WIRQAS Model, streamflow data were obtained from direct measurements made routinely at U.S. Geological Survey gaging stations on tributaries and the main-stem Willamette River. (See Circular 715–I, section on "Streamflow.") The Survey streamflow gage at Salem (fig. 2) was used as the reference gage. Flow measured at Salem was routed downstream on the basis of times-of-travel calculated by the volumetric-displacement technique. Measured inflows from tributaries and waste-water outfalls were simply added to the mainstem flow to obtain a cumulative flow at any downstream location. During summer low-flow periods no major diversions occur in the segment of interest, RM 86.5–5.0. Water losses from evaporation, river-to-groundwater seepage, and irrigation are small, and they were considered to be balanced by the small volume of unmeasured surface and ground-water inflows.

CHANNEL GEOMETRY

Definition of channel geometry was accomplished as follows:

1. In the Tidal Reach (RM's 0–26.5), recently compiled (1972) channel geometry (width and depth) maps were available from the Portland District, U.S. Army Corps of Engineers. Soundings on these maps are referenced to a specific river-discharge and tidal condition. This facilitated adjustments to obtain channel geometry data consistent with the discharge and tidal conditions encountered during model calibration and verification.
2. In the Newberg Pool (RM's 26.5–52.0), new channel geometry data were obtained by making cross-sectional traverses in a boat equipped with a recording fathometer. The traverses were made at longitudinal intervals of approximately 0.2 mi during periods of low flow in the summer and early fall of 1973. Auxiliary staff gages were installed to develop stage-discharge ratings.
3. As described in Circular 715–I, the Upstream Reach (RM's 52.0–187) is shallow, meandering, and characterized by year-to-year shifts in channel shape. Therefore, for the modeled portion, a detailed definition of channel geometry with the recording fathometer was considered of dubious value. Consequently, time-of-travel values for use in the model were calculated on the basis of dye-tracer data reported by Harris (1968). Generalized values for average cross-sectional depth, cross-sectional area, and segment volume were obtained using the continuity equation (equation 7) in conjunction with width measurements made from high-resolution aerial photos taken under known conditions of streamflow.

Once compiled, the channel geometry data for the three reaches were collated so as to define relatively homogeneous 0.2–1.0 mi segments for which representative values of depth, width, and channel volume could be assigned. The averaged values were those actually used in the model for computational purposes. Besides channel geometry data, the location of waste-water outfalls and tributaries was used as a criterion for establishing river segment boundaries. In all, 260 discrete segments were established between RM's 86.5 and 5.0.

WATER TEMPERATURE

Water-temperature data were obtained from measurements made during the course of data

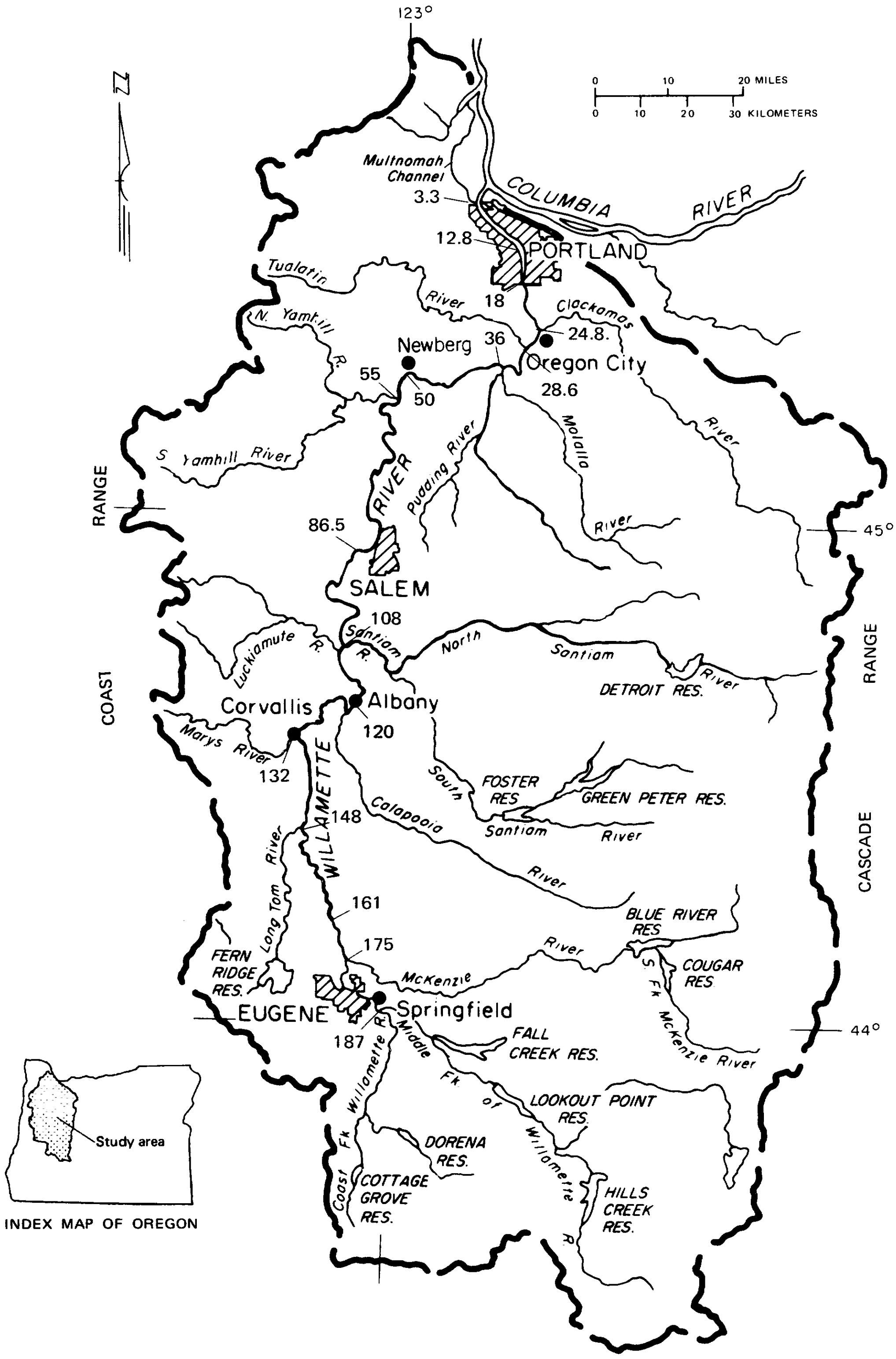

FIGURE 2.—Willamette River basin, Oregon, emphasizing principal tributaries, major reservoirs, and river mile locations on main-stem Willamette River.

collection for model calibration and verification. Average daily temperatures were used in the model as calculated from individual values having a maximum range at any site of ±3°C.

CALIBRATION

Calibration is the procedure whereby model parameters are quantified and adjusted so that model outputs (for a specified set of input data such as streamflow, water temperature, and waste-water loads) approximate a set of observed DO and BOD data. The quantification of model parameters and the range within which they can be realistically adjusted should be based primarily on field and laboratory data, an understanding of the particular river system, and sound professional judgment. For the calibration to be credible, it should not be based on arbitrary parameter optimization routines and computerized curve fitting (see Hines and others, 1975). This means that parameter values should be similar to and consistent with (though not necessarily identical to) those values calculated from field and laboratory studies of the river system. Further, if adjustments of parameters are necessary to make model outputs approximate observed data, they should be readily explainable.

Model parameters, input data, and other pertinent information related to the calibration of the WIRQAS Model are summarized in table 1. The model parameter values were developed from the results of the synoptic studies reported in Circular 715–I. Specifically, the model calibration involved data on flow, waste-water loading, and measured in-river parameters from the synoptic studies of August 6, 7 and 12–14, 1974. As discussed in Circular 715–I, the 1974 data were used for calibration because the nitrogen and BOD results were of better quality than those obtained in 1973.

Streamflow in the Willamette River was low (approximately 6,760 ft^3/s at Salem) and steady during the early-August 1974 calibration period. On the basis of precalibration sampling (see Rickert and others, 1976), BOD, nitrogen, and DO concentrations in the river and waste-water effluents were also stable on a daily average basis.

Using the information in table 1, a model computer run was made to produce a predicted DO profile of the Willamette River between RM's 86.5 and 5.0. The predicted profile is compared in figure 3 with the ranges and averages of the measured calibration data. In general, there is good agreement between the two profiles; the largest discrepancy occurs at RM 72 where the predicted DO concentration is 5 percent lower than the daily average.

A further calibration check was made by comparing results of predicted and measured loads of ultimate BOD (BOD_{ult}). As shown in figure 4, the two profiles compare reasonably well, except in the segment between RM's 13 to 7 where measured loads are approximately 27,000 lb/d higher than predicted. As described elsewhere (Circular 715–I, in the section on "Anomalously High BOD in the Tidal Reach") oxygen-demanding benthic materials are suspected as one major cause of this discrepancy.

A third, though somewhat limited, calibration check involved the comparison of predicted and measured nitrogen concentrations (Circular 715–I, fig. 14) in the zone of active nitrification (RM's 86.5–55.2). As noted in table 1 and explained in Circular 715–I (in the section on "Nitrification"), the WIRQAS Model incorporates an effective nitrification rate that does not generate segment-to-segment predictions for nitrate-, nitrite-, and ammonia-N concentrations. However, a predicted ammonia-N concentration can be obtained at RM 55 by flow routing and decaying the cumulative loadings from above this point. On this basis, the WIRQAS Model predicted an ammonia-N concentration of 0.36 mg/L at RM 55, whereas the measured value was 0.22 mg/L. Considering the likelihood of ammonia-N losses to algal assimilation, this is considered a reasonable check.

Table 2 presents a reach-by-reach accounting of changes in the concentration (mg/L) and mass (lb-O_2/d) of DO in the Willamette during calibration conditions. In terms of oxygen loss, the percentages over the 81.5 mi are nitrification—38 percent, carbonaceous deoxygenation—47 percent, and benthic demand—15 percent. All the nitrogenous demand occurs in the Upstream Reach, and all the benthic demand occurs in low-

TABLE 1.—*Summary and explanation of parameters, major input data, and information used in calibration of the WIRQAS DO Model*

[Data collected August 1–15, 1974. Unless otherwise noted, see Circular 715–I for details on the cited parameters and information]

1. Carbonaceous deoxygenation. Simulated with first-order decay kinetics with the following rate coefficients k_r (20°C): (a) RM 86.5–55.2, k_r = 0.06/d, (b) RM 55.2–5.0, k_r = 0.03/d. For k_r at temperatures other than 20°C the adjustment formula was $K_T = K_{20\,°C} \times 1.047^{(T-20°C)}$.
2. Nitrification. Simulated with first-order decay kinetics. Significant oxygen-demanding nitrification was found to occur only in the shallow surface-active segment RM 86.5–55.2. The effective rate of nitrification (k_n) calculated from the rate of appearance of nitrate–N = 0.7/d. No temperature adjustment was necessary because water temperatures in the affected river segment were essentially 20°C.
3. Benthic-oxygen demand. Simulated as an oxygen-demanding load distributed over the segment RM's 12.8–5.2. The total load in the reach was estimated to be approximately 27,000 lb/d. As discussed in Circular 715–I, only part of this demand is thought to result from "in place" benthic-oxygen demand. The remainder probably results from several additional causes.
4. Photosynthesis and respiration. DO produced and consumed by algae were taken to be in balance over the 81.5 mi stretch of river. This assumption is generally supported by primary production data and by DO mass balance computations made with preliminary versions of the model. See Circular 715–I for details.
5. Atmospheric reaeration. Calculated on segment-by-segment basis using the Velz (1970) method. The reaeration at Willamette Falls (RM 26.5) was simulated by adding 13,400 lb/d of DO to the profile calculation. This increment was consistent with measurements made above and below the Falls during 1974 low-flow conditions.
6. Streamflow. Boundary condition discharge at RM 86.5 = 6760 ft^3/s as measured at the Salem gage. Below RM 86.5, inflows from tributaries and waste-water outfalls were added to flow in the mainstem to produce a cumulative total at any site. Water losses due to evaporation and diversions were assumed to be equalized by seepage and inflows of small unmeasured tributaries.
7. Water temperature. Boundary condition water temperature at RM 86.5 = 20°C. Water temperature showed a gradual increase in the downstream direction to 21°C at RM 52.6, to 22°C at RM 45.0, to 23°C at RM 37.0, and to 23.5°C at RM 25.6 and below. These data were used directly into the model.
8. Channel geometry. See section in text entitled "Channel Geometry" for description of how channel geometry characteristics were calculated and used in the model.
9. Waste loading. See summary below.

Description of waste input	Location (RM)	Flow (ft^3/s)	DO (percent saturation)	BOD_{ult} load (lb/d)	NOD load (lb/d)[1]
Residual load in Willamette River	86.5	6,760	92	87,300	25,200
Boise Cascade Corp	85.0	24.9	10	13,100	93,100
Salem municipal STP	77.9	40.4	50	11,700	7,500
Yamhill River	55.0	75	90	1,400	
Newberg municipal STP	50.5	1.2	20	[2]100	
Publishers Paper Co	49.8	18.0	10	7,300	
Wilsonville municipal STP	39.0	.2	20	[2]20	
Molalla River	35.8	151	100	1,500	
Canby municipal STP	33.0	.5	20	[2]70	
Tualatin River	28.4	39	100	5,300	
Publishers Paper Co	28.0	19.9	10	11,000	
West Linn municipal STP #1	27.8	.7	20	[2]100	
Crown Zellerbach Corp	27.6	20.7	40	4,900	
Oregon City municipal STP	25.0	4.3	50	[2]140	
Clackamas River	24.8	1,290	96	9,600	
West Linn municipal STP #2	24.1	1.0	50	[2]170	
Tryon Creek municipal STP	20.2	5.7	50	[2]220	
Oak Lodge municipal STP	19.9	3.1	50	[2]120	
Kellogg Creek	18.5	1.0	70	[2]260	
Johnson Creek	18.4	2.0	80	[2]40	
Milwaukie municipal STP	18.4	2.1	50	[2]220	

[1] Only those NOD loads subject to nitrification are listed. See Circular 715–I, Table 8 for summary of nitrogen loading. See page J27 of this circular for the method used to compute NOD from ammonia–N data.

[2] Estimate based on samples collected in 1973. Sensitivity analysis showed that these small BOD_{ult} loads had minimal impact on DO concentration.

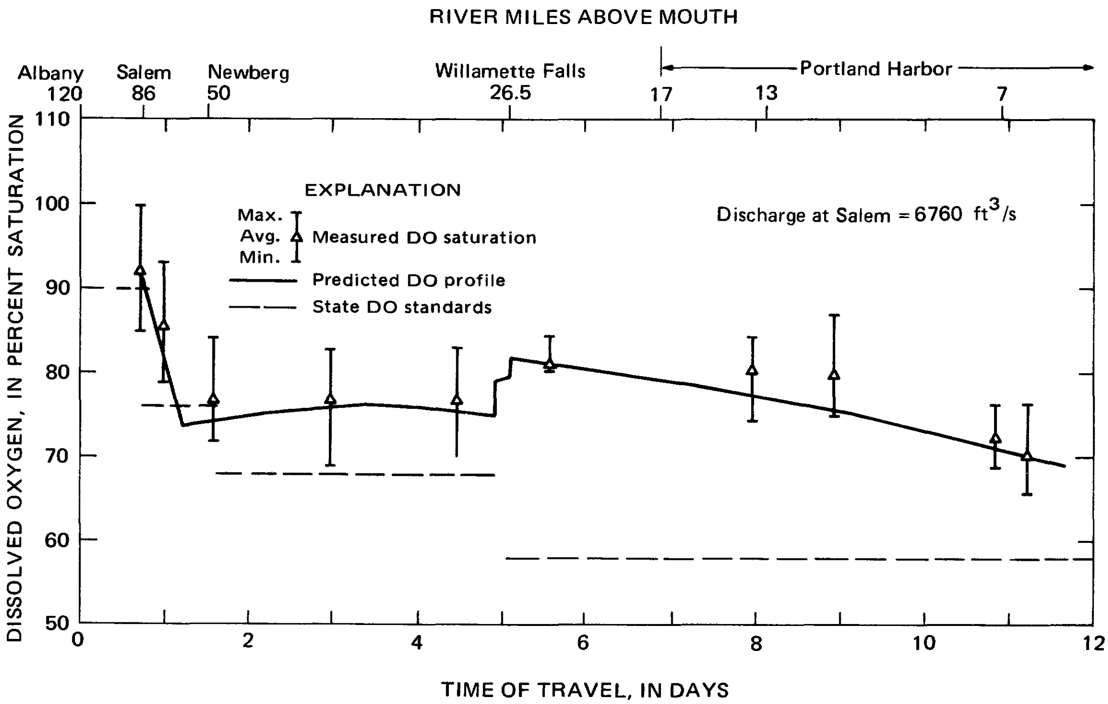

FIGURE 3.—Comparison of WIRQAS Model predictions with percent DO saturation measured during calibration conditions, August 1974.

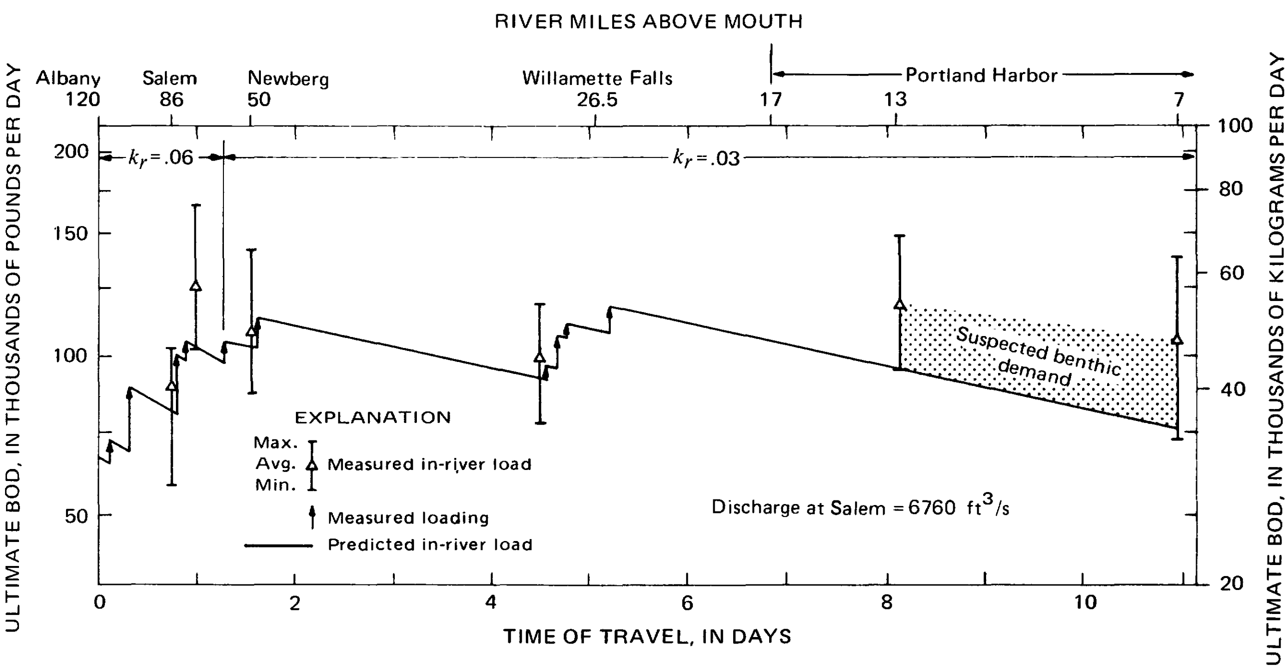

FIGURE 4.—Comparison of predicted BOD_{ult} loads with loads measured during calibration conditions, August 1974.

er Portland Harbor (RM's 12.8–5.0). In contrast, the carbonaceous demand is spread over the entire 81.5 mi. In assessing the relative importance of carbonaceous deoxygenation, the reader should note (as explained in Circular 715–I) that about one-half of the exerted demand originates from near natural, nonpoint-source loads of tributary streams. Such loads are not amenable to treatment.

VERIFICATION

Verification, by definition, implies the "proof of truth" of the model. However, Bella (1969) cautioned that model verification should not be thought of in these absolute terms. All models have limitations and specific domains of applicability. Thus, model verification is more realistically described as a means for validating or substantiating the model's predictive power under a specific set of environmental conditions. In practice, verification should involve the use of a calibrated model (that is, the same model parameters developed during calibration) and a new set of observed data. Some of the new data establish the initial and boundary conditions necessary to "start" and "run" the model. The remainder serve as an independent set of observations for comparison with model predictions.

Verification data for the WIRQAS Model were obtained from synoptic studies conducted during a prolonged low-flow period of late July to mid August 1973 (Circular 715–I, fig. 10 and table 4). As was the case for the calibration period, stable hydrologic and waste-water loading conditions made the Velz-Lagrangian modeling approach compatible with its underlying steady-state assumptions.

Table 3 summarizes the model parameters, input data, and other information used in verification of the WIRQAS Model. Note that in keeping with the described requirement for verification, the model parameter values for items 1–5 are identical with those used for calibration (see table 1).

Based on the information in table 3, a predicted DO profile was generated by the WIRQAS Model. The predicted profile is compared in figure 5 with average measured DO values from the synoptic studies of July 24–26 and August 15–18, 1973. The two profiles are in good agreement throughout the 81.5 mi segment. The largest difference occurs at RM 28.6 where the predicted DO saturation is 4 percent lower than the daily average.

The in-river 1973 data for BOD_{ult} and ammonia-N were considered too poor to be used as a basis for additional model verification. However, we consider the model to be fully verified for future use by the closeness of fit between the predicted and measured DO profiles (fig. 5). Circular 715-I describes the difficulties encountered with the 1973 data for BOD_{ult} and nitrogen.

SENSITIVITY ANALYSIS

Sensitivity analysis is concerned with changes in model outputs that result from variations in model parameters and data inputs. In most cases, the primary concern is with the identification of those factors that are most important in controlling model outputs. For example, a pertinent question to ask in the sensitivity analysis of the WIRQAS Model is "What is the impact, in terms of predicted DO concentrations, if (with all other variables held constant) water temperatures were 3°C higher or lower than those used in calibration?" By inserting the changed values of water temperature into the model and making a run on the computer, one can observe whether the impact on predicted DO concentrations is small or large. If small, the model is said to be "insensitive" to water temperature (at least in the analyzed range). If the impact is large, it suggests that water temperature is an important control of the DO regimen.

Sensitivity analyses such as the one described above have at least two general categories of use. First, they help to identify those factors that deserve most attention in model formulation. This is to say, sensitivity analysis can lead the investigator to spend more time and effort on those data and parameters that are most important to the model's simulatory and predictive capability. Perhaps of equal importance is a second use. Sensitivity analysis can lead to a better recognition of the management alternatives that are most efficient and practical for controlling river-quality problems. Only the first type of sensitivity analysis is addressed here, because a subse-

TABLE 2.—*Reach-by-reach account of DO gains*

[Flow at Salem gage = 6,760 ft^3/s. Note that as discharge increases in the downstream direction,

Modeled river segment (RM's)	DO losses		
	Factor causing loss	Amount of loss ($lb-O_2/d$)	Percentage of total loss in reach
86.5–55.2 (traveltime= 0.5 days)	Nitrification	69,300	90
	Carbonaceous deoxygenation	7,600	10
	Total	76,900	100
55.2–26.5 (traveltime= 3.7 days)	Carbonaceous deoxygenation	28,400	100
26.5–12.8 (traveltime= 3.1 days)	Carbonaceous deoxygenation	25,900	100
12.8–5.0 (traveltime= 3.7 days)	Carbonaceous deoxygenation	24,200	47
	Benthic demand	27,200	53
	Total	51,400	100
86.5–5.0 (traveltime= 11.0 days)	Nitrification	69,300	38
	Carbonaceous deoxygenation	86,100	[1]47
	Benthic demand	27,200	15
	Grand total	182,600	100

TABLE 3.—*Summary and explanation of parameters, major input data, and information used in verification of WIRQAS DO model*

[Data collected July 24–August 7, 1973]

1. Carbonaceous deoxygenation ———— See table 1.
2. Nitrification ———— Do.
3. Benthic oxygen demand ———— Do.
4. Photosynthesis and respiration ———— Do.
5. Atmospheric reaeration ———— Do. (12,200 lb/d DO added at Willamette Falls (RM 26.5) based on observations during 1973 low-flow conditions).
6. Streamflow-boundary condition discharge at RM 86.5 = 6,000 ft^3/s as determined from average of measurements made at Salem gage for the period July 15–August 15, 1973. See table 1, item 6, for further discussion.
7. Water temperature—boundary condition water temperature at RM 86.5 = 20°C. Water temperature showed a gradual increase in the downstream direction to 21°C at RM 52.6; and to 22°C at RM 20.9 and below.
8. Channel geometry ———— See table 1.
9. Waste loading ———— See summary below.

Description of waste input	Location (RM)	Flow (ft^3/s)	DO (percent saturation)	BOD_{ult} load (lb/d)	NOD load (lb/d)[1]
Residual load in Willamette River	86.5	6,000	93	106,600	16,800
Boise Cascade Corp	85.0	25	10	11,600	69,100
Salem municipal STP	77.9	49	50	13,100	9,900
Yamhill River	55.0	50	90	1,600	--
Newberg municipal STP	50.5	1.2	20	110	--
Publishers Paper Co	49.8	16	10	9,500	--
Wilsonville municipal STP	39.0	0.2	20	20	--
Molalla River	35.8	118	100	1,270	--
Canby municipal STP	33.0	0.5	20	70	--
Tualatin River	28.4	6.0	80	320	--
Publishers Paper Co	28.0	19	25	6,050	--
West Linn municipal STP #1	27.8	0.7	20	100	--
Crown Zellerbach Corp.	27.6	20	25	1,410	--
Oregon City municipal STP	25.0	4.3	50	140	--
Clackamas River	24.8	910	96	9,200	--
West Linn municipal STP #2	24.1	1.0	50	170	--
Tryon Creek municipal STP	20.2	5.7	50	220	--
Oak Lodge municipal STP	19.9	3.1	50	120	--
Kellogg Creek	18.5	1.0	70	260	--
Johnson Creek	18.4	2.0	80	40	--
Milwaukie municipal STP	18.4	2.1	50	220	--

[1] Only those NOD loads subject to nitrification are listed.

and losses for calibration conditions

it is possible for the mass of DO (in lb-O_2/d) to increase while the DO concentration (in mg/L) decreases]

DO gains			Net DO changes		
Factor causing gain	Amount of gain (lb-O_2/d)	Percentage of total gain in reach	Loss (lb-O_2/d)	Gain (lb-O_2/d)	Gain or loss in DO concentration (mg/L)
Tributary inflows	1,100	8	--	--	--
Atmospheric reaeration	12,000	92	--	--	--
Total	13,100	100	63,800	--	−1.8
Tributary inflows	12,800	27	--	--	--
Atmospheric reaeration	20,900	44	--	--	--
Reaeration at Willamette Falls	13,400	29	--	--	--
Total	47,100	100	--	18,700	+.2
Tributary inflows	57,500	85	--	--	--
Atmospheric reaeration	10,000	15	--	--	--
Total	67,500	100	--	41,600	−.1
Atmospheric reaeration	14,700	100	36,700	--	−.80
Tributary inflows	71,400	50	--	--	--
Atmospheric reaeration	57,600	40	--	--	--
Reaeration at Willamette Falls	13,400	10	--	--	--
Grand total	142,400	100	40,200	--	−2.5

[1]About one-half of the carbonaceous-oxygen demand entering the Willamette River originated from nonpoint-source loads of tributary streams. As explained in Circular 715–I and in Rickert, Hines, and McKenzie, 1975, the tributary loads represent near natural conditions and are not amenable to reduction through wastewater treatment.

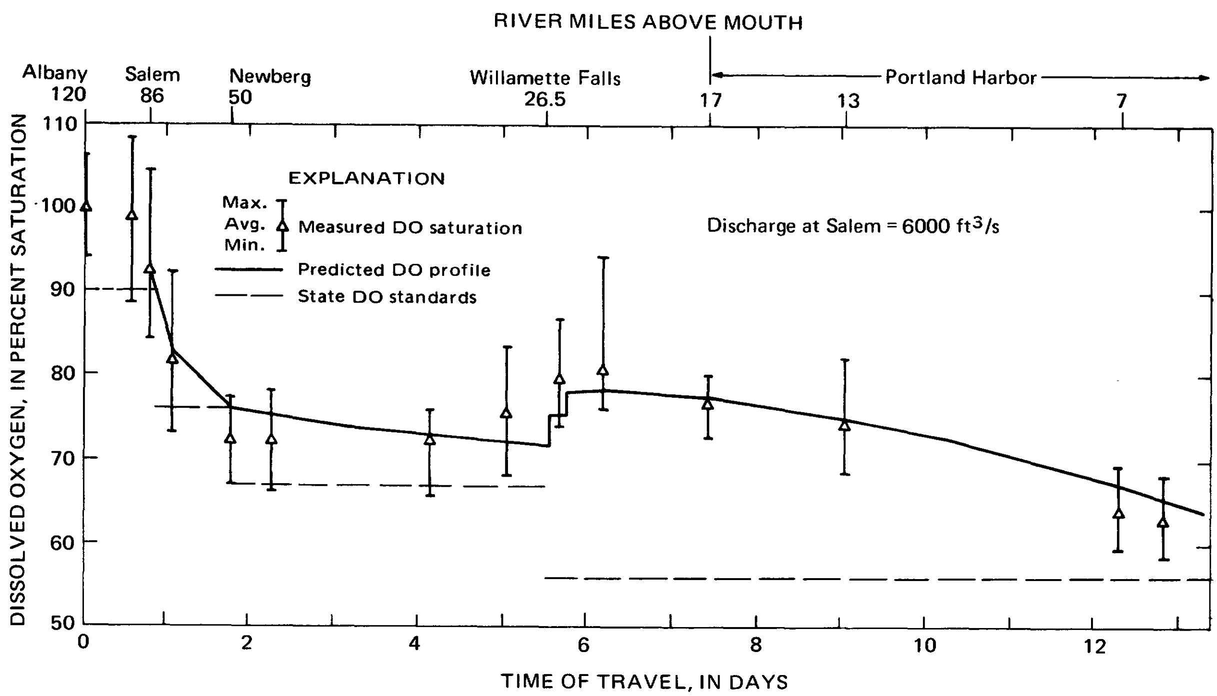

FIGURE 5.—Comparison of WIRQAS Model predictions with percent DO saturation measured during verification conditions, July-August, 1973.

quent publication (Circular 715–K) will focus on management implications derived from analysis of numerous production runs of the WIRQAS Model.

Figures 6–15 provide a graphical depiction of the sensitivity of the WIRQAS DO Model to changes in selected model parameters and data. During the model runs, one parameter or data input was varied within a specified range of values while all other variables were held constant. All sensitivity analyses were based on a *"standard condition"* comprised of flows, temperatures, rate constants, and waste loadings identical to those measured during early August 1974 (the calibration period), except for ammonia loading at Boise Cascade Corp. (RM 85.0). Because, during this period, the ammonia loading from Boise Cascade was well above normal (for the summers of 1973–74), the measured value of 93,000 lb/d was decreased to 70,000 lb/d to create a more standard river condition. To permit comparisons, the same standard profile is included in each of the sensitivity analysis figures (figs. 6–15). The results of the analyses, as presented in the 10 figures, are summarized and compared in Table 4.

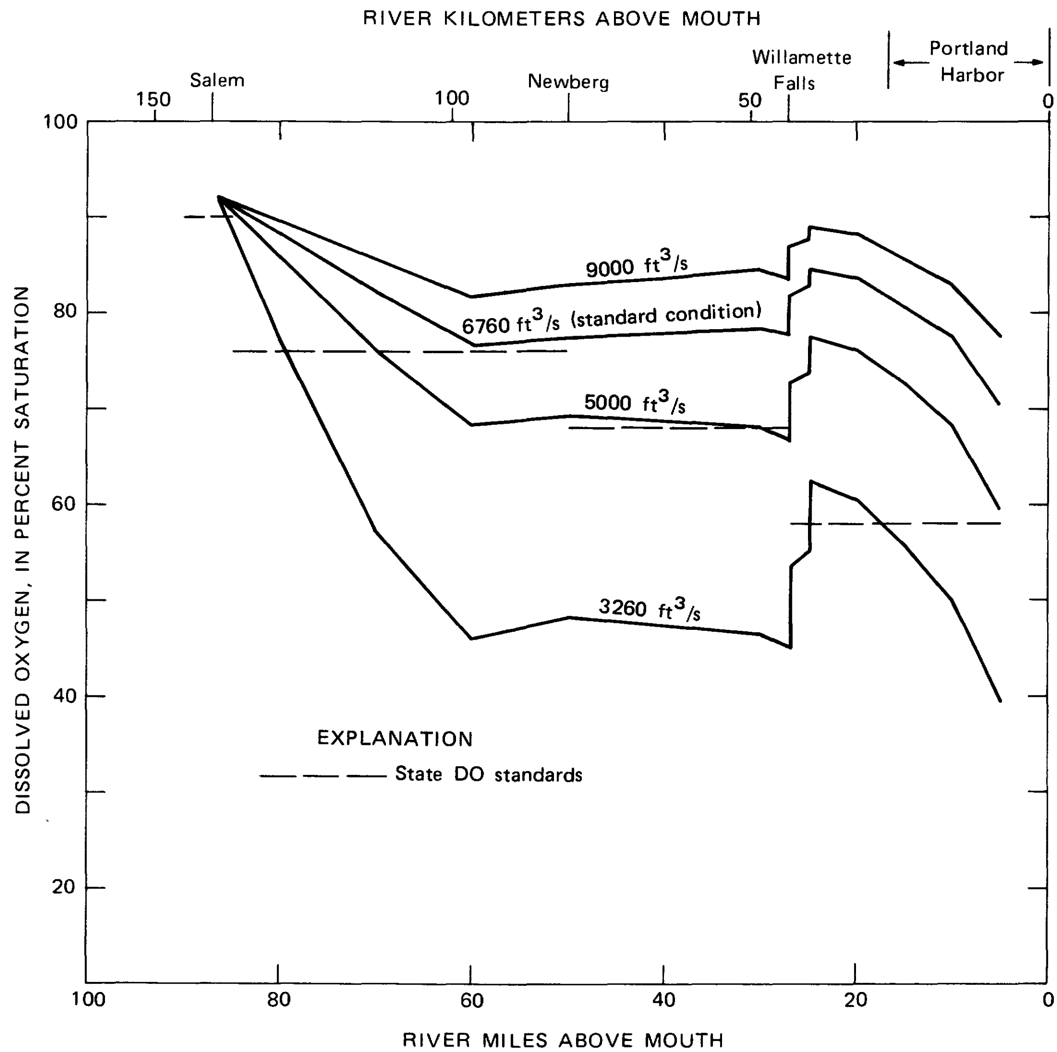

FIGURE 6.—DO profiles of the Willamette River for selected levels of streamflow. For the predicted profiles, BOD_{ult} and ammonia-nitrogen were handled as follows: (1) At RM 86.5 the concentrations were held constant at standard conditions. (2) Below RM 86.5 the loadings were held constant at standard conditions.

DISCUSSION AND SUMMARY

A chronic problem with the configuration of river DO models appears to be a failure to develop models that are both simple and conceptually satisfying. In an earlier paper, Hines (Hines and others, 1975) suggests that this situation is at least partly attributable to the proliferation of the "general case" model. That is, in an attempt to make DO models capable of handling all conceivable river conditions (presumably in the name of conceptual satisfaction), complex mathematical configurations have been used. Such models are often proposed for steady-state application. However, the conceptual simplicity and explanatory power offered by the steady-state concept has all too often been lost in dealing with the complexity of the "general case" model.

A second, chronic problem with DO models lies in the methods and data that are used for calibration and verification. In applying steady-state models, it has been common practice among modelers having little field experience to

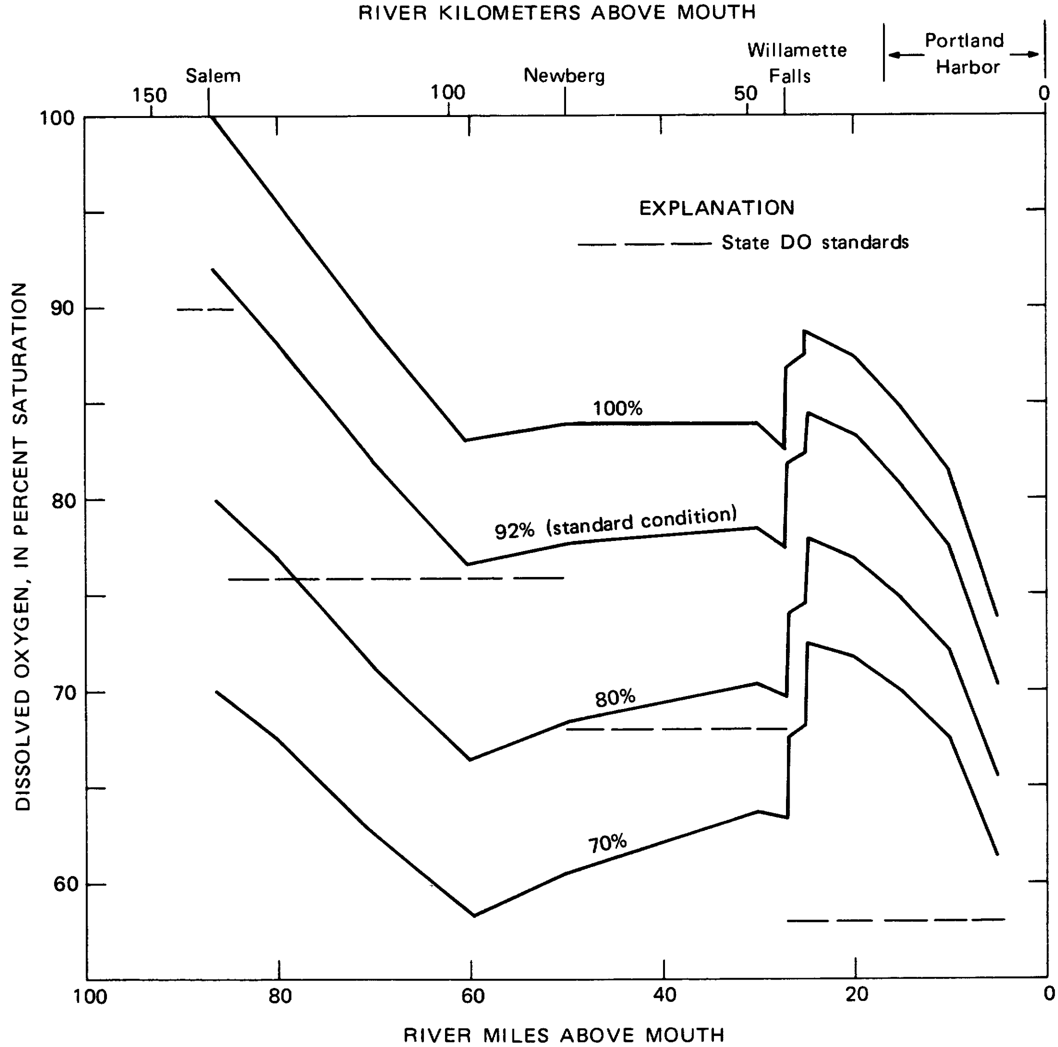

FIGURE 7.—DO profiles of the Willamette River assuming different percent DO saturations at RM 86.5. All other factors held constant at standard conditions.

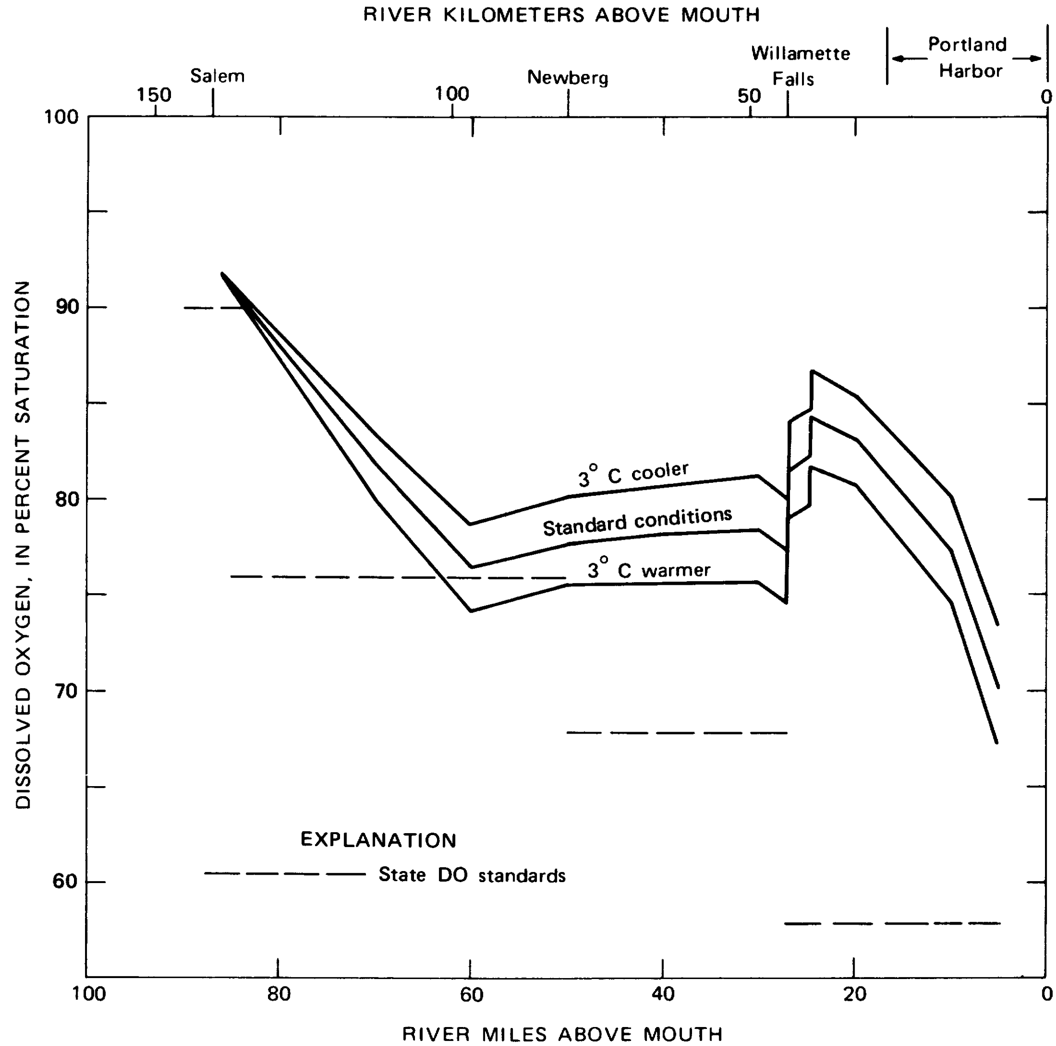

FIGURE 8.—DO profiles of the Willamette River for a temperature range from 3°C above to 3°C below standard conditions. All other factors held constant.

calibrate and (supposedly) verify with data that, even in the most optimistic sense, were not collected during steady-state conditions. This is evident in that many discussions of river DO models deal with steady-state only in the context of the river's transport and waste-loading regimes. Thus, for example, a 2- or 3-day stability in average daily streamflow and waste loads is commonly erroneously cited as proof of a steady-state condition. Worse yet is the case wherein numerous measurements of streamflow and waste loads have been made during a hydrologically variable 1- or 2-month period, and then, averaged and used as data for calibration and verification of a steady-state model. These examples reflect a lack of fundamental understanding as to what constitutes a steady-state DO regimen.

What does determine a steady-state condition for rivers? In our view, steady state involves nothing less than a short-term *ecological stability* of the river. In addition to a stable transport and waste-loading regimen, this ecological steady state must reach a day-to-day constancy in biochemical processes and reaction rates at any given cross section. The attainment of such a steady state entails, in turn, an antecedent stability of the river's "immediate environment" (Hines and others, 1976) as reflected primarily by streamflow, water temperature, and channel-

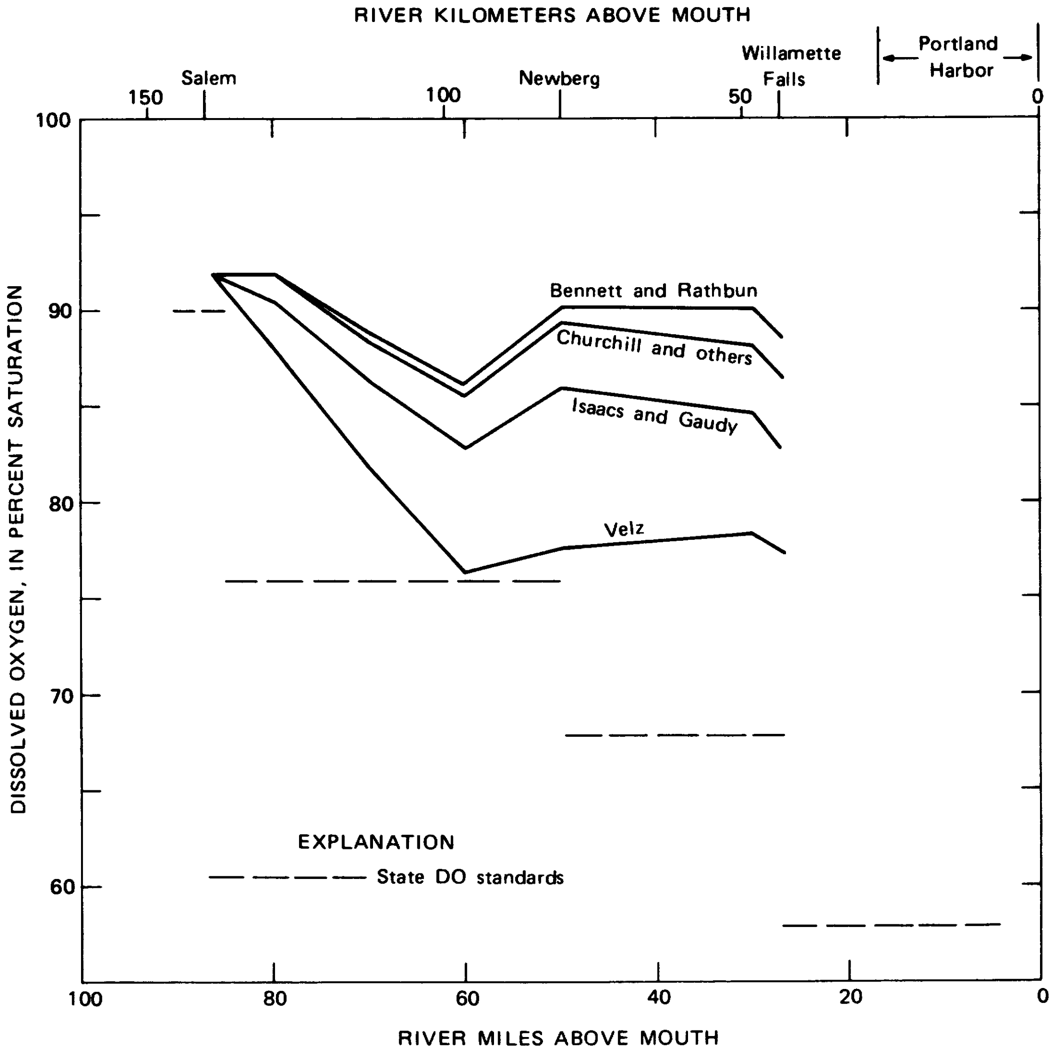

FIGURE 9.—DO profiles of the Willamette River between RM's 86.5 and 26.5 using four methods of calculating reaeration. No comparison is presented below RM 26.5 because only the Velz method is applicable to tidal rivers. The equations are: Bennett and Rathbun (1972), $k_2 = (20.17)(V^{.607}/D^{1.689})(1.024^{(T-20)})$; Churchill, Elmore, and Buckingham, $k_2 = (11.58)(V^{.969}/D^{1.673})(1.024^{(T-20)})$; Isaacs and Gaudy (1968), $k_2 = (5.62)(V/D^{1.5})(1.024^{(T-20)})$. For the Velz method, see Velz, 1970, p. 184–197. All factors other than k_2 held constant at standard conditions.

morphology conditions. This antecedent constancy is necessary for the river's chemical and biological subsystems to adjust to the surrounding environment—that is, to get "used to" (or to come to a dynamic equilibrium with) the immediately surrounding environment.

Without the antecedent stability of the river environment, measurements used for calibration and verification are unlikely to reflect a steady-state DO regimen. Consequently, even if model predictions "fit" the observed calibration or verification data, the model is likely to be deterministically erroneous. Invariably, such a model will be a poor explanatory and predictive tool.

The WIRQAS modeling effort was designed to overcome the problems described above. With regard to the problem of extraneous mathematical complexity, simple algorithms were devised. The algorithms incorporate the Velz (1970) bookkeeping-type DO accounting system in conjunction with a Lagrangian moving-reference frame. The resulting configuration is extremely simple, yet applicable to simulation of the low-flow DO regimen of the Willamette River.

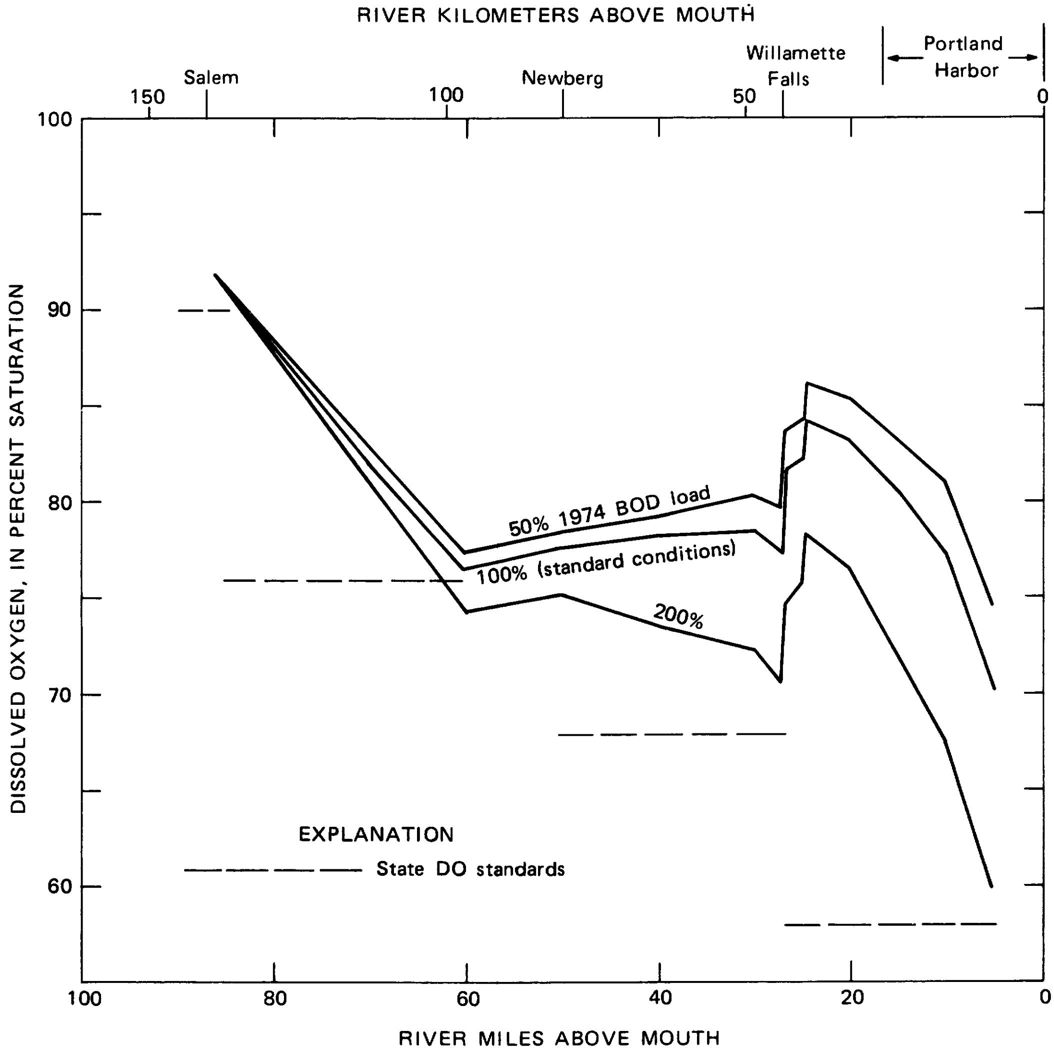

FIGURE 10.—DO profiles of the Willamette River for a fourfold range of BOD_{ult} loading. Loading of BOD_{ult} at RM 86.5 and at each downstream source was varied by the indicated percentage of the standard conditions. All other factors held constant.

To provide reliable data for calibration and verification, a series of intensive field and laboratory studies was conducted during the summers of 1973 and 1974 (Circular 715–I). Importantly, in keeping with the notion of steady state, the two independent sets of data were collected under extended low-flow, high-temperature conditions. During the study periods, the Willamette River DO regimen was in a state of relative ecological stability and, thus, compatible with the underlying assumptions of the steady-state concept. Moreover, DO depletion was maximum during these low-flow, steady-state conditions, thus making the periods the "critical condition" for basing the design of waste treatment and river-management plans.

Calibration and verification of the WIRQAS DO Model involved comparison of model predictions with measured data. With minor exceptions, good agreement was found between predictions and observations. Agreement was particularly good between predicted and measured percent DO saturation (figs. 3 and 5). Nowhere over the modeled 81.5 mi of river were there differences of more than 5 percent saturation.

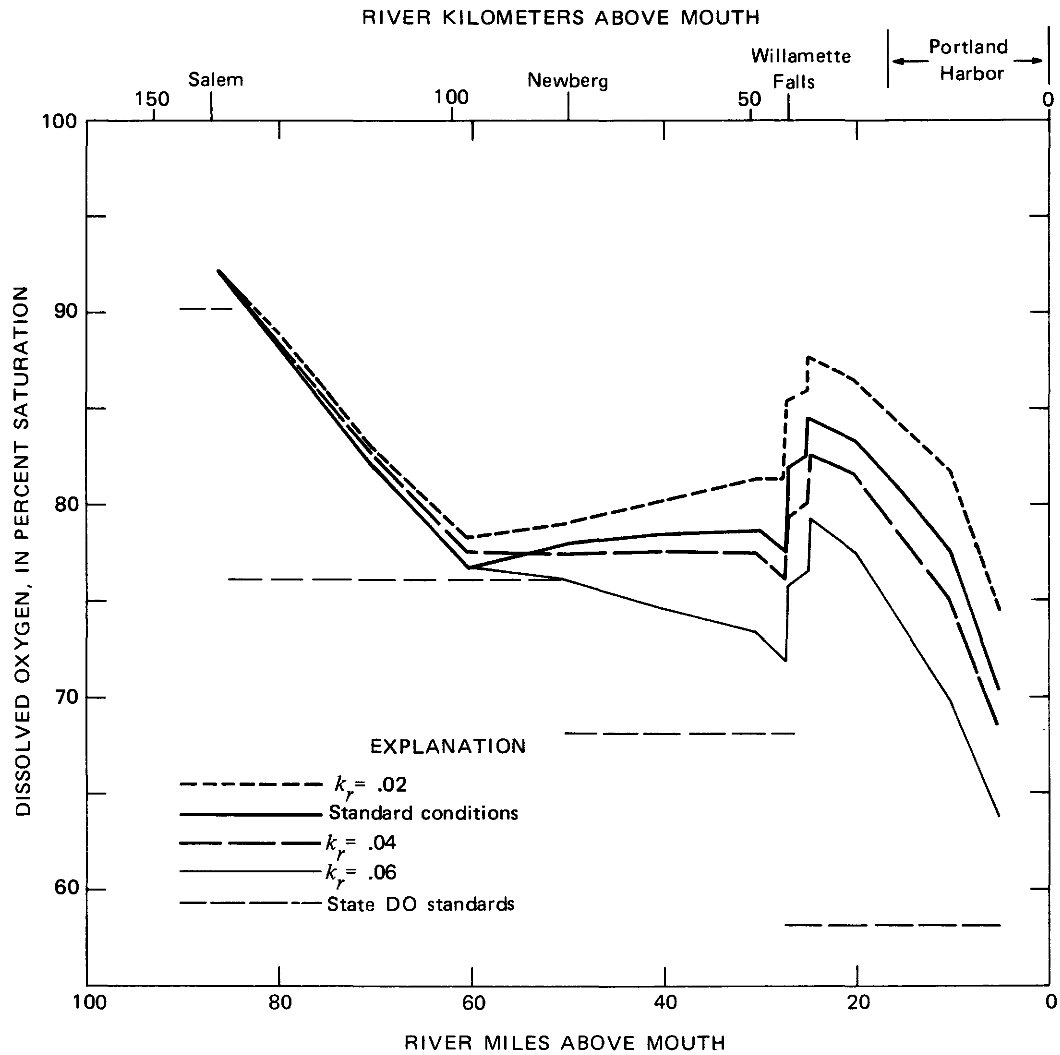

FIGURE 11.—DO profiles of the Willamette River for selected rates of carbonaceous deoxygenation. All other factors held constant at standard conditions.

Based on the DO calibration and verification results, the WIRQAS Model appears to be a valid mathematical description of the summertime, steady-state DO regimen of the Willamette River between RM's 86.5–5.0.

Sensitivity analysis suggests that the WIRQAS DO Model is relatively insensitive to changes in water temperature (fig. 8), BOD loading (fig. 10), carbonaceous deoxygenation rate (fig. 11), and nitrification rate (fig. 13). The model is relatively sensitive to changes in streamflow (fig. 6), the initial DO concentration at RM 86.5 (fig. 7), ammonia-N loading upstream of RM 55 (fig. 12), and benthic-oxygen demand in Portland Harbor (fig. 15). Based on comparative reaeration computations (fig. 9), the model is also sensitive to the method of calculating reaeration. The WIRQAS Model employs the Velz (1970) reaeration calculation method. This method resulted in good agreement between predicted and observed data (figs. 3 and 5), while the other methods shown in figure 9 did not. Reasons for the differences in predicted DO profiles based on the various reaeration computation methods await further research.

Based on the results discussed in this report and in Circular 715–I, the WIRQAS DO Model is considered to be a reliable simulatory and predictive tool, subject to the following conditions and limitations:

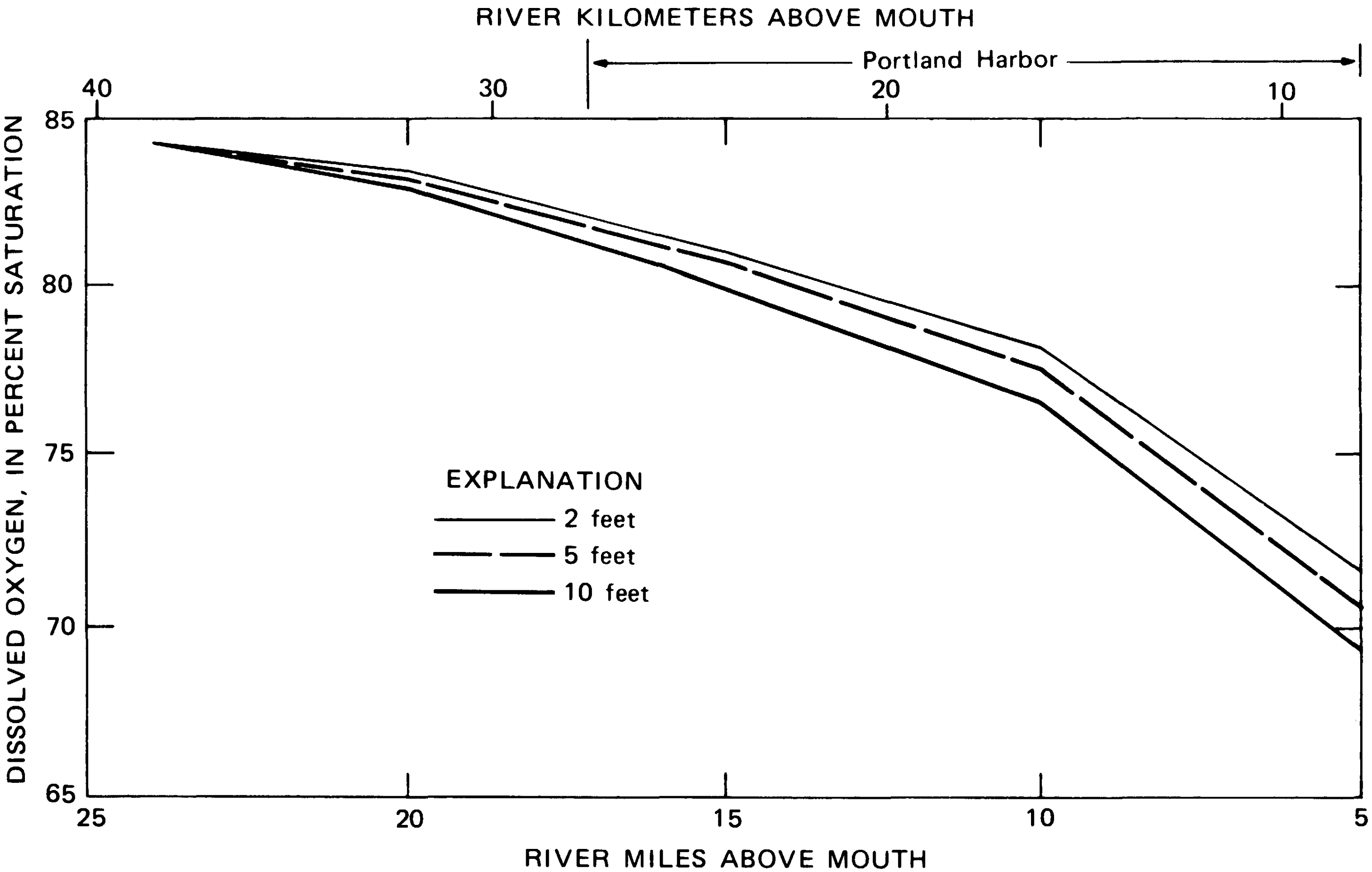

FIGURE 14.—DO profiles of the Willamette River between RM's 24.0 and 5.0 for various conditions of backwater. Two feet was the average for 1973 conditions; 5 feet was the average for 1974 conditions. Depths are referenced to gage at Morrison Street Bridge, RM 12.8. All factors other than river stage held constant at standard conditions.

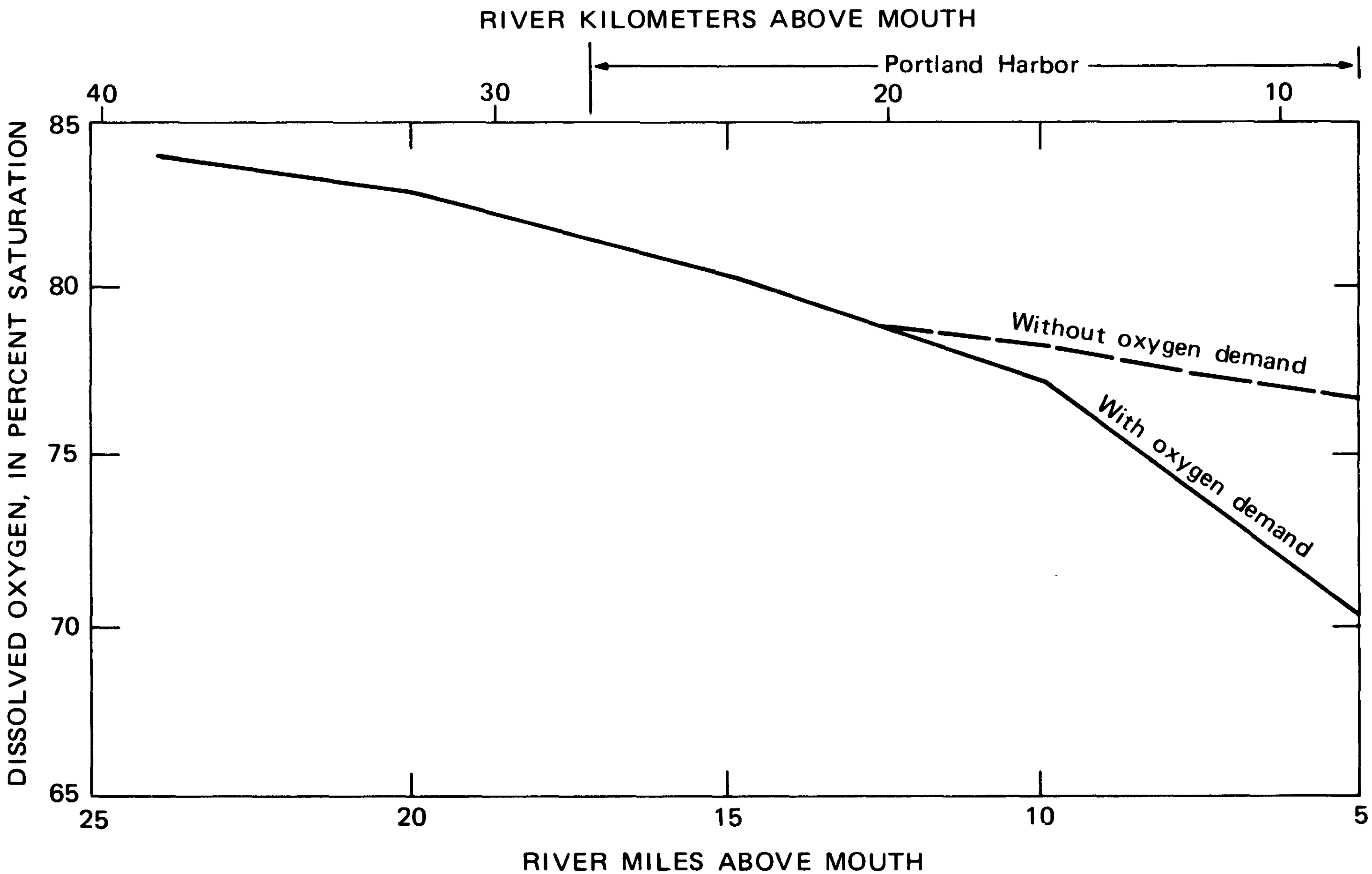

FIGURE 15.—DO profiles of the Willamette River with and without an assumed oxygen demand between RM's 12.8 and 5.2. All other factors held constant at standard conditions.

TABLE 4.—*Sensitivity analysis summary of the WIRQAS DO Model*

[Based on figs. 6–15 which show the impacts on percent DO saturation which result from varying selected model parameters and data inputs. See page J14 for explanation of standard conditions]

Variable tested	Applicable river mile segment	Figure showing results	Comments
Streamflow	86.5–5.0	6	Model is sensitive to flow, particularly at values less than 6,760 ft^3/s. At 5,000 ft^3/s, predicted percent DO saturations are as much as 10 percent less than those at 6,760 ft^3/s. At 3,260 ft^3/s (estimated natural low flow for July, 1973), predicted values are as much as 30 percent lower than standard conditions. At 9,000 ft^3/s, predicted values are higher by 6–8 percent saturation.
Percent DO saturation at boundary point (RM 86.5)	do	7	Model is sensitive to changes in initial percent of DO saturation. The major impact is near the boundary point; differences between profiles become smaller with downstream distance.
Water temperature	do	8	For the reasonably expected range of summertime water temperatures, the model is insensitive to temperature changes. Maximum predicted deviation from standard conditions are ± 3 percent of DO saturation.
Reaeration calculation method	86.5–26.5	9	Model is sensitive to the method used to calculate reaeration. Only the Velz method gave segment-by-segment reaeration inputs which resulted in good agreement of predicted and observed DO profiles.
BOD loading	86.5–5.0	10	Model is relatively insensitive to BOD_{ult} load variations. A doubling of 1974 loads (from each point source) results in deviations of 5–9 percent DO saturation from the standard profile. Reducing the point-source BOD load by 50 percent causes insignificant changes in predicted DO levels.
Rate of carbonaceous deoxygenation(k_r)	do	11	Model is relatively insensitive to changes in k_r over a three-fold range of 0.02–0.06. Predicted DO concentrations deviate no more than 6 percent saturation from standard profile.
Ammonia-N loading	do	12	Model is sensitive to variations in ammonia-N loading. A doubling of loads (from outfalls in the nitrifying segment RM 86.5–55) results in as much as a 14 percent reduction in percent DO saturation values from the standard profile. Reducing the ammonia loading by 50 percent increases the predicted DO values by up to 8 percent saturation.
Rate of nitrogenous deoxygenation (k_n)	do	13	Model is insensitive to changes in k_n over a range of 0.5–0.9. Predicted DO concentrations differ from standard profile (k_n = 0.7) by less than 3 percent. Note that differences decrease with downstream distance.
Variation in water depth owing to backwater or tidal influences	24.8–5.0	14	Model is insensitive to expected range of changes in summertime water depth in the Tidal Reach. Predicted DO values differ from standard profile by less than 3 percent saturation.
Benthic demand	12.8–5.0	15	The model is sensitive to benthic-oxygen demand exerted between RM's 12.8–5.2. If the demand is removed, the predicted DO value at RM 5.0 is 8 percent higher than the standard condition.

REFERENCES CITED

Bella, D. A., 1969, A further note on verification: In modeling the eutrophication process, Proc. workshop sponsored by Federal Water Quality Adm. and Univ. Florida, St. Petersburg, Fla., November 19–21, 1969, p. 21–25.

Bella, D. A., and Dobbins, W. E., 1968, Difference modeling of stream pollution: Am. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 94, SA5, p. 995–1016.

Bennett, J. P., 1971, Convolution approach to the solution for dissolved oxygen balance equation in a stream: Water Resources Research, v. 7, no. 3, p. 580–590.

Bennett, J. P., and Rathbun, R. E., 1972, Reaeration in open-channel flow: U. S. Geol. Survey Prof. Paper 737, 75 p.

Churchill, M. A., Elmore, H. L., and Buckingham, R. A., 1962, The prediction of stream reaeration rates: Internat. Jour. Air and Water Pollution, v. 6, p. 467–504.

Columbia Basin Interagency Committee, Hydrology Subcommittee, 1963, River mile index Willamette River and tributaries: Columbia Basin Interagency Committee, 57 p.

Gleeson, G. W., 1972, The return of a river, the Willamette River Oregon: Advisory Comm. on Environmental Sci. and Technology and Water Resources Inst., Oregon State Univ., Corvallis, 103 p.

Harris, D. D., 1968, Travel rates of water for selected streams in the Willamette River basin, Oregon: U.S. Geol. Survey Hydrol. Inv. Atlas HA–273.

Hines, W. G., McKenzie, S. W., Rickert, D. A., and Rinella, F. A., 1977, Dissolved-oxygen regimen of the Willamette River, Oregon under conditions of basinwide secondary treatment: U.S. Geol. Survey Circ. 715–I, 52 p.

Hines, W. G., Rickert, D. A., McKenzie, S. W., and Bennett, J. P., 1975, Formulation and use of practical models for river-quality assessment: U.S. Geol. Survey Circ. 715–B, 13 p.

Hines, W. G., Rickert, D. A., and McKenzie, S. W., 1976, Hydrologic analysis and river-quality data programs: U.S. Geol. Survey Circ. 715–D, 20 p.

Isaacs, W. P., and Gaudy, A. F., Jr., 1968, Atmospheric oxygenation in a simulated stream: Am. Soc. Civil Engineers Proc., Jour. Sanitary Eng. Div., v. 94, SA2, p. 319–344.

Rickert, D. A., Hines, W. G., and McKenzie, S. W., 1975, Planning implications of dissolved-oxygen depletion in the Willamette River, Oregon, *in* Whipple, William, Jr., ed., Urbanization and water-quality control: Minneapolis, Am. Water Resources Assoc., p. 70–84.

Rickert, D. A., Hines, W. G., and McKenzie, S. W., 1976, Project development and data programs for assessing the quality of the Willamette River, Oregon: U.S. Geol. Survey Circ. 715–C, 31 p.

Streeter, H. W., and Phelps, E. B., 1925, A study of the pollution and natural purification of the Ohio River: U.S. Public Health Service, Public Health Bull. 146, 75 p.

Velz, C. J., 1970, Applied stream sanitation: New York, John Wiley and Sons, 619 p.

EXPLANATION OF WIRQAS MODEL PRINTOUT

Table 5 is an example of the computer printout of the WIRQAS DO Model. The illustrated printout includes 29 columns of information that were used to calibrate the model at the first five river cross sections between RM's 86.5 and 84.0. Columns 1 through 11 together with input coefficients for k_r and k_n provide the information necessary to initiate and drive the model. Columns 12–16 summarize model calculations of carbonaceous deoxygenation, whereas columns 17–21 summarize similar calculations for nitrification. Columns 22–29 complete the printout by listing reaeration calculations and a summary of DO gains and losses.

To aid the reader, column 1, which shows the section boundary stations, has been included at the left of each part of the table. The reader should note that the first seven columns of the printout includes double spacing for each station, whereas the rest of the columns have single spacing. The double spacing is necessitated by the river segment averaging calculations listed in columns 2, 5, 6, and 7.

The model begins at RM 86.5 and the startup is handled by treating the conditions at this station as those from an inflowing tributary. Values in each column are exactly as observed on the original printout sheets; there has been no rounding to selected significant figures.

A complete explanation of each column is presented on the following pages.

Column 1. STATION is the station location in river miles as measured from the mouth. These values correspond with the Willamette River Mile Index as established by the Hydrology Subcommittee, Columbia Basin Interagency Committee (June, 1963).

Column 2. WATER TEMP is water temperature in degrees Celsius. The temperature values are used in adjusting self-purification process rate coefficients. Note that the model calculates and uses an average water temperature for each river segment.

Column 3. TIME PASS is the cumulative time-of-passage in days from the first station to the downstream station of interest. Time-of-pas-

TABLE 5.—*Example of the computer printout of the WIRQAS DO model*

1	2	3	4	5	6	7	8	9	10	11
STATION	WATER TEMP	TIME PASS	TRIB DIS	EFF DEP	RIV VOL	AREA	IM DEM	DIS BOD	SLUDGE	NBOD
86.50	20.00	0.0	6,760	5.27		2,400	0	363,912	0	105,000
	20.00			6.85	66	2,400				
85.80	20.00	0.01519	0	8.42		2,400	0	0	0	0
	20.00			7.45	57	2,400				
85.20	20.00	0.02821	0	6.49		2,400	0	0	0	0
	20.00			6.18	19	2,375				
85.00	20.00	0.03250	25	5.88		2,350	0	54,400	0	388,000
	20.00			5.09	93	2,350				
84.00	20.00	0.05367	0	4.31		2,350	0	0	0	0

1	12	13	14	15	16	17	18	19	20	21
STATION	k_r	COD DIS	COD RESUS	TOT COD	T COD SAST	k_n	NOD DIS	NOD RESUS	TOT NOD	T NOD SAST
86.50	0.0	363,912	0	363,912	0	0.0	105,000	0	105,000	0
85.80	0.0600	0	363,149	363,149	763	0.7000	0	102,461	102,461	2,539
85.20	0.0600	0	362,497	362,497	1,415	0.7000	0	100,333	100,333	4,667
85.00	0.0600	54,400	362,282	416,682	1,630	0.7000	388,000	99,641	487,641	5,359
84.00	0.0600	0	415,465	415,465	2,847	0.7000	0	471,286	471,286	21,715

1	22	23	24	25	26	27	28	29
STATION	TOT SAST	TOT RAST	PE AT SAT	NET	REAERATION	DO BAL	PCT SAT	MG/L CONC
86.50	0	1,282,114	1,393,603	1,282,114	0	1,282,114	92.00	8.45
85.80	3,302	1,282,114	1,393,603	1,278,812	470	1,279,281	91.80	8.44
85.20	6,082	1,282,114	1,393,603	1,276,032	367	1,276,868	91.62	8.42
85.00	6,989	1,282,627	1,398,736	1,275,637	161	1,276,635	91.27	8.39
84.00	24,562	1,282,627	1,398,736	1,258,065	1,133	1,260,196	90.10	8.28

sage between two successive stations is calculated by the equation:

$$\text{Time of passage (days)} = \frac{0.0611(A)\,(x)}{Q} \qquad (8)$$

where
A = cross-sectional area (ft^2)
x = length of segment (mi)
Q = discharge (ft^3/s)

Column 4. TRIB DIS is a listing of tributary and waste-water discharges (ft^3/s) into Willamette River. The model can use discharge values to the nearest 0.01 ft^3/s, whereas the printout values in column 4 are rounded to the nearest whole ft^3/s. The value shown for station 86.50 is the inflowing discharge of the mainstem Willamette River (6,760 ft^3/s). The model uses the discharge at Salem as the index flow and routes flow downstream accounting for inflowing tributary and waste-water discharges.

Column 5. EFF DEP is the effective depth (ft) at each cross section. Effective depth is calculated by dividing the cross-sectional area, column 7, by the water-surface width (required as input to the program but not printed). Note that the model calculates and uses an average effective depth for each river segment.

Column 6. RIV VOL is the volume of water between stations, in millions of gallons. The river volume may be calculated from

$$\text{RIV VOL} = 0.0394(A)(x) \qquad (9)$$

where A and x are as defined for equation 8. Note that the model calculates and uses an average volume for each river segment.

Column 7. AREA is the cross-sectional area in ft^2. Areas were determined by field measurement or from existing channel maps provided by the U.S. Army Corps of Engineers and the U.S. Coast Guard. Note that the model calculates and uses an average area for each river segment.

Column 8. IM DEM provides for a listing for inflowing loads of "immediate" oxygen demand (see Velz, 1970) in units of population equivalents. One population equivalent (PE) is defined as

$$PE = \frac{BOD_{ult}(\text{lb/d})}{0.24} \qquad (10)$$

No immediate demands occur in the modeled river segment.

Column 9. DIS BOD is the load, in PE, of the ultimate carbonaceous biochemical-oxygen demand for each inflowing tributary or waste-water discharge. For station 86.50, the tributary discharge is equal to the Willamette in-river load of 363,912 PE. This value is calculated from

$$\begin{aligned} PE &= (\text{discharge})\,(BOD_{ult}\ \text{concentration})\,(\text{conversion factor}) \\ &= (6{,}760\ ft^3/s)\,(2.4\ mg/L)\,\frac{(34.7)}{(1.547)} \\ &= 363{,}912 \end{aligned} \qquad (11)$$

Column 10. SLUDGE is the oxygen demand, in PE's, at specific stations due to benthic deposits. Benthic demand was found to be significant only in the Portland Harbor area (not included in table 5).

Column 11. NBOD is the inflowing nitrogenous oxygen demand, in PE's, from each tributary or waste-water discharge. Nitrification occurs only between stations 86.50 and 55.20. The oxygen demand of ammonia is calculated as follows:

$$PE = (\text{unit } O_2 \text{ demand of } NH_4\text{–}N)\,(NH_4\text{–}N\ \text{concentration})(\text{discharge})\,(\text{conversion factor}) \qquad (12)$$

For example, at station 85.00, the NBOD is as follows:

$$\begin{aligned} NBOD_{(PE)} &= (4.33)(160\ mg/L)(25.0\ ft^3/s)\frac{(34.7)}{(1.547)} \\ &= 388{,}000 \end{aligned}$$

Column 12. k_r is the temperature corrected in-river rate of carbonaceous deoxygenation (day^{-1}.) Values of k_r at 20°C are input to the model and corrected for actual water temperature by the expression:

$$k_{r(t)} = k_{1(20°C)}(1.047)^{(T\text{-}20)} \qquad (13)$$

where T is the average temperature between stations as listed in column 2.

Column 13. COD DIS is the inflowing load of BOD_{ult} from each tributary or waste-water discharge, in PE's. The river was sectioned so there would be no more than one inflowing load for each designated segment. COD DIS is calculated by adding the values for IM DEM (column 8) and DIS BOD (column 9).

Column 14. COD RESUS is the residual BOD_{ult} load, in PE's, remaining at each station. COD RESUS is equal to the BOD_{ult} load remaining after the total load at the upstream station (TOT COD, column 15) has been satisfied at the specified deoxygenation rate (k_r column 12) for the incremental time-of-passage between successive stations (calculated from column 3). For further details, see Circular 715–I, p. 40.

Column 15. TOT COD is the total BOD_{ult} load, in PE's, remaining at each station. TOT COD is equal to the residual load remaining in the river (COD RESUS, column 14) plus the inflowing load (COD DIS, column 13).

Column 16. T COD SAST is the cumulative load of satisfied BOD_{ult}, in PE's.

Column 17. k_n is the in-river rate of nitrification (day^{-1}) at 20°C. Significant nitrification occurs only between stations 86.50 and 55.20. During calibration and verification conditions, the average daily water temperatures in this river segment were essentially 20°C; therefore, no temperature corrections were made for k_n.

Column 18. NOD DIS is the inflowing nitrogenous-oxygen demand, in PE's, from each tributary or waste-water discharge. This column is identical to column 11 (NBOD). The data are repeated here so all computations related to nitrogenous demand appear as a unit in the printout (columns 17–21).

Column 19. NOD RESUS is the residual nitrogenous-oxygen demand, in PE's, remaining at each station. NOD RESUS is equal to the nitrogenous-oxygen demand remaining after the total demand at the upstream station (TOT NOD, column 20) has been satisfied at the specified nitrification rate (k_n,column 17) for the incremental time-of-passage between successive stations (calculated from column 3). For further details, see Circular 715–I, p. 42.

Column 20. TOT NOD is the total nitrogenous-oxygen demand, in PE's, remaining at each station. TOT NOD is equal to the residual load remaining in the river (NOD RESUS, column 19) plus the inflowing load (NOD DIS, column 18).

Column 21. T NOD SAST is the cumulative load of satisfied nitrogenous-oxygen demand, in PE's.

Column 22. TOT SAST is the cumulative total satisfied oxygen demand, BOD_{ult} and nitrogenous, in PE's. For a specific station, TOT SAST is the sum of T COD SAST (column 16) plus T NOD SAST (column 21).

Column 23. TOT RAST is the cumulative total DO, in PE's, resulting from inflowing tributaries and waste-water discharges.

Column 24. PE AT SAT is the amount of DO, in PE's, that would be in the river if the water were oxygen saturated at the temperature listed in column 2.

Column 25. NET is the DO, in PE's, remaining after the BOD_{ult} and nitrogenous demands have been subtracted. NET equals TOT RAST (column 23) minus TOT SAST (column 22).

Column 26. REAERATION is the DO added, in PE's, due to atmospheric reaeration within each river segment.

Column 27. DO BAL is the amount of oxygen, in PE's, in the river after reaeration has been added. DO BAL equals NET (column 25) plus the cumulative reaeration which is found by summing successive values of REAERATION (column 26).

Column 28. PCT SAT is the DO concentration in percent saturation. PCT SAT equals DO BAL (column 27) divided by PE AT SAT (column 24) times 100.

Column 29. MG/L CONC is DO concentration in mg/L. MG/L CONC is calculated as follows:

$$DO_{mg/L} = \frac{(\text{DO BAL (PE)})}{(\text{discharge})}(\text{conversion factor}) \quad (14)$$

For example, at station 86.50 the DO in mg/L is as follows:

$$DO_{mg/L} = \frac{(1,282,114)}{(6760)} \; \frac{(1.547)}{(34.7)}$$
$$= 8.45$$