Evaluation of Planning Alternatives for Maintaining Desirable Dissolved-Oxygen Concentrations in the Willamette River, Oregon

River-Quality Assessment of the Willamette River Basin, Oregon

GEOLOGICAL SURVEY CIRCULAR 715-K

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By David A. Rickert, 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—carbonaceous biochemical oxygen demand
BOD_{ult}—ultimate BOD
BOD_5—5-day BOD at 20°C
DO—dissolved oxygen
N—nitrogen
NOD—nitrogenous-oxygen demand
NPS—nonpoint source
k_n—nitrogenous deoxygenation rate ($\log_{10}$) in river
k_r—river carbonaceous deoxygenation rate ($\log_{10}$), corrected for temperature
k_1—carbonaceous deoxygenation rate ($\log_{10}$) as measured in BOD bottle at 20°C
RM—river mile
STP—municipal sewage-treatment plant

CONVERSION FACTORS

Factors for converting inch-pound units to the International System of Units (SI) are given below to four significant figures.

Inch-pound English	*Multiply by*	*Metric (SI)*
ft^3/s (cubic feet per second)	2.832×10^{-2}	m^3/s (cubic meters per second)
lb (pounds)	4.535×10^{-1}	kg (kilograms)
mi (miles)	1.609	km (kilometers)

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ABSTRACT

Basinwide secondary treatment of municipal and industrial waste waters has resulted in a dramatic increase of summertime dissolved-oxygen concentrations in the Willamette River. Rates of carbonaceous decay are low (0.03 to 0.06 per day), and point-source carbonaceous biochemical oxygen demand loadings now account for less than one-third of the satisfied oxygen demand. Nitrification is now the dominant cause of dissolved-oxygen depletion. Future achievement of dissolved-oxygen standards will require continued low-flow augmentation in addition to pollution control. A minimum summertime streamflow of 6,000 cubic feet per second at Salem gage will be needed even with increased removal of oxygen-depleting materials. The greatest immediate incremental improvement in dissolved oxygen can be made through reduction in point-source industrial ammonia loading. The pros and cons of upgrading treatment efficiencies for carbonaceous biochemical oxygen demand removal would best be determined after the ammonia loading has been reduced. For the foreseeable future, there is no need for municipal advanced waste treatment to protect dissolved-oxygen levels in the Willamette River.

INTRODUCTION

BACKGROUND

Historically, maintenance of high dissolved-oxygen (DO) concentration has been the critical problem in the Willamette River (fig. 1). During summer low-flow periods, the DO concentration in Portland Harbor was often zero (Velz, 1961; Gleeson, 1972), and for years, low DO levels inhibited the fall migration of salmon from the Columbia River.

In recent years, summer DO levels have increased dramatically and fall salmon runs have returned. The improvement has resulted from a reduction in the loading of point-source carbonaceous biochemical oxygen demand (BOD), coupled with streamflow augmentation from storage reservoirs. However, the Oregon Department of Environmental Quality (DEQ) still regards maintenance of high DO levels as the factor of highest priority in planning the future of the Willamette River.

Today (1979) the Willamette is the largest river in the United States on which all point-source discharges receive secondary waste-water treatment. The Willamette thus offers a unique opportunity to evaluate key alternatives for managing river quality. The primary concern is whether advanced waste treatment will be necessary to achieve desirable DO levels under future conditions of waste loading and streamflow.

PURPOSE AND SCOPE

This circular describes the impacts of various quality-planning alternatives on summertime DO levels in the Willamette River. Annually, the lowest DO concentrations occur during the summer with the low flow, high temperature conditions of July and August. This period is the one of most concern for river quality and therefore, the "critical condition" on which to base the design of waste-treatment and quality-management plans.

This circular completes a three-set series on summertime DO conditions of the Willamette. Circular 715–I (Hines and others, 1977) provided a detailed data base and the interpretations necessary to describe the summertime DO regimen below river mile (RM) 86, the his-

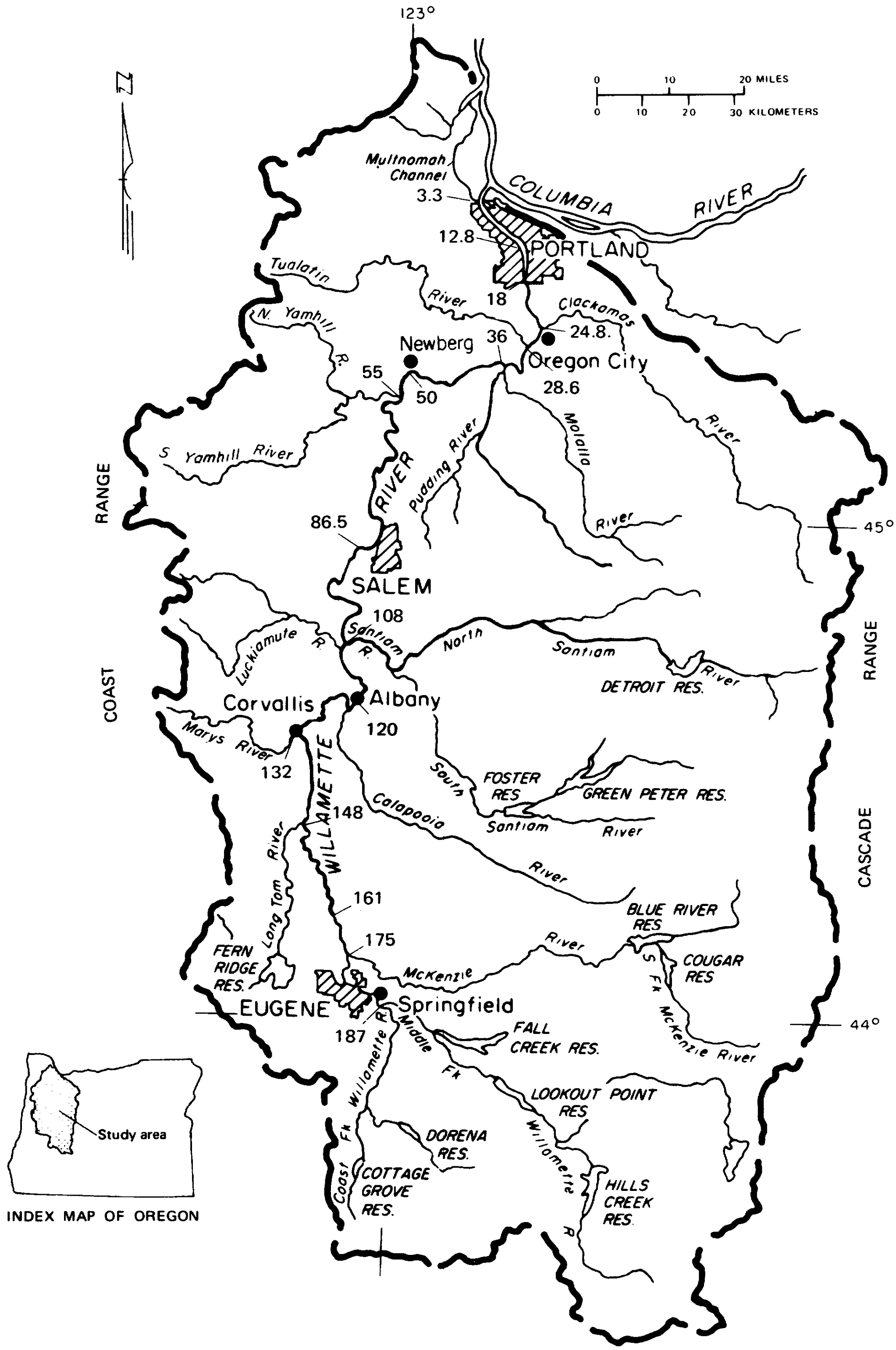

FIGURE 1.—Willamette River basin, Oregon, emphasizing principal tributaries, major reservoirs, and river-mile locations on main stem Willamette River.

torical zone of DO depletion. Circular 715–J (McKenzie and others, 1979) followed by describing how data in Circular 715–I were used to calibrate and verify a DO model useful as a practical tool for assessing planning alternatives.

To aid the reader, the following two sections provide brief synopses of (1) the summertime DO regimen of the Willamette, and (2) the basic character of the verified DO model.

DO SOURCES AND DEMANDS

Figure 2 shows the predominant factors controlling DO concentrations in various segments of the Willamette River under summer low-flow conditions. The profile represents average daily DO concentrations measured in 1973 and is constructed with time of travel on the horizontal axis to permit examination of the rate of change in measured DO levels.

Along the course of the Willamette River, the observed DO profile is the net balance of oxygen demands exerted and oxygen resources contributed. Nitrification, carbonaceous deoxygenation, and a "benthic demand" are the oxygen demands, whereas natural and augmented streamflow, tributary inflows, atmospheric reaeration, aeration at the Willamette Falls, and Columbia River water are the oxygen sources. As indicated in figure 2, the DO profile is influenced along the entire 187 miles (mi) by natural and augmented streamflow, atmospheric reaeration, and carbonaceous deoxygenation. In contrast, the other factors are involved only in the noted segments and locations.

Before describing the segment-to-segment character of the DO profile, it is necessary to provide a brief background on the measured DO levels (see Supplement E, Circular 715–I). First, each DO level in figure 2 represents the average of at least 2 days of around-the-clock (diel) sampling. The values at many locations were computed from continuously recorded data, and for manually sampled sites, the levels represent the average of as many as 128 samples.

Second, diel DO variations resulting from algal photosynthesis and respiration occurred at each site represented in figure 2 (see Supplement E, Circular 715–I). Magnitudes of DO variations were small below RM 50, but far-

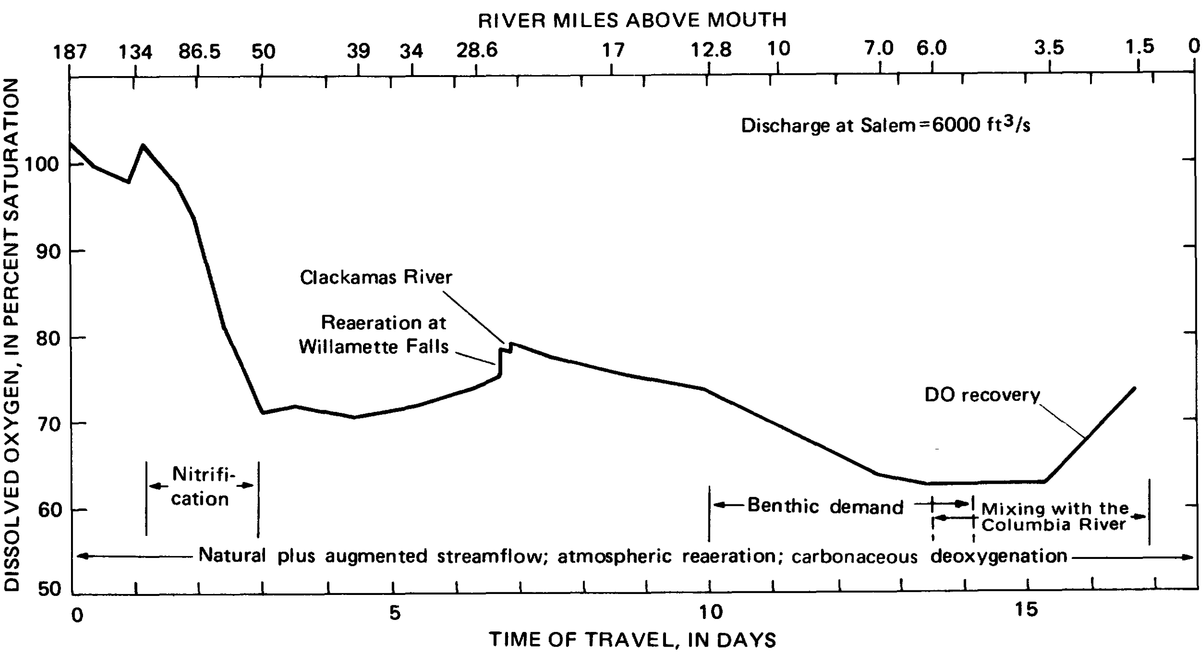

FIGURE 2.—Composite DO profile of the Willamette River under observed 1973 steady low-flow conditions. The profile is plotted on a time-of-travel basis to emphasize the relative rates that DO is removed or added in various reaches. Major controlling factors are noted for appropriate reaches.

ther upstream, daily variations were large owing to growth of attached algae on the shallow, cobbly bottom.

RM 185–120

In figure 2, the average DO levels between Eugene–Springfield (RM 185) and Albany (RM 120) are consistently near 100-percent oxygen saturation, or about 9.4 milligrams per liter (mg/L) at the prevailing summer water temperatures of 18° to 19°C. The McKenzie River enters the Willamette at RM 175 but, with a DO saturation of 100 percent, does not cause any measurable change in DO levels. The impact of waste-water loads from municipalities and industries in Eugene–Springfield, Corvallis, and other smaller communities is discernible only in the immediate vicinity of outfalls. Because of the fairly light loading of ammonia, nitrification is insignificant, and the high atmospheric reaeration capability of the shallow fast-moving segment quickly counterbalances the slow rate of carbonaceous deoxygenation.

RM 120–50

Beginning at RM 114, the percentage of DO saturation decreases slowly, and then, below Salem (RM 85), it decreases rapidly. Between RM's 120 and 50, the level declines from nearly 100 percent to 70 percent, a drop of approximately 2.5 mg/L at the prevailing water temperatures. The decrease results from large industrial loads of ammonia that induce the growth of nitrifying bacteria on the shallow, cobbly, diatom-encrusted river bottom. The bacterially induced nitrification proceeds at a high rate, outpacing the capacity of the river to replenish DO through atmospheric reaeration.

RM 50–10

Changes in average DO levels between RM 50 to 10 are minor relative to the large decrease between RM 120 to 50. The observed DO variations include (1) an approximate 5-percent increase in saturation caused by reaeration at Willamette Falls and the inflow of cool, highly oxygenated water from the Clackamas River, (2) a slight decline in percent saturation between RM's 21 and 12.8 resulting from carbonaceous deoxygenation, and (3) a somewhat sharper decline between RM 12.8 to 10 owing to the additive effects of carbonaceous deoxygenation and a benthic oxygen demand. Because the rate of carbonaceous deoxygenation is low, total reaeration effectively balances total deoxygenation and keeps the percentage of DO saturation at a fairly even level.

RM 10–1.5

Between RM's 10 and 6, there is a gradual decrease in percent DO saturation (7 percent) resulting from a combination of benthic demand and carbonaceous deoxygenation. Between RM 6.0 to 3.5, DO levels remain fairly constant (approximately 63 percent saturation or 5.4 mg/L). In the vicinity of RM 3.5, near the entrance to Multnomah Channel, DO levels begin to rise sharply owing to mixing with highly oxygenated Columbia River water. At RM 1.5, the DO level has risen to 74 percent saturation. Thereafter, DO continues to increase, finally reaching 97 percent saturation at the Columbia confluence.

WIRQAS DO MODEL

After testing several models, the one chosen for the study was that developed and used for more than 30 years by C. J. Velz. The basic model (Velz, 1970) is applicable to conditions of steady (invariable), nonuniform (changing cross-sectional geometry), plug (nondispersive) flow. The computer program as formulated for the present study is named the WIRQAS (Willamette Intensive River-Quality Assessment Study) DO Model.

The WIRQAS Model has been applied only for summer low-flow, high-temperature, steady-state conditions. The model was calibrated using 1974 waste-loading, streamflow, and water-temperature conditions and verified against similar data collected in 1973. Details of the model, the calibration, and the verification are presented in Circular 715–J. In addition, Supplement A of the present report provides a summary of the model's characteristics and application ranges.

EXPLANATION OF BASE CONDITION

STREAMFLOW

Using the verified WIRQAS Model, a series of computer runs have been made to simulate an array of hydrologic and waste-loading conditions. Results of these runs were used to construct the "predictive control curves" presented in figures 3 through 15. All curves in these figures were computed around a selected base condition representing a Salem streamflow of 6,000 ft^3/s. This flow was selected as the comparative base for all figures because (1) the U.S. Army Corps of Engineers attempts to maintain this level as the minimum, summer low flow needed for navigation purposes, and (2) observations by the Oregon DEQ (Oregon Department of Environmental Quality, 1975) and the U.S. Geological Survey (Rickert and others, 1975) indicate this discharge is needed as a summertime minimum in order to achieve State DO standards. Water temperatures used for the base condition were those measured during the 1973 verification period when the average streamflow was 6,000 ft^3/s. For all curves, DO saturation at the model boundary point (RM 86.5) was set at the 1973–74 average of 92 percent.

WASTE LOADINGS

In addition to a base-condition flow, it was also necessary to select among loading data measured during 1973 and 1974 to obtain an average summer condition defined by reliable data. The selected base-condition data are shown in table 1 where both point- and nonpoint-source (NPS) loadings of ultimate BOD (BOD_{ult}) and nitrogenous-oxygen demand (NOD) are referred to river-mile location. All loadings were computed using the base-condition flow of 6,000 ft^3/s. The methods of computing the loadings are described in the footnotes for table 1, and the manner of selecting data to use in the computations is given below:

TABLE 1.—*Summary of BOD_{ult} loadings, NOD loadings, and information used for base-condition inputs to the WIRQAS DO Model*

[Computed for a Salem flow of 6,000 ft^3/s]

Location (RM)	Description of waste input	Flow (ft^3/s)	DO (percent saturation)	BOD_{ult} load: Point source[1,2] (lb/d)	BOD_{ult} load: Nonpoint source[3,4] (lb/d)	BOD_{ult} load: Total (lb/d)	NOD load[5,6]: Point source (lb/d)	NOD load[5,6]: Nonpoint source (lb/d)	NOD load[5,6]: Total (lb/d)
86.5	Residual load in Willamette River	6,000.0	92	30,500	51,700	82,200	18,900[7]	5,600[7]	24,500[7]
85.0	Boise Cascade Corp	24.9	10	13,100	-----	13,100	70,300	----	70,300
77.9	Salem STP	40.4	50	11,700	-----	11,700	7,500	----	7,500
55.0	Yamhill River	62.5	90	900	900	1,800	-----	----	------
50.5	Newberg STP	1.2	20	100	-----	100	-----	----	------
49.8	Publishers Paper Co	18.0	10	7,300	-----	7,300	-----	----	------
39.0	Wilsonville STP	.2	20	20	-----	20	-----	----	------
35.8	Mollala River	134	100	470	930	1,400	-----	----	------
33.0	Canby STP	.5	20	70	-----	70	-----	----	------
28.4	Tualatin River	22.5	90	2,300	500	2,800	-----	----	------
28.0	Publishers Paper Co	19.9	10	11,000	-----	11,000	-----	----	------
27.8	West Linn STP 1	.7	20	100	-----	100	-----	----	------
27.6	Crown Zellerbach Corp	20.7	40	4,900	-----	4,900	-----	----	------
25.0	Oregon City STP	4.3	50	140	-----	140	-----	----	------
24.8	Clackamas River	1,100	96	-----	9,300	9,300	-----	----	------
24.1	West Linn STP 2	1.0	50	170	-----	170	-----	----	------
20.2	Tryon Creek STP	5.7	50	220	-----	220	-----	----	------
19.9	Oak Lodge STP	3.1	50	120	-----	120	-----	----	------
18.5	Kellogg Creek	1.0	70	-----	260	260	-----	----	------
18.4	Johnson Creek	2.0	80	-----	40	40	-----	----	------
18.4	Milwaukie STP	2.1	50	220	-----	220	-----	----	------
	Total	------	--	83,330	63,630	146,960	96,700	5,600	102,300

[1] Based on point-source BOD_{ult} loads discharged directly to the main stem Willamette River and into tributaries. Residual load at RM 86.5 represents the flow-routed sum of all upriver, individual, point-source loads. Decay calculated from temperature corrected rates based on k_r=0.06/d at 20°C.

[2] All point-source BOD_{ult} loads above RM 86.5 based on 1973 data. Loads below RM 86.5 based on 1974 data, except those less than 500 lb/d which were sampled in 1973.

[3] Based on BOD_{ult} concentrations measured in Cascade Range tributaries above waste-water outfalls plus estimated NPS contributions from minor tributaries (that is, those with flows less than 100 ft^3/s). Residual load at RM 86.5 represents the flow routed sum of all upriver, individual, NPS loads. Decay calculated from temperature corrected rates based on k_r=0.06/d at 20°C.

[4] All NPS BOD_{ult} loads represent averaged 1973–1974 data.

[5] NOD loadings were calculated from ammonia-N data using an oxygen-to-nitrogen ratio of 4.33 (see Wezernak and Gannon, 1967).

[6] In the modeled segment of river (RM's 86.5 to 5.0), measurable nitrification occurs only from RM 86.5 to 55.2. Therefore, NOD's are reported only for those ammonia loads that enter this 31.5-mi zone of nitrification. The dashed lines thus signify a lack of exerted nitrogenous demand rather than a lack of ammonia loading.

[7] Residual point and NPS loads at RM 86.5 were based on an average ammonia-N concentration of 0.16 mg/L measured during early and mid-August 1974, when flows were about 6,760 ft^3/s. The NPS component was taken to be 0.04 mg/L based on the average of measurements in major Cascade Range tributaries above known point sources. This concentration was converted to the reported NOD loading consistent with the base-condition flow of 6,000 ft^3/s. The remaining 0.12 mg/L was assumed to be a point-source component that is flow independent. No flow routing of individual sources was possible owing to lack of ammonia decay rates above RM 86.5 .See Supplement B in this report for further details.

1. Where available, 1974 BOD data were used for municipal and industrial waste-water discharges. Below RM 86.5, 1974 data were available for all point sources discharging more than 500 pounds (lb) ultimate BOD per day (BOD_{ult}/d). The 1974 data were the more reliable because of improvements in analytical technique.

2. BOD data from 1973 were used for all point-source discharges above RM 86.5 and for the small discharges (less than 500 lb BOD_{ult}/d) below this location.

3. NOD loadings were computed from 1974 ammonia data except for the Boise Cascade mill at RM 85.0. NOD for this source was based on the lower ammonia concentrations measured in 1973, because inspection of several years of records showed these were more representative of average summer conditions.

4. For all tributaries, the flows, BOD_{ult} loadings, and DO levels were averaged from 1973 and 1974 data. This was done because the summer of 1973 was unusually dry, whereas the summer of 1974 was quite wet. By averaging the data, more representative tributary conditions were obtained than those offered by either year's results.

To evaluate the significance of the data in table 1, it was necessary to determine the quantities and percentages of point and NPS BOD_{ult} and NOD that entered the Willamette in various river segments. Table 2 shows such results for BOD_{ult}, and table 3 gives similar data for NOD.

The important points in table 2 are that only 54 percent of the total BOD_{ult} is derived from point sources and that the point-source loadings are distributed fairly evenly over the

TABLE 2.—*Base condition, dry-weather BOD_{ult} loading to the main stem Willamette River*

[All point-source BOD_{ult} loads above RM 86.5 based on 1973 samples. Point-source loads below RM 86.5 based on 1974 data except those less than 500 lb/d which were sampled in 1973. All NPS BOD_{ult} loads represent averaged 1973–74 data]

River segment (RM)	Point sources [1] (municipal and industrial outfalls)			Nonpoint sources [2]			Total loading	
	BOD_{ult} (lb/d)	Percentage of point-source loading	Percentage of total loading to river	BOD_{ult} (lb/d)	Percentage of nonpoint-source loading	Percentage of total loading to river	BOD_{ult} (lb/d)	Percentage by segment
187 –86.5 [3]	36,800	41	22	65,100	85	39	101,900	61
86.5–52.0	25,600	29	15	900	1	.5	26,500	16
52.0–26.5	26,300	29	16	1,400	2	.5	27,700	17
26.5– 5.0	900	1	0.5	9,600	12	6	10,500	6
Total	89,600	100	54	77,000	100	46	166,600	100

[1] Outfalls discharging directly to main stem Willamette River plus flow-routed point-source loads discharged into tributaries. Of the total point-source loading, 41 percent is from municipal waste-water treatment plants and 59 percent is from industrial discharges.
[2] Based on BOD_{ult} concentrations measured in Cascade Range tributaries above waste-water outfalls plus estimated NPS contributions from minor tributaries (that is, those with flows less than 100 ft^3/s).
[3] Loadings for the segment (RM's 187–86.5) differ from model input loadings at RM 86.5 (see table 1) owing to in-river decay.

TABLE 3.—*Approximate base condition, dry-weather ammonia nitrogen loading to the main stem Willamette River*

[Based on data collected during the summer low-flow periods of 1973–74]

River segment (RM)	Point source [1] (municipal and industrial outfalls)			Nonpoint sources [2]			Total loading	
	Lb/d as N	Percentage of point-source loading	Percentage of total loading to river	Lb/d as N	Percentage of nonpoint-source loading	Percentage of total loading to river	Lb/d as N	Percentage by segment
187 –86.5 [3]	14,500 [4]	39	37	1,500	79	4.0	16,000	41
86.5–52.0	18,000	49	47	100	5	.3	18,100	47
52.0–26.5	2,800	8	7	150	8	.4	2,950	8
26.5– 5.0	1,600	4	4	160	8	.4	1,760	4
Total	36,900	100	95	1,910	100	5	38,810	100

[1] Outfalls discharging either directly to Willamette River or into Middle Fork, McKenzie, Santiam, and Clackamas Rivers less than 20 mi from confluence with Willamette.
[2] Estimated from nitrogen concentrations measured in tributaries above waste-water outfalls.
[3] Loadings for this segment (RM's 187–86.5) differ from model input loadings at RM 86.5 (see table 1) owing to in-river decay.
[4] Nitrogen mass-balance calculations based on measured loadings and in-river concentrations indicate an undefined source contributed up to 12,000 lb/d of ammonia-N in the Albany-Millersburg area (RM 120–114). DEQ and USGS are currently (1979) involved in a detailed study of ammonia loading between RM's 120 and 86.5.

160.5 mi between Eugene (RM 187) and the Willamette Falls (RM 26.5). In addition, as described in Table 2, footnote 1, 41 percent of the total point-source loading is from municipal waste-water treatment plants, whereas 59 percent is from industrial discharges.

The important point from table 3 is the overwhelming contribution of point source (95 percent) relative to NPS ammonia (5 percent). Moreover, the data used to compile table 3 show that about three-fourths of the point-source ammonia comes from two sources: (1) the Boise Cascade mill at RM 85.0 and (2) a yet undefined, localized source in the Albany-Millersburg area (RM 120–114) (see table 3, footnote 4).

Whereas tables 1–3 show the magnitude of waste-water loadings, table 4 summarizes the oxygen demands exerted by the loads in passage through the modeled river segment of RM 86.5 to 5.0. From table 4, the total demand exerted by all sources is 177,900 lb/d. Based on the bottom row of data, the percentage contributions to this total are as follows:

1.	Point-source carbonaceous deoxygenation	28
2.	NPS carbonaceous deoxygenation	22
3.	Nitrification of point-source ammonia	32
4.	Nitrification of NPS ammonia	2
5.	Benthic-oxygen demand	16
	Total	100

The results show that oxidation of point-source ammonia represents the largest oxygen demand in the modeled river segment. Moreover, because nitrification occurs at a very high rate ($k_n=0.7$/d; see Supplement A of this report) and exclusively from RM 86.5 to 55, the nitrogenous demand induces a sharper and deeper depression in DO than do any of the other factors (see fig. 2). In a similar manner to nitrogenous demand, the benthic oxygen demand is exerted exclusively within one segment of the river (RM 12.8–5.0). However, while significant, the impact of benthic demand on DO is far less dramatic than that caused by nitrification (fig. 2).

In contrast to the other oxygen demands, carbonaceous deoxygenation is exerted over the entire river. Furthermore, the rate of exertion is low and, hence, the effect on the DO profile is less pronounced. The largest localized impact is between RM's 12.8 and 5.0, where tidal effects and river geometry cause slow travel times, thus enabling carbonaceous deoxygenation to occur for about 5 days.

In evaluating the total impact of carbonaceous deoxygenation, it is important to note the relative proportion of the point and NPS demands. The importance arises because during summer low-flow conditions, NPS BOD_{ult} loading in the Willamette River represents essentially natural background demands that seemingly cannot be modified. This means, for base conditions, that only slightly more than one-half the materials causing carbonaceous deoxygenation are point-source derived and, therefore, amenable to reduction through waste-water treatment.

TABLE 4.—*Oxygen demands exerted in the modeled segment of the Willamette River under base conditions*

[Base conditions represent a Salem flow of 6,000 ft^3/s and the waste loadings given in table 1]

River segment (RM)	Carbonaceous[1]				Nitrogenous[2]				Benthic[3]		Total	
	Point source (lb/d)	Percentage	Nonpoint source (lb/d)	Percentage	Point source (lb/d)	Percentage	Nonpoint source (lb/d)	Percentage	Amount (lb/d)	Percentage	Amount (lb/d)	Percentage
86.5–52.0	4,700	5	4,700	5	57,300	94	3,400	6	-----	---	70,100	39
52.0–26.5	15,800	18	12,700	15	-----	--	-----	--	-----	---	28,500	16
26.5– 5.0	29,000	33	21,300	24	-----	--	-----	--	29,000	100	79,300	45
Total	49,500	56	38,700	44	57,300	94	3,400	6	29,000	100	177,900	100

[1] Computed assuming that all point-and nonpoint-source BOD_{ult} loadings decay in the river at $k_r=0.06$/d above RM 55.2 and at 0.03/d below this location (see Supplement C of this report for discussion).
[2] Computed using a first-order decay rate $k_n=0.7$/d. Field data indicate that measurable nitrification occurs only between RM's 86.5 and 55.2 of the modeled river segment.
[3] As noted in the text, the "benthic demand" between RM's 12.8 and 5.0 is thought to represent a combination of several different types of oxygen exertion. The model treats part of the demand as a flowing load decayed at a rate of 0.1/d. Thus, the total computed benthic demand varies with flow, and the result reported here for base conditions (Salem flow=6,000 ft^3/s) differs slightly from the value reported for calibration conditions (Salem flow=6,760 ft^3/s) in tables 1 and 2 of Circular 715–J.

PLANNING IMPLICATIONS

As an aid to river-quality planning, the WIRQAS Model has been used to test planning alternatives concerning (1) BOD loading, (2) ammonia loading, (3) low-flow augmentation, and (4) the effects of possible removal or reduction of the "benthic oxygen demand" in Portland Harbor. This section defines the major implications of the alternatives by comparing DO profiles generated by the verified model with the reference base-condition profile.

A fact the reader should bear in mind in examining the following illustrations (figs. 3–7) is that, for ease of presentation, the DO profiles are plotted as a function of river location. Thus, unlike the profile in figure 2, the slopes of curves in specific subreaches do not represent the actual rates at which oxygen is added to or lost from the river. For example, the profiles in figures 3–7 suggest a rapid rate of oxygen depletion below Willamette Falls. Actually, the steepness of the curves is caused by the slow time of travel in the Tidal Reach (see Circular 715–I) rather than by an accelerated rate of oxygen depletion.

Waste loadings and flow levels examined in figures 3–7 were selected to provide envelopes for summer low-flow conditions of probable future occurrence. Most likely, any future changes in point-source BOD_{ult} loading will fall within a span of a 50 percent decrease to a 200 percent increase around the base condition. The same reasoning holds for the examined range of point-source NOD loadings and for the investigated flow range of 3,260–10,000 ft^3/s.

In developing figures 3–7 (and all subsequent curves), the assumption was made that no changes would occur in the location of wastewater outfalls. This was done because the location of possible new outfalls and changes in existing ones could not be fully anticipated. In addition, all waste sources were treated as receiving secondary treatment, and, except where noted, the percentages of loading increases or decreases were applied uniformly to all point sources.

As previously noted, the base-condition DO profile is included in each of figures 3–7. Also included are the State DO standards, which change from segment-to-segment as follows (Oregon Department of Environmental Quality, 1975): (1) RM 0–26.5, 5 mg/L, to protect anadromous fish passage and population by resident fish; (2) RM 26.5–50, 6 mg/L, to protect anadromous fish passage and salmonid rearing; (3) RM 50–85, 7 mg/L, to protect salmonid fish rearing and spawning; and (4) above RM 85, 90 percent of saturation, to protect salmonid spawning.

It should be noted in figures 3–7 that the DO levels computed for the base condition violate the standard between RM 64 to 50. This violation is caused almost entirely by nitrification, and more will be said about this in the following sections.

BOD IMPACT

The effect of BOD loading on summertime DO is reflected in figure 3. The curve labeled 100 percent represents the average DO profile of the river at the flow, water temperatures, ammonia loading, and BOD loading representative of the base condition. The upper and lower curves represent the predicted DO profiles at 50 percent and 200 percent of the base-condition point-source BOD loading with all other variables held constant.

The upper curve in figure 3 indicates that only a slight improvement in DO can be obtained by a 50 percent decrease of BOD loading from each point source in the basin. The predicted increase in DO would be less than 5 percent of saturation near the downstream end of the Newberg Pool (RM 27) and about 5 percent at RM 5, the low DO point in the river.

In contrast, a doubling of BOD loading from each point source would depress DO by more than 5 percent of saturation at RM 27 and by more than 10 percent at RM 5. This increase in loading would also cause the violation of the State DO standard to increase in magnitude between RM 64 to 50.

Figure 4 compares the base-condition profile with one representing the application of a BOD_5 effluent standard of 10 mg/L to all municipal treatment plants discharging directly into the Willamette River. Such a standard, supposedly attainable by high-level secondary treatment, is being considered by the Oregon

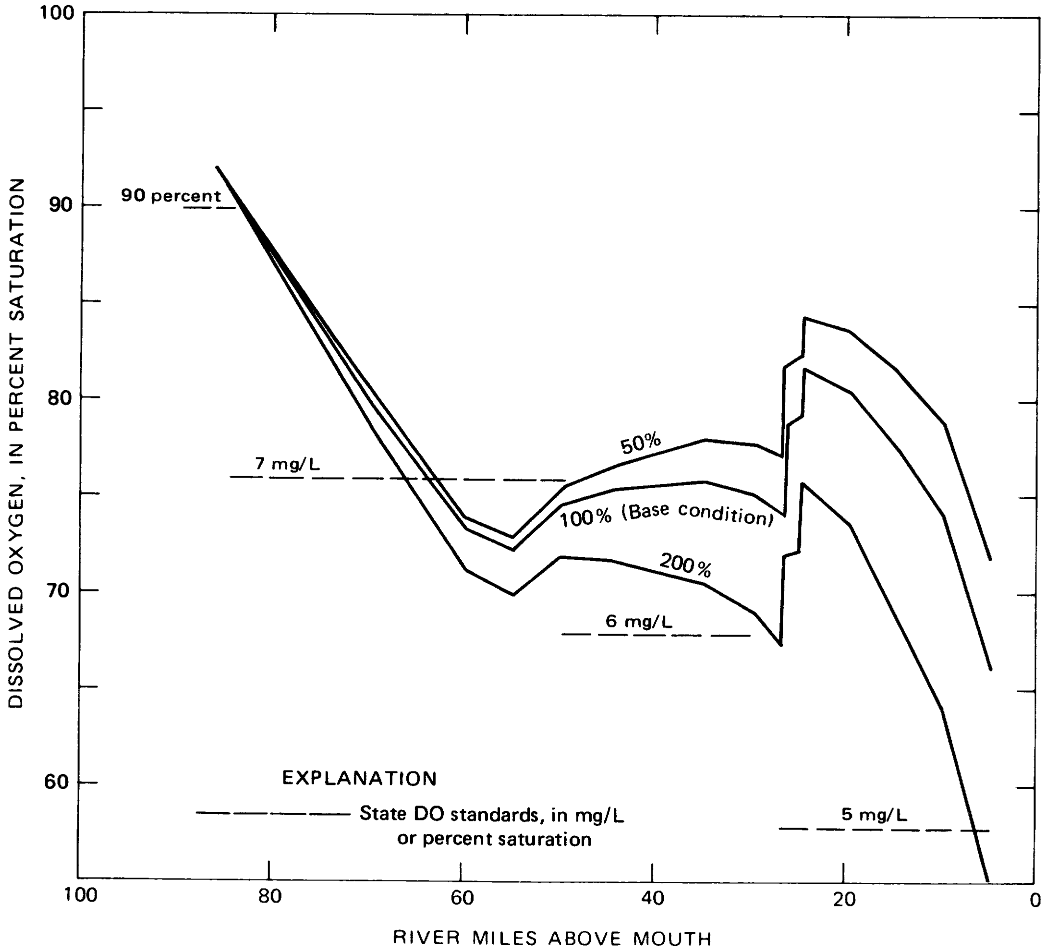

FIGURE 3.—DO profiles for selected point-source BOD_{ult} loadings. The profile labeled 100 percent results from the base condition defined in table 1. Flow (6,000 ft^3/s at Salem), NOD loadings, and NPS BOD_{ult} loadings held constant.

DEQ. Application of the 10 mg/L standard to base conditions would decrease municipal summertime loading of BOD_{ult} to the Willamette from about 30,400 to 17,400 lb/d. The largest individual decrease would be about 7,000 lb/d at the Salem municipal sewage-treatment plant (STP) (RM 77.9). The modeling results (fig. 4) indicate that the reduced loading would produce only minor improvements in DO saturation, the maximum increase being 2 percent at RM 5. This virtual lack of improvement stems from (1) the small reduction attainable in the total loading of BOD_{ult} (about 9 percent), (2) the low rates at which BOD_{ult} is exerted in the river, and (3) the dispersed locations within the basin of the larger municipal waste-water treatment plants (see Circular 715–I).

AMMONIA IMPACT

Figure 5 illustrates the effect of point-source NOD on summertime DO in the Willamette. Compared to the base condition, a one-third reduction in NOD loading would increase DO by about 5 percent of saturation near the lower end of the Upstream Reach (RM 55) and also at RM 27. Between RM's 64 to 50, the improvement in DO levels would enable the State DO standard to be met under base conditions. A two-thirds reduction in point-source NOD loading would substantially increase DO levels, by about 10 percent of saturation at RM's 55 and 27 and by more than 5 percent at RM 5.

In contrast, increased NOD loading would cause rather drastic decreases in DO levels. An increase of point-source NOD loading to 150

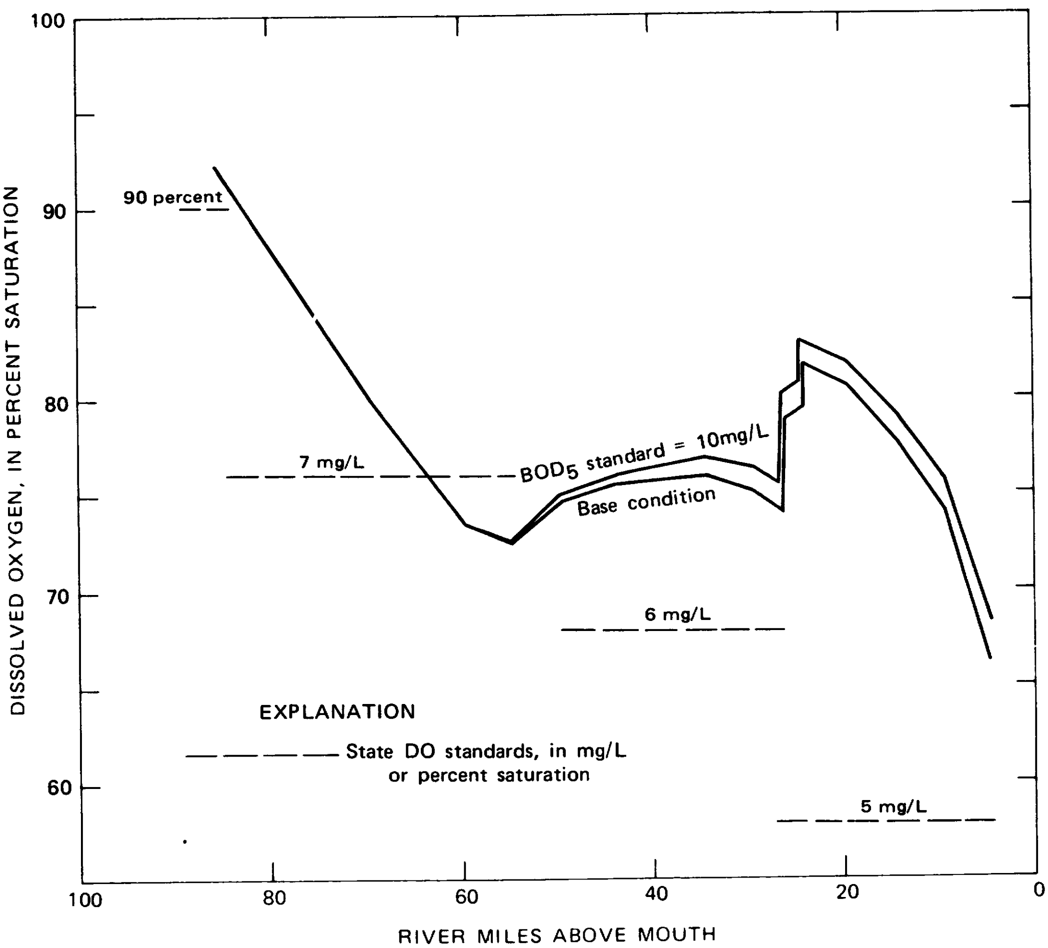

FIGURE 4.—DO profiles computed for the base condition and predicted for a BOD_5 municipal effluent standard of 10 mg/L. The effluent standard was applied (1) only to those municipal sewage treatment plants that discharge directly into the Willamette River and (2) with flow (6,000 ft³/s at Salem), NOD loadings, and the industrial and NPS components of BOD_{ult} held at the base condition (see table 1).

percent of the base condition would decrease the percent of DO saturation by about 8 percent at RM 55, 6 percent at RM 27, and 4 percent at RM 5. Furthermore, the resultant decreases would cause State DO standards to be violated from RM 72 to the Willamette Falls.

The results illustrate two important points. First, over the modeled part of the Willamette, ammonia loading has its greatest effect on DO in the active zone of nitrification between RM's 85 and 55. Thereafter, measurable nitrification ceases to occur and the upstream effects of the process are gradually diminished by atmospheric reaeration. Second, comparison of figures 3 and 5 indicates that point-source NOD loading has a greater influence on Willamette River DO than point-source BOD loading. At the comparative point-source loadings (BOD_{ult} =83,000 lb/d, NOD=96,700 lb/d, see table 1), this finding results primarily from the much greater rate at which NOD is exerted (k_n =0.7/d, k_r=0.06 or 0.03/d).

Most of the ammonia that is oxidized in the Willamette below RM 86 is discharged from the Boise Cascade mill at RM 85. Control of ammonia from this one source would greatly reduce the impact of nitrification on the DO regimen of the river.

IMPACT OF LOW-FLOW AUGMENTATION

The effect of flow augmentation is illustrated in figure 6, in which the base-condition profile

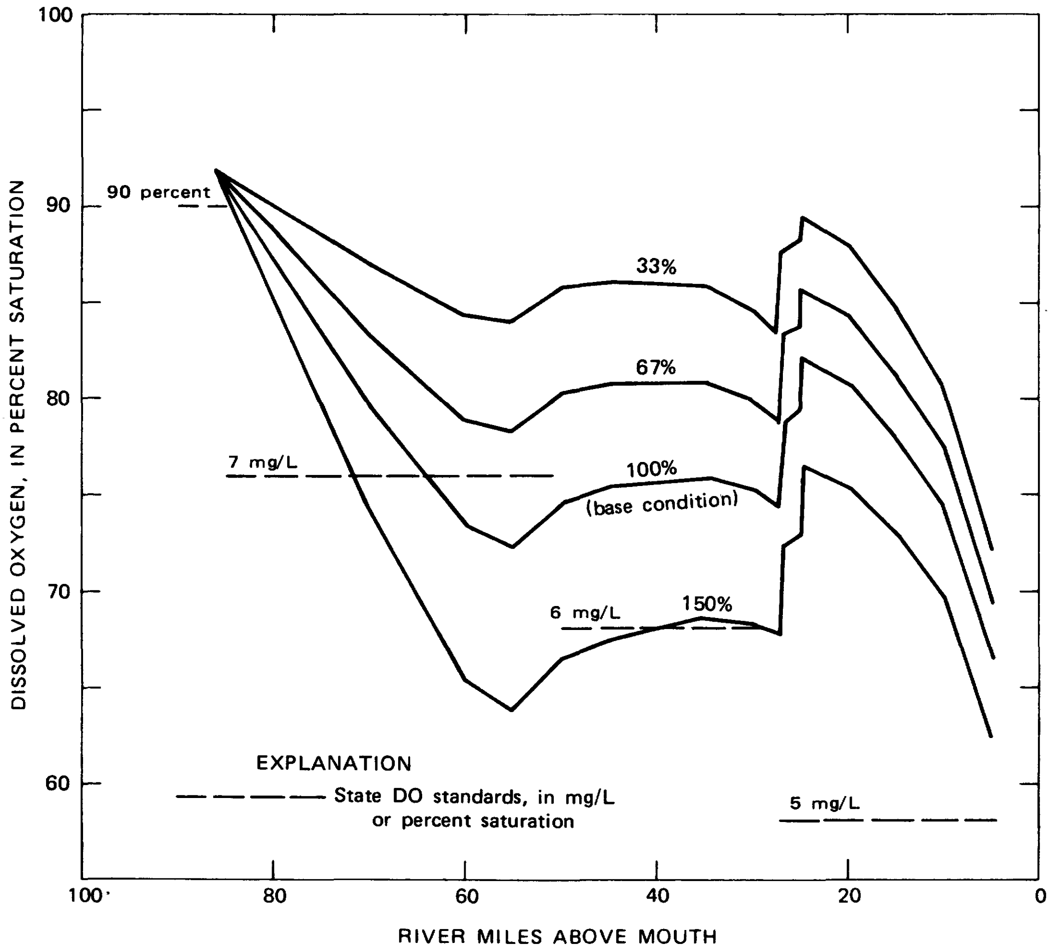

FIGURE 5.—DO profiles for selected point-source NOD loadings. The profile labeled 100 percent results from the base condition defined in table 1. Flow (6,000 ft^3/s at Salem), BOD_{ult} loadings, and NPS NOD loadings held constant.

is compared with profiles predicted for 3,260, 5,000, 8,000, and 10,000 ft^3/s (see Supplement B for discussion of waste-load computations at different flows). The profile for 3,260 ft^3/s requires some mention. This discharge is near the lowest minimum monthly flow ever recorded for July under natural (nonaugmented) conditions (Velz, 1951). Moreover, predictions from a hydrologic model (Shearman, 1976) indicate that without flow augmentation, natural streamflow would have approximated this level during July of the unusually dry year of 1973. Because of difficulties with loading assumptions (see Supplement B under "NPS BOD_{ult} Loading"), the 3,260 ft^3/s curve is considered as an estimate of the actual DO profile, rather than an accurate prediction. With this reservation, it is, nevertheless, presented to provide an important historical baseline indicating the drastic effect of natural drought flows and the importance of flow augmentation.

Figure 6 shows the marked impact that flow augmentation has on river DO levels. At the 3,260 ft^3/s discharge, the base-condition BOD and ammonia loadings would cause violations of State DO standards by wide margins at most locations. The estimated DO saturation levels at 3,260 ft^3/s are about 25 percent less than the base condition (flow augmented to 6,000 ft^3/s) at RM 55 and about 20 percent less at RM's 27 and 5.

At a flow of 5,000 ft^3/s, the State DO standards would be violated between RM 70 to 50

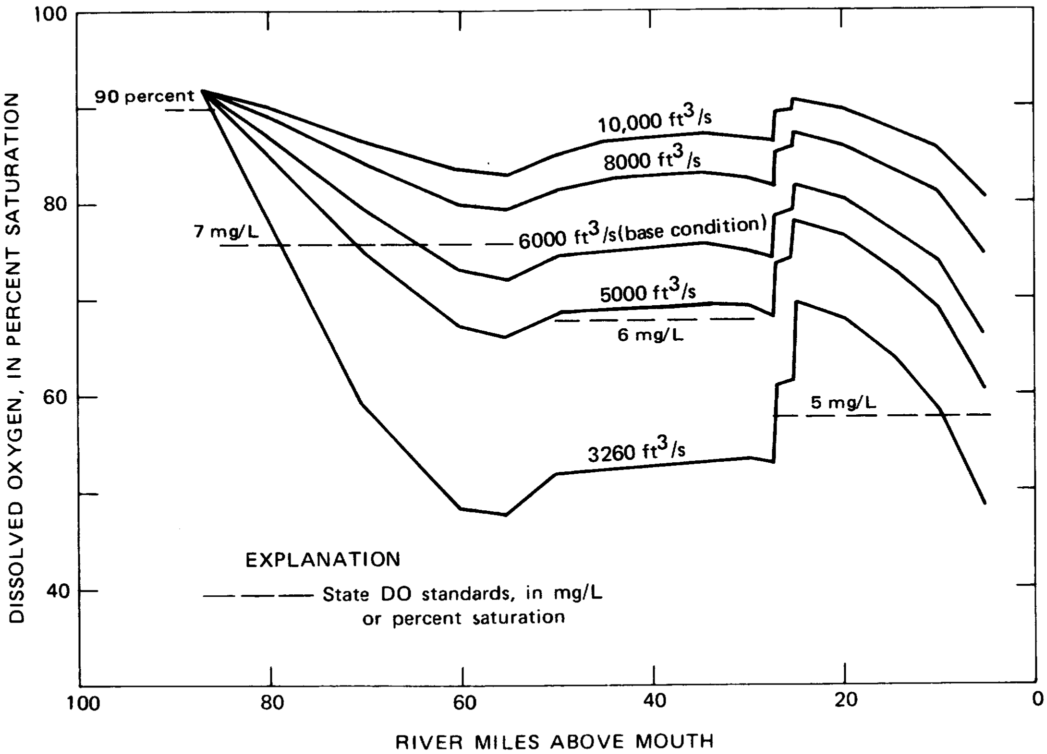

FIGURE 6.—DO profiles for selected levels of streamflow at Salem. Point-source BOD_{ult} and NOD loadings held constant.

by as much as 10 percent of DO saturation. Moreover, at this flow and these base-condition loadings, the DO standards would barely be met in the Newberg Pool and in the lower end of Portland Harbor.

In evaluating increased flow augmentation, it should be recognized that improvements in quality are less dramatic as the DO profile is raised toward the level of saturation. Thus, increasing flow from 6,000 to 8,000 ft^3/s causes DO improvements of only slightly greater magnitude than that achieved through an increase from 5,000 to 6,000 ft^3/s. At higher levels, an increase from 8,000 to 10,000 ft^3/s results in only about half of the DO improvements obtained by moving from 6,000 to 8,000 ft^3/s. For the base-loading condition, it appears that augmentation of flows to above 7,000 ft^3/s (computed but not shown) would not provide enough improvement in DO levels to warrant taking the water from competitive uses. Nevertheless, under future waste-loading conditions, augmented flows in excess of 7,000 ft^3/s should always be investigated as a possible alternative to expensive, energy-consuming, advanced waste-treatment processes.

Figure 7 illustrates the combined effects of reduced NOD loading and flow augmentation. Curve *c* relative to *d* shows the improvements in DO that would occur at a 3,260 ft^3/s flow by applying an ammonia-N effluent limit of 10 mg/L at the Boise Cascade mill (RM 85.0) and the Salem STP (RM 77.9). The improvement is similar to that obtained by augmenting streamflow to 6,000 ft^3/s and maintaining the base-condition loading of ammonia (curve *b* relative to *c*). Comparison of curves *a* and *b* shows the DO improvement that would result from applying the same ammonia-N effluent limitation at a flow of 6,000 ft^3/s. The result is a nearly 10 percent increase in DO saturation between RM 60 and 27, which would provide significant safety margins above the State standards.

Curve *c* portrays a very significant finding for dry year conditions such as 1973. Even with complete secondary treatment and the

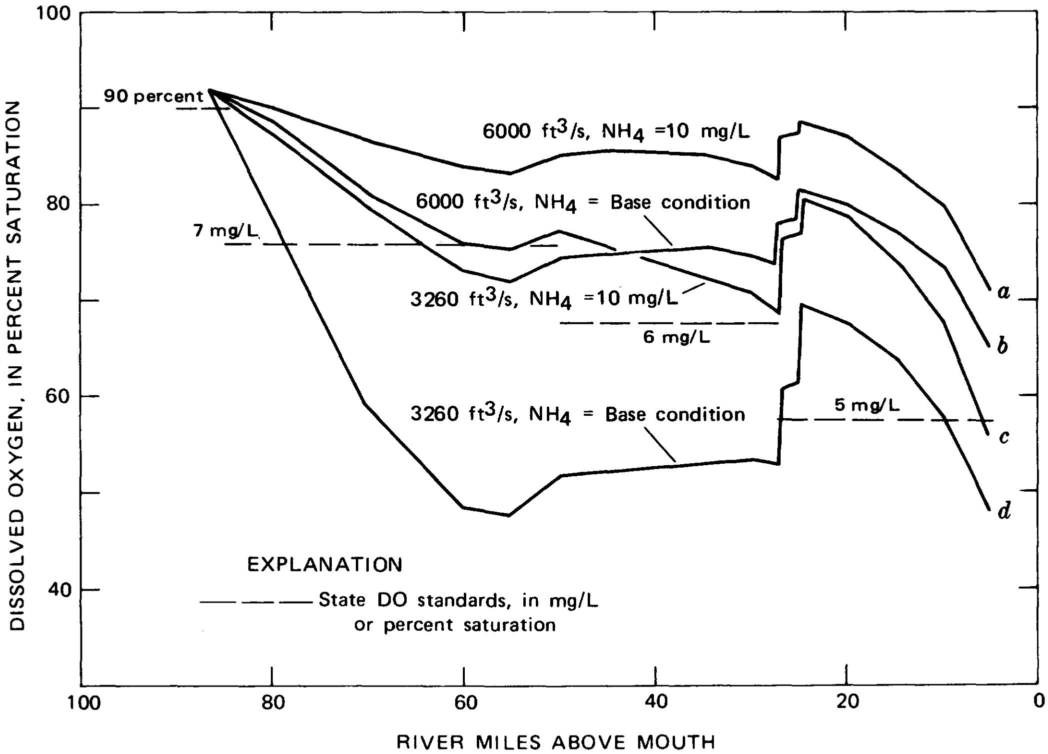

FIGURE 7.—DO profiles for selected Salem streamflows and point-source ammonia loadings. Curve *b* results from the base condition defined in table 1 for flow and NOD loading. Point-source BOD_{ult} loadings held constant.

noted limitation on ammonia loading, low-flow augmentation would be necessary to ensure achievement of DO standards at several locations below RM 60.

BENTHIC-OXYGEN-DEMAND IMPACT

During 1970, benthal respirometer studies (John Sainsbury, written commun., 1970) of the lower Willamette River documented a benthic oxygen demand of 27,000–54,000 lb/d in the segment between RM's 13 and 7. The river at that time still received some raw sewage from combined sewer overflows and a moderate loading of fibers and other settleable solids from pulp and paper mills. Because these sources of solids were largely controlled by 1972, it was anticipated that the benthic demand would be greatly reduced, if not eliminated, by 1974. However, during preliminary runs of the WIRQAS Model, predicted DO concentrations between RM's 13 and 5 were higher than those measured in the river, whereas predicted BOD_{ult} concentrations were considerably lower. Further modeling tests suggested an undetermined oxygen demand of up to 30,000 lb/d in this segment.

For lack of a better term, the demand is referred to in this circular as a benthic-oxygen demand, although field investigations conducted during 1973–1974 suggested the demand was both suspended and benthic in origin. Based on recent studies conducted by the U.S. Geological Survey (Steven E. Mellor, oral commun., USGS, Oregon District Office, Water Resources Division, Portland Oreg.), the demand has been tentatively proportioned as follows:

1. ¼–⅓ due to "inplace" benthic-oxygen demand.

2. ¼–⅓ due to excess algal respiration—that is, O_2 consumption due to respiration is greater than photosynthetic O_2 production (for details see Rickert and others, 1977, and also Circular 715–I).

3. ¼–½ due to an unknown combination of (a) sewer overflows, (b) ship discharges, (c) navigation dredging, and (d) resuspension of benthic materials by tidal current and ship propwash.

It is hoped that all or at least part of the demand can be eventually related to controllable sources. If so, management control of such sources would provide a means for improving summertime DO by as much as 8 percent of saturation at RM 5.

PLANNING CONTROL CURVES

Numerous planning insights can be gleaned from the predicted profiles in figures 3–7. However, the curves fail to portray the integration of various combinations of BOD_{ult} loading, NOD loading, and streamflow so tradeoffs can be evaluated for attaining desired DO levels at critical locations.

To permit evaluation of alternative tradeoffs, an extensive series of DO profiles was prepared through numerous runs of the WIRQAS Model. From the computer outputs, two groups of planning curves have been developed for convenient interpolation. In the first group, figures 8–10 integrate two factors, holding the third factor constant, whereas in the second group, figures 11–15 integrate all three factors.

TWO-FACTOR CONTROL CURVES

Figures 8–10 show predicted DO levels at five locations along the Willamette River where BOD_{ult} loading, NOD loading, and flow are varied two at a time. In each figure, as two factors are varied, the third is held constant at the base condition.

VARIATION OF POINT-SOURCE NOD LOADING AND STREAMFLOW

Figure 8 shows predicted percentages of DO saturation at Salem flows of 5,000 to 8,000 ft^3/s and point-source NOD loadings of 33 to 150 percent of the base condition (BOD_{ult} loadings held constant). Five sets of curves, I–V, apply respectively to specific locations at RM's 72.0, 55.2, 28.6, 12.0 and 5.0, as designated at the top of the figure. The percentages of point-source NOD loadings are noted at the bottom of each set of curves. Within the figure, the four curves in each set refer to streamflow, designated from top to bottom as 8,000, 7,000, 6,000, and 5,000 ft^3/s. To provide a reference, the base-condition point of 6,000 ft^3/s and 100 percent NOD loading is noted by an open circle in each set of curves.

Vertical movement within a curve set is representative of a change in streamflow. For example, at RM 28.6 (set III), movement from point A (the base condition) to point B represents an increase in flow from 6,000 to 7,000 ft^3/s, and a consequent change in DO saturation from about 75 to nearly 80 percent. In contrast, movement downward from A to C represents a decrease in flow to 5,000 ft^3/s, which results in a predicted decrease to about 69 percent of DO saturation.

Movement along a curve in figure 8 represents a change in NOD loading as reflected on the bottom scale. Movement from point A to D represents an increase of NOD loading to 150 percent of the base condition and results in a predicted decrease in DO saturation from 75 to 68 percent. In contrast, movement up the 6,000 ft^3/s curve from A to E represents a decrease in NOD loading to 33 percent of the base condition, which results in an increase in DO saturation to 84 percent.

In figure 8, the shape of the curves in each set provides considerable insight into the interaction of streamflow and NOD loading in the control of river DO. The two factors have differing intensities of impact at the five locations as indicated by curve slopes and the vertical distances between curves. For example, the curves are steepest in set II at RM 55.2. Curve steepness is determined in this figure by the effect of NOD loading. Thus, the results indicate that the impact of nitrification is greater at RM 55.2 than at any of the other four sites. Another observation is that the vertical distances between curves are greatest across the full range of NOD loading at RM 5.0. Because the separation between curves is determined by the effect of streamflow, the observation indicates that the impact of flow augmentation is generally greater at RM 5.0 than at the other four sites.

The cone shape of the curve clusters in sets I and II changes to more generally parallel curves in sets III, IV, and V. This change re-

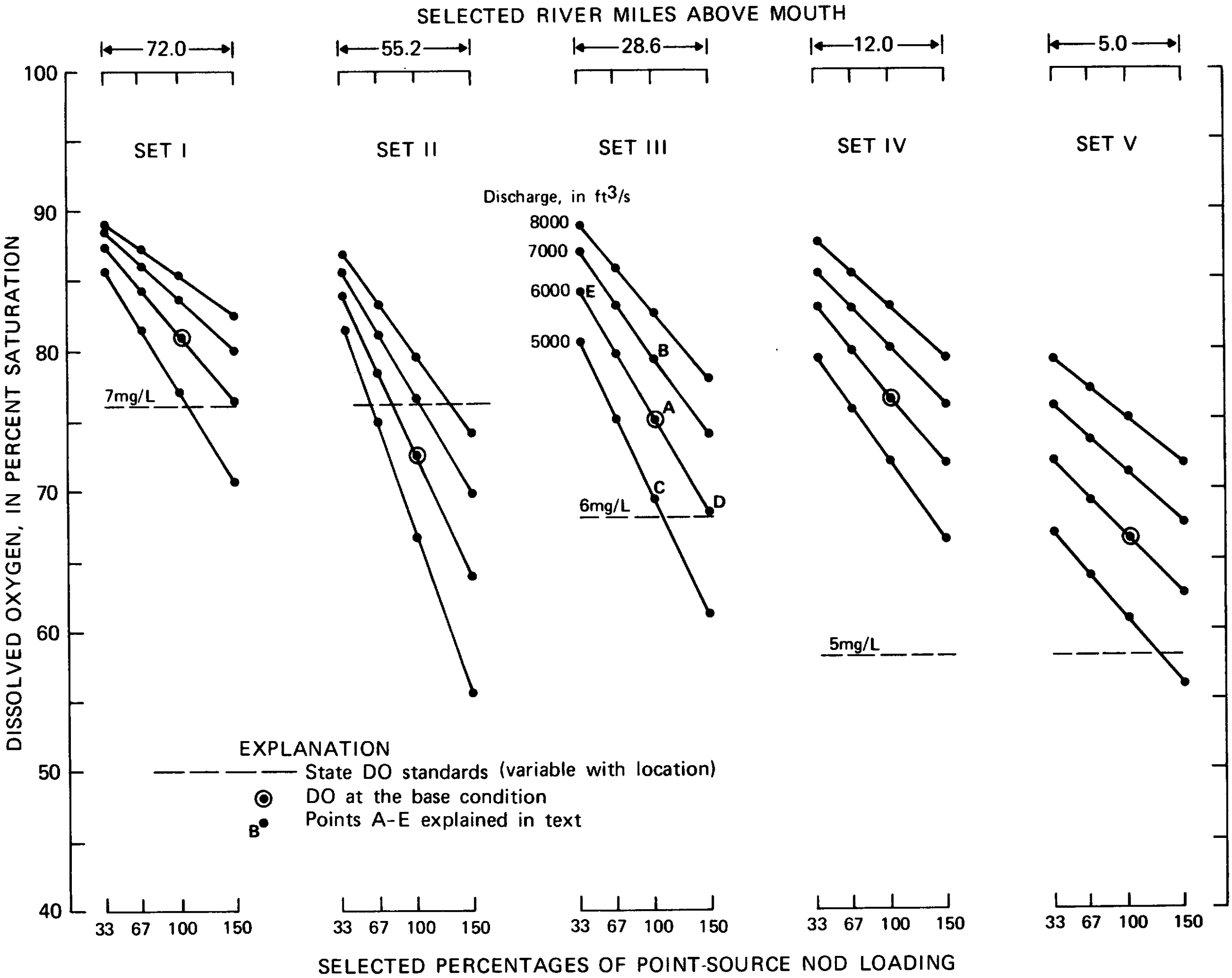

FIGURE 8.—DO levels at various river-mile locations for selected combinations of Salem streamflow and point-source NOD loading. Point-source BOD_{ult} loading held constant at the base condition.

flects a downriver decrease in the interactive effects of streamflow and NOD, and is consistent with the fact that measurable nitrification does not occur below RM 55. The impact of NOD on the curve shapes at RM's 28.6, 12.0, and 5.0 is a downriver translation of an upstream effect. However, beginning at RM 28.6, the effect of nitrification is less at each consecutive site as indicated by the fact that the curves become more parallel.

The relationship between flow and NOD results from their effects on intermediate factors. The level of streamflow affects time-of-passage (for NOD exertion), the initial quantity of DO, and several aspects of the reaeration potential. The loading of NOD directly affects the magnitude of oxygen deficit, which, in turn, is a driving force behind reaeration potential (Further details on these and other factors are available in Supplement A of Circular 715–I.).

In figure 8, the horizontal dashed line in each set of curves indicates the State DO standard. In set I, the base condition is a fair distance above the standard. However, as previously noted, the base condition violates the DO standard in the segment between RM's 64 and 50. Therefore, in set II at RM 55.2, the circle indicating the base condition falls below the dashed line.

Referring back to figure 5, nitrification is the cause of the rapid DO decrease between RM's 85 and 55. Therefore, three management alternatives are available for dealing with the

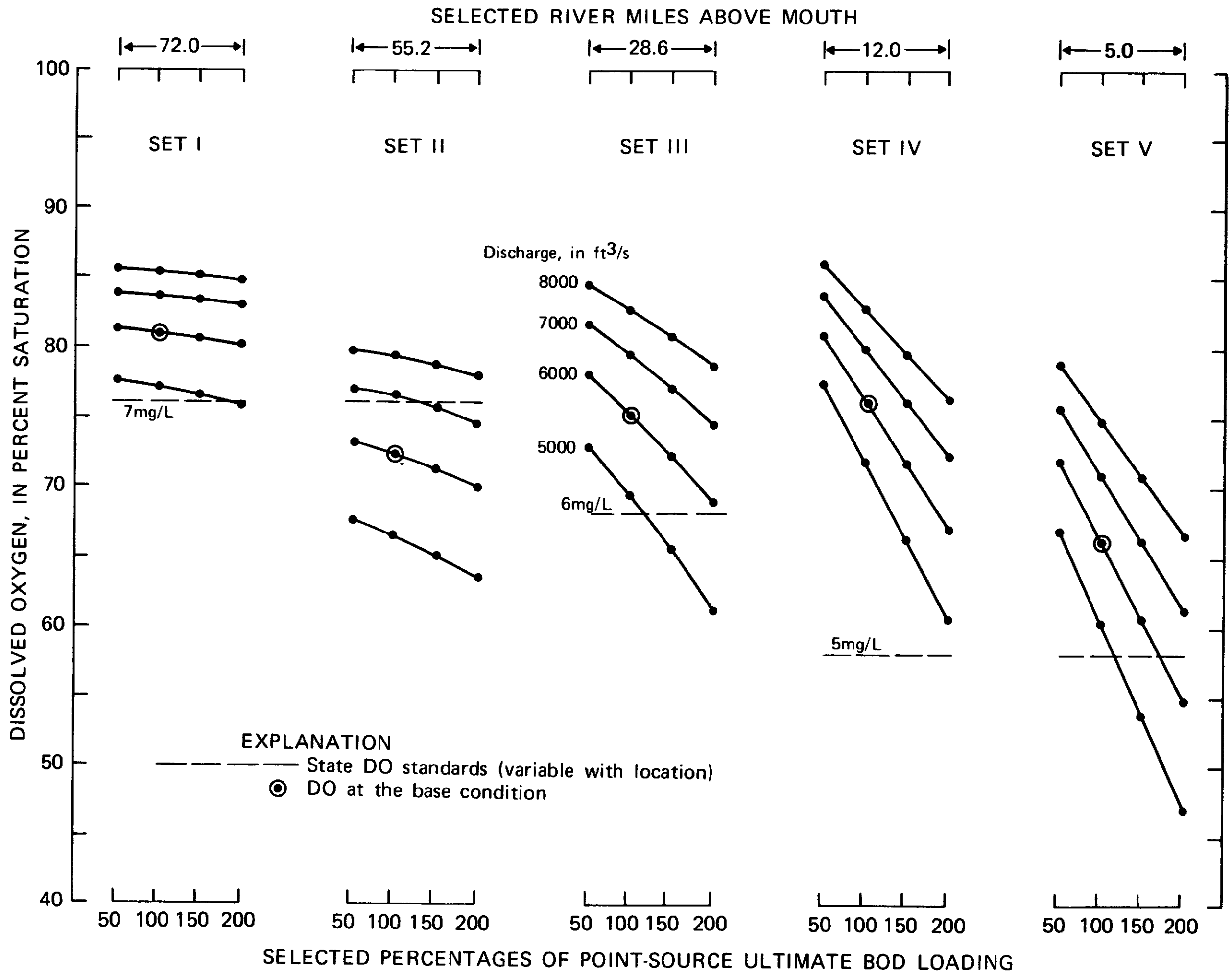

FIGURE 9.—DO levels at various river-mile locations for selected combinations of Salem streamflow and point-source BOD_{ult} loading. Point-source NOD loading held constant at the base condition.

situation in the 14-mi segment between RM's 64 and 50: (1) reduce the NOD loading, (2) increase streamflow, and (3) lower the DO standard. Assuming that the third option is unacceptable, figure 8 can be used to determine the NOD loading/flow tradeoffs for achieving the standard at the base condition. To just meet the standard at RM 55.2, the base-condition NOD loading would need to be cut by about 20 percent at a flow of 6,000 ft^3/s, or else the NOD loading could be maintained (see table 1) and the flow increased to about 6,800 ft^3/s.

At RM 28.6, the State DO standard is met by all but one of the investigated combinations of NOD loading and flow. The improvement relative to RM 55.2 results somewhat from increases in DO levels in the river, but primarily from the lowering of the DO standard to 6.0 mg/L. At RM 12.0, all points of the entire curve set are well above the DO standard of 5.0 mg/L. However, at RM 5.0, the position of the curves is lower owing to the previously described combination of carbonaceous deoxygenation, benthic demand, and decreased atmospheric reaeration.

VARIATION OF POINT-SOURCE BOD_{ult} LOADING AND STREAMFLOW

Figure 9 represents predicted percent DO saturations at Salem flows of 5,000–8,000 ft^3/s, with point-source BOD_{ult} loadings of 50–200 percent of the base condition. In this case, NOD loading has been held constant. As in figure 8, the base-condition point in each set of curves is noted by an open circle.

Analysis of curve shapes in figure 9 shows that the steeper slopes occur at the downstream river-mile sites. This is in contrast to figure 8 and reflects the fact that BOD_{ult} loading has slight impact on DO at RM's 72.0 and 55.2, but thereafter an increasing impact to a maximum at RM 5.0. Also in figure 9, the vertical distance between curves is considerable within each set indicating that streamflow has a marked impact on DO at all locations. The third shape factor is the relative lack of cone-shaped outlines for the five sets of curves. This reflects a lower degree of interactive effect of the two factors on DO than that occurring between NOD and flow (fig. 8). RM's 28.6, 12.0, and 5.0 exhibit moderately cone-shaped outlines, thus indicating that flow and BOD_{ult} loading do interact to a considerable degree in the Newberg Pool (RM 52.0–26.5) and the Tidal Reach (RM 26.5–0). The cause of the interaction results from effects on the same intermediate factors noted in the discussion of NOD and flow.

In relation to DO standards, the critical sites in figure 9 are RM's 55.2 (set II) and 5.0 (set V). As previously noted, the condition at RM 55.2 is dominated by flow and NOD. In contrast, DO levels at RM 5.0 are affected by upstream nitrification, the benthic demand, flow, and the loading of BOD_{ult}. With regard to the last two factors, curve set V (fig. 9) indicates there is a considerable safety factor between the base condition and the State DO standard. In fact, the standard at RM 5.0 would still be met at a flow of 5,000 ft^3/s with up to a 20 percent increase in the point-source loading of BOD_{ult}.

VARIATION OF POINT-SOURCE NOD AND BOD_{ult} LOADINGS

Figure 10 shows predicted percent DO saturations representing point-source NOD loadings of 33–150 percent of base conditions, together with point-source BOD_{ult} loadings of 50–200 percent. For this figure, flow has been held constant at 6,000 ft^3/s.

Analysis of curve shapes in figure 10 provides several interesting results. First, curve slopes are controlled by the effects of NOD loading and are, therefore, similar to those in figure 8, with the greatest impact at RM 55.2 (set II). Second, the vertical distance between curves is controlled by BOD_{ult} loading. Thus, the closeness of the curves at RM's 72.0 and 55.2 is further proof of the low impact of BOD on DO above RM 50. In contrast, the increasing space between individual curves at RM's 28.6, 12.0, and 5.0 is further proof of the increasing impact of BOD_{ult} loading on DO levels in the Newberg Pool and Portland Harbor. Third, the lack of cone-shaped outlines of the curve sets reflects the absence of interactive effects between the loadings of NOD and BOD_{ult}. This result is expected because, under conditions observed in the Willamette River, nitrification and carbonaceous deoxygenation should proceed almost entirely as independent processes.

THREE-FACTOR CONTROL CURVES

Figures 11–15 present graphs in which the three factors of point-source NOD loading, point-source BOD_{ult} loading, and streamflow are each varied within the ranges previously described. When three factors are varied at once, a full figure is required to present results for each site. However, because of the integration of the three factors, these curves provide a more powerful tool for river-quality planning.

EXPLANATION

Each of figures 11–15 refers to a single location on the river, which are RM's 72.0, 55.2, 28.6, 12.0, and 5.0 (the same sites as in figs. 8–10). In turn, each figure is composed of four sets of curves, I–IV, corresponding to the four cited (at the top) levels of point-source BOD_{ult} loading of 50, 100, 150, and 200 percent of the base condition. Within each curve set, there are four curves corresponding, from top to bottom, to the designated streamflows of 8,000, 7,000, 6,000, and 5,000 ft^3/s. The scale included below each curve set shows the level of point-source NOD loading, with 100 percent corresponding to the base condition.

There is only one point in each of figures 11–15 that represents the base condition. This point is noted by an open circle, and is located

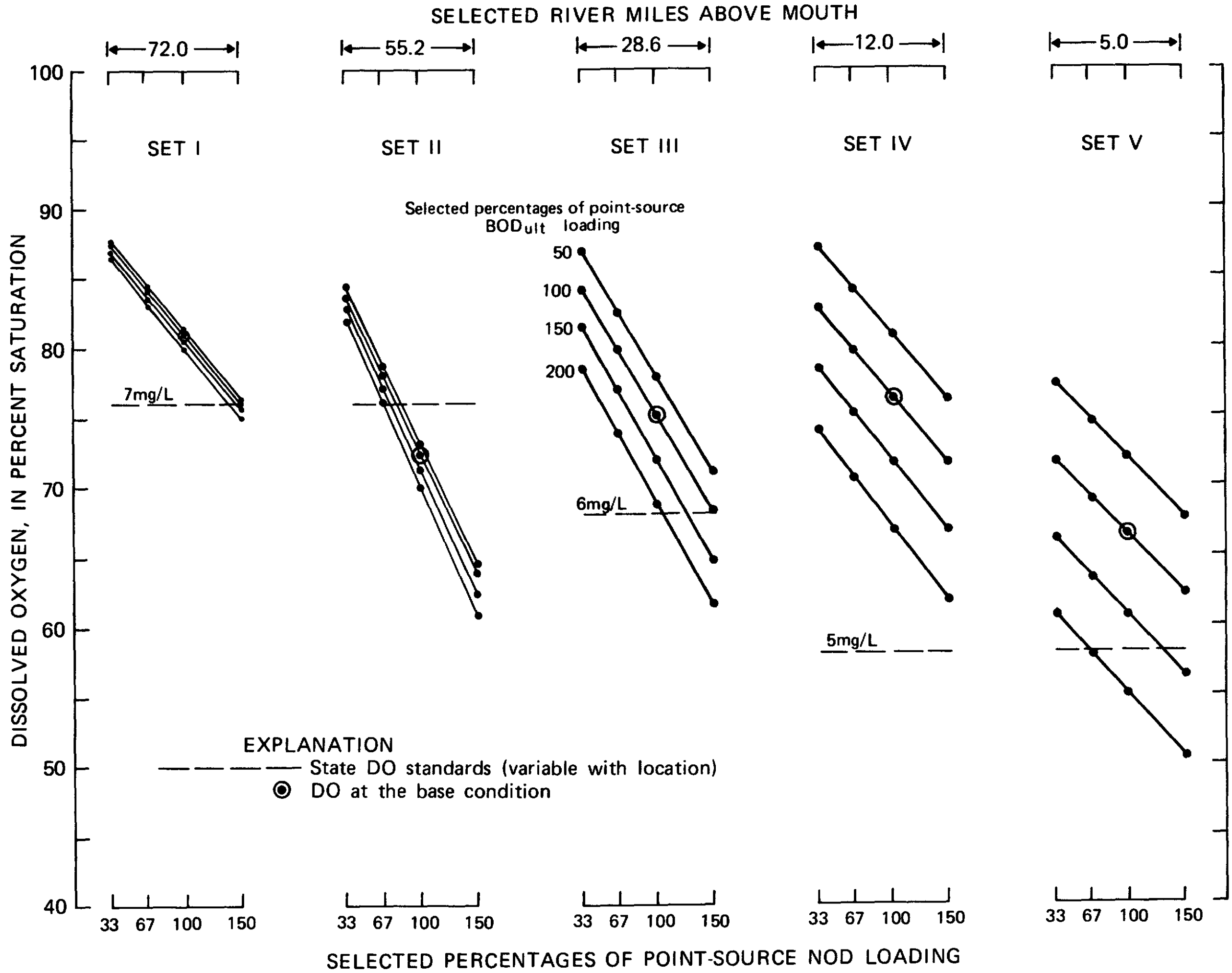

FIGURE 10.—DO levels at various river-mile locations for selected combinations of point-source loadings of BOD_{ult} and NOD. Flow held constant at the base condition (6,000 ft^3/s).

in set II (100 percent BOD_{ult} loading) of each figure on the second curve from the bottom (6,000 ft^3/s) and at 100 percent NOD loading. Within each curve set in each figure, a downward or upward movement along a specific curve represents a change in NOD loading, and a vertical movement from one curve to another represents a change in flow. In contrast, movement from one set of curves to another represents a change in the loading of BOD_{ult}.

ANALYSIS OF CURVE SHAPES

Curve shapes in figures 11–15 can be summarized by the following comments:

1. The base shape of each set of curves in each figure is determined primarily by the degree of interaction between the effects of streamflow and point-source NOD loading. Thus, the shape of the curve sets is very similar from left to right in each figure. It is helpful to note that curve set II in each figure (100 percent BOD_{ult} loading) is identical to the site counterpart in figure 8.

2. The vertical distance between individual curves within a set is determined by the effect of flow. Differences in vertical distances between curves in different sets of a figure result from the effects of point-source BOD loading.

3. Within each figure, the differences in DO levels in moving from left to right result from increased loadings of BOD_{ult}. Consistent

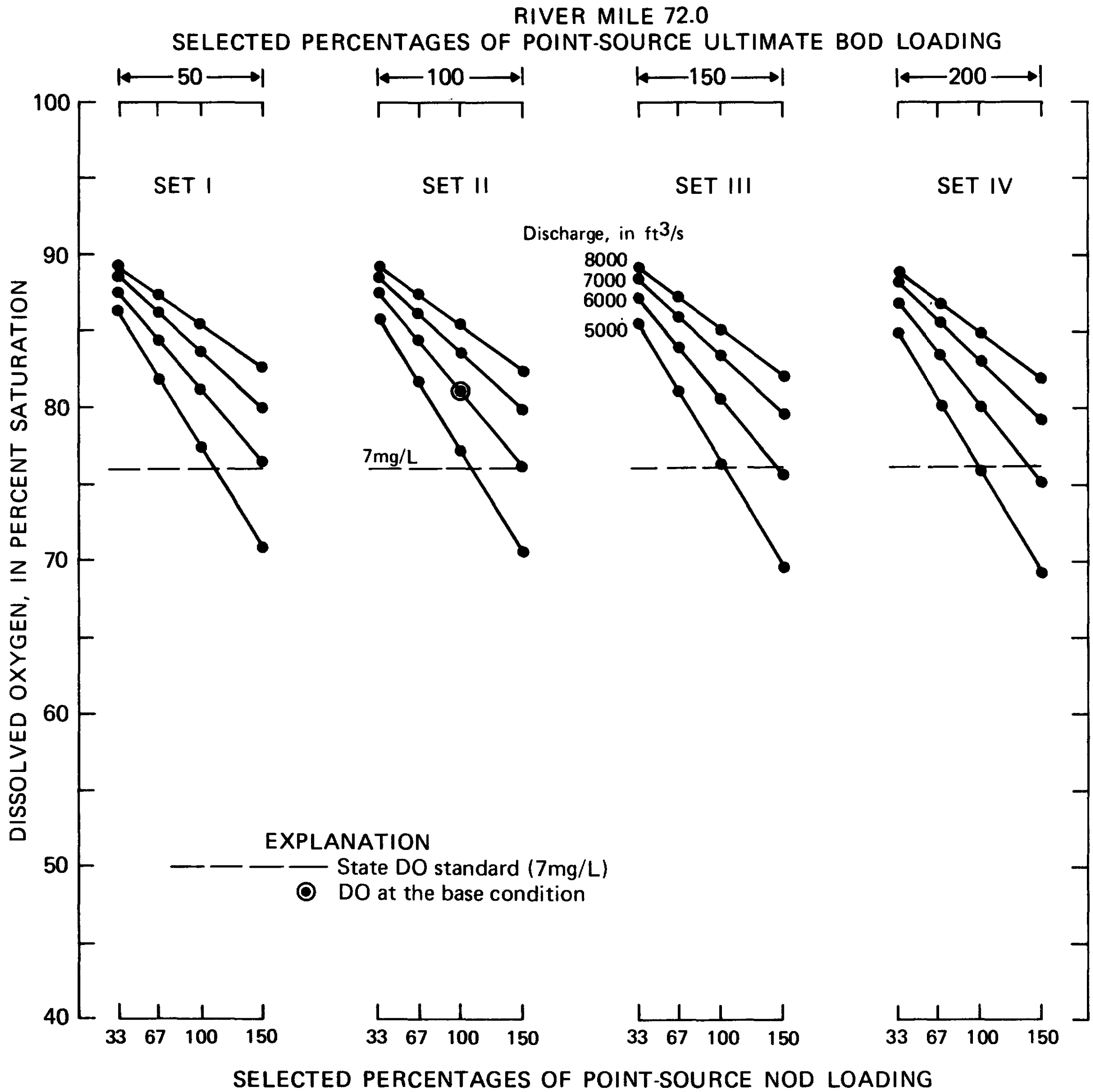

FIGURE 11.—DO levels at RM 72.0 for selected combinations of Salem streamflow, point-source BOD_{ult} loading, and point-source NOD loading.

with previous discussions, there are only slight changes in the curve sets in moving across figure 11 (RM 72.0) and figure 12 (RM 55.2). However, in figure 13 (RM 28.6), there is a significant lowering of DO levels in the left-to-right progression from 50 to 200 percent point-source BOD_{ult} loading. In figures 14 (RM 12.0) and 15 (RM 5.0), the decreases are increasingly marked.

USE

To illustrate the potential use of the three-factor control curves, reference will be made to figure 14. This figure was selected from among the five because the three factors—NOD loading, BOD loading, and streamflow—all have a significant impact on DO at RM 12.0. In figure 14, three sets of conditions are illustrated for selected combinations of the three factors. The following items present the conditions and describe how to estimate the percentage of DO saturation:

1. BOD_{ult}=100 percent, flow=6,000 ft^3/s, and NOD=125 percent: Use curve set II which represents 100 percent BOD_{ult} loading; find the

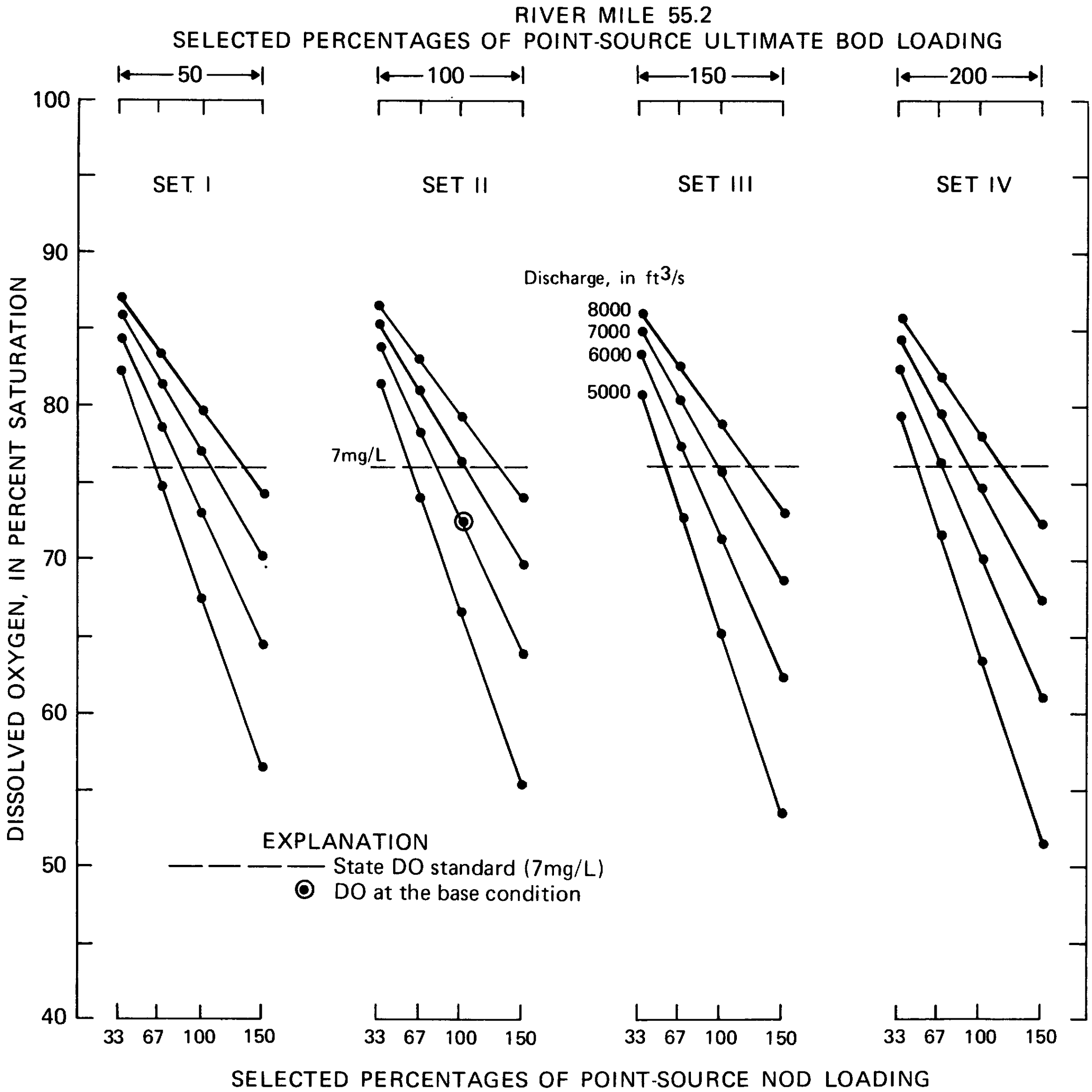

FIGURE 12.—DO levels at RM 55.2 for selected combinations of Salem streamflow, point-source BOD_{ult} loading, and point-source NOD loading.

6,000 ft^3/s curve; vertically extend a straight edge from the 125 percent NOD loading on the bottom scale to the 6,000 ft^3/s curve; from the intersection point, noted by the letter A, the DO saturation is read on the *Y*-axis as about 74 percent.

2. BOD_{ult}=75 percent, flow=6,000 ft^3/s, and NOD=125 percent: Locate the 6,000 ft^3/s curves in both set II (100 percent BOD_{ult}) and set I (50 percent BOD_{ult}); next, locate the 125 percent NOD loading on each curve (this step is identical to that required in item 1 above); the located points are identified as point A in set II and point B in set I; connect points A and B with a straight line and locate the midpoint; this point, labeled C, is the approximate location of the 75 percent BOD_{ult} loading; the corresponding DO saturation on the *Y*-axis is about 76 percent.

3. BOD=100 percent, flow=6,500 ft^3/s, and NOD=50 percent: Use the set II curves for the 100 percent BOD_{ult}; vertically extend a straight edge from the 50 percent NOD loading scale to intersect the 6,000 and 7,000 ft^3/s

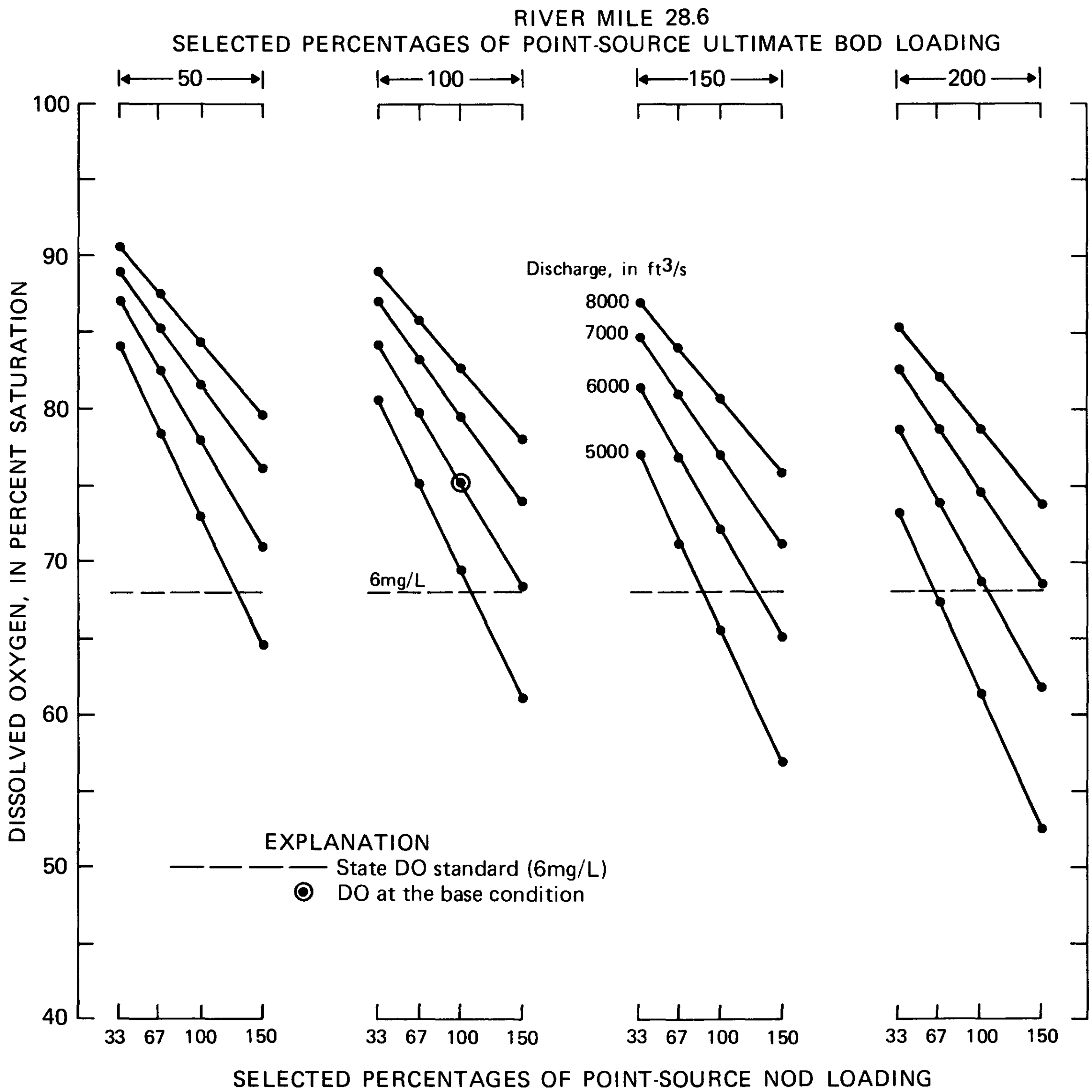

FIGURE 13.—DO levels at RM 28.6 for selected combinations of Salem streamflow, point-source BOD_{ult} loading, and point-source NOD loading.

curves; the intersection points are labeled D and E, respectively; estimate the mid-point of the new line which corresponds to the flow of 6,500 ft^3/s; the midpoint is labeled F; the corresponding DO saturation as read from the *Y*-axis is about 83 percent.

Any possible combinations can be evaluated that occur within the investigated ranges of the three factors. With care, the graphical estimates will be adequate for many planning purposes, thereby avoiding the need for costly and time-consuming computer runs to test each new combination. As previously shown, the authors have selected data at RM's 72.0, 55.2, 28.6, 12.0, and 5.0 for compiling figures 11–15. Similar data are available for constructing graphs to represent any location between RM's 86.5 and 5.0.

However, a word of caution is needed as to limitations of the control curves. It must constantly be kept in mind that the curves are based on the assumptions that (1) the locations of waste outfalls will remain unchanged, and (2) all waste sources will receive second-

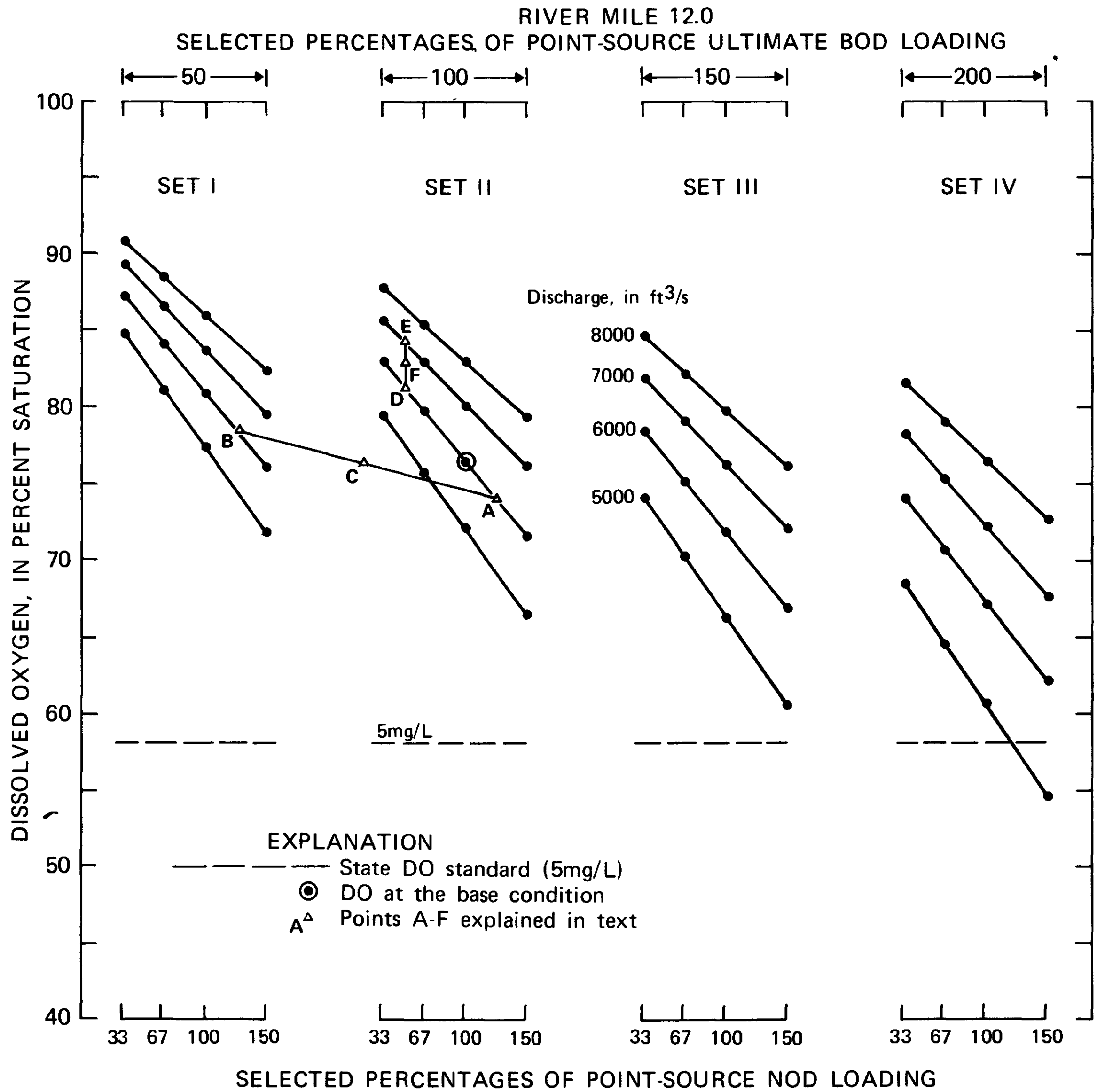

FIGURE 14.—DO levels at RM 12.0 for selected combinations of Salem streamflow, point-source BOD_{ult} loading, and point-source NOD loading.

ary treatment. In addition, the percentages of increased or decreased loadings in the curves are applied uniformly to all point sources. In the event of significant deviation from these conditions, the curves do not apply. For example, if a new large industry with a significant waste loading should build a new outfall, the control curves would no longer apply.

In such cases, the WIRQAS Model (see Supplement A of this report) can be used directly for incorporating new information with existing data to predict the DO impacts. Although this would entail extra time and cost, most of the necessary data would be available from the present study. Thus, a rerun of the model could be readily achieved with modest cost.

It is the hope of the authors that practical use will be made of both the curves in this report and the WIRQAS DO Model.

SUMMARY AND CONCLUSIONS

Future achievement of DO standards in the Willamette River will require continued aug-

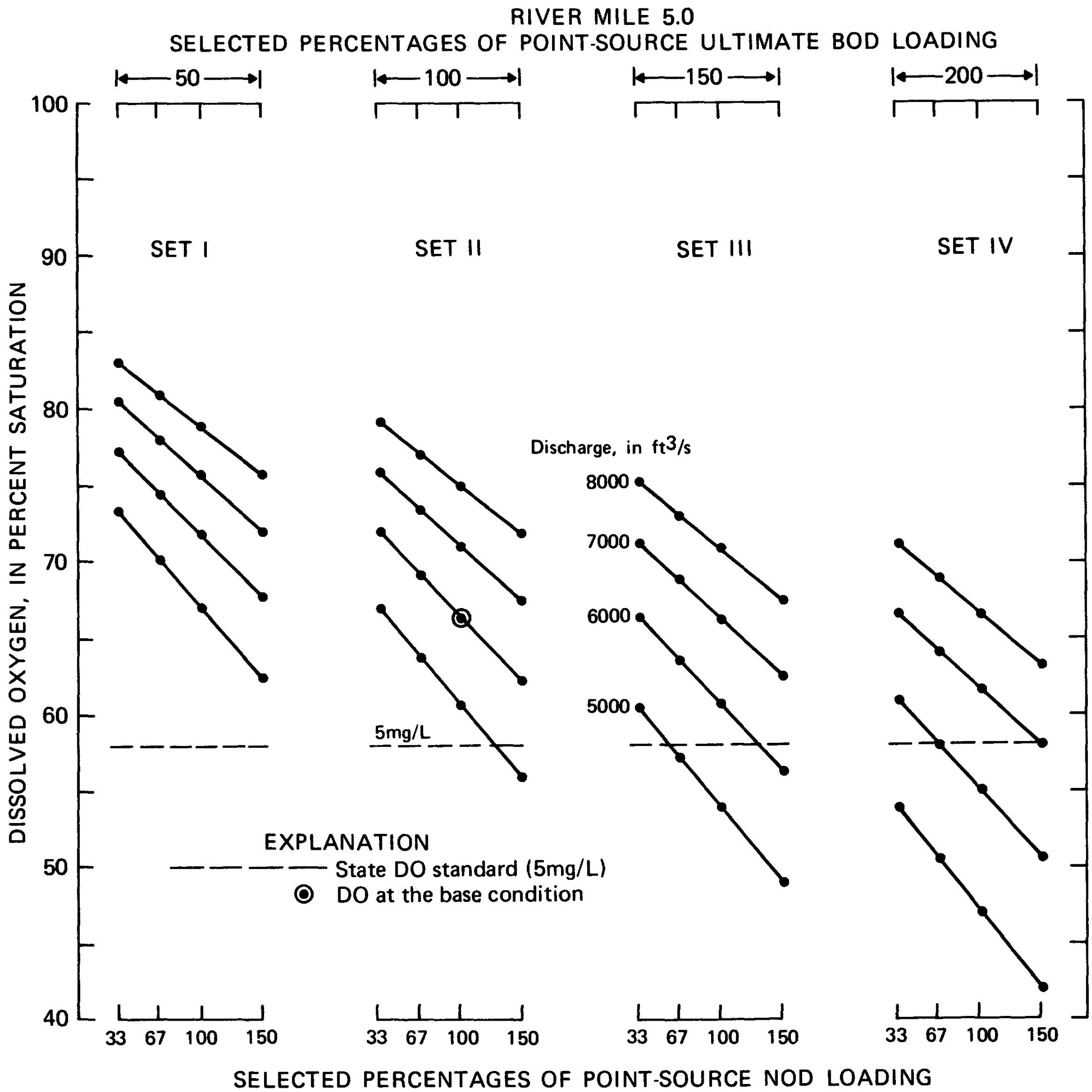

FIGURE 15.—DO levels at RM 5.0 for selected combinations of Salem streamflow, point-source BOD_{ult} loading, and point-source NOD loading.

mentation of summer low flows in addition to pollution control. At present (1979), minimum summer flows in excess of 6,000 ft^3/s (Salem gage) are needed to meet the standards at all locations below Salem.

Point-source loading of ammonia is the major cause of oxygen depletion in the modeled segment of river (RM 86.5–5.0). Because most of the ammonia comes from one industrial source, reduction of ammonia loading offers a relatively simple alternative for achieving a large improvement in summertime DO.

Although DO levels in Portland Harbor are currently above the State standard, removal or partial reduction of a localized benthic demand would improve summer DO concentrations between RM's 10 and 5. However, the feasibility of reducing the demand has yet to be determined.

BOD loading from municipal waste-water treatment plants presently exerts a relatively small impact on DO. However, increased efficiency of BOD removal at the largest municipal plants and at selected industrial plants might be desirable in the future. The benefits to be gained from this alternative would best be determined after the industrial ammonia loading has been reduced to a lower level.

For the foreseeable future, there is no need for municipal advanced waste treatment to protect DO levels in the Willamette River. Maintenance of a minimum low flow of 6,000 ft^3/s and reduction of industrial ammonia loading are the important management needs.

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REFERENCES

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

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.

McKenzie, S. W., Hines, W. G., Rickert, D. A., and Rinella, F. A., 1979, Steady-state dissolved-oxygen model of the Willamette River, Oregon: U.S. Geol. Survey Circ. 715–J, 28 p.

Oregon Department of Environmental Quality, 1975, Water quality control in Oregon—A status report: Oregon Dept. Environmental Quality Rept., 68 p.

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

Rickert, D. A., Petersen, Richard, McKenzie, S. W., Hines, W. G., and Wille, S. A., 1977, Algal conditions and the potential for future algal problems in the Willamette River, Oreg.: U.S. Geol. Survey Circ. 715–G, 39 p.

Shearman, J. O., 1976, Reservoir system model for the Willamette River basin, Oregon: U.S. Geological Survey Circular 715–H, 22 p.

Velz, C. J., 1951, Report on natural purification capacities, Willamette River: Natl. Council for Stream Improvement of the Pulp, Paper, and Paperboard Industries, Inc.: Michigan Univ., School of Public Health, Ann Arbor, 80 p.

——— 1961, Supplementary report on lower Willamette River waste assimilation capacity: Natl. Council for Stream Improvement of the Pulp, Paper, and Paperboard Industries, Inc.: Michigan Univ., School of Public Health, Ann Arbor, 28 p.

——— 1970, Applied stream sanitation: New York, John Wiley & Sons, Inc., 619 p.

Wezernak, C. T., and Gannon, J. J., 1967, Oxygen-nitrogen relationships in autotrophic nitrification: Applied Microbiology, v. 15, no. 5, p. 1211–1215.

SUPPLEMENTAL INFORMATION

SUPPLEMENT A—SUMMARY OF THE CHARACTERISTICS AND APPLICATION RANGES OF THE WIRQAS DO MODEL

Based on results presented in Circulars 715–I and J, the WIRQAS Model is considered to be a reliable simulatory and predictive tool, subject to the following conditions and limitations:

1. Location. The model is presently (1979) calibrated and verified for the main stem Willamette River between RM's 86.5 to 5.0.

2. Ecological conditions. The model is applicable to summer, steady state conditions. Use is for prediction of average daily DO concentrations during low-flow, high-temperature conditions that have been preceded by at least 5, and preferably, 10 days of relatively stable streamflow and water temperature. Such conditions annually occur in the Willamette and represent the most critical periods for long range, water-quality planning.

3. Streamflow:

a. Applicable range—5,000–8,000 ft^3/s. This range is based on measured data from 5,900–6,800 ft^3/s and detailed knowledge of the morphology and self-purification processes of the Willamette River. Furthermore, the model can probably be used at flows up to 10,000 ft^3/s without the introduction of large errors.

b. Routing. In computing discharge below RM 86.5, the inflows from tributaries and waste-water outfalls are added to flow in the main stem to produce a cumulative total at any site. Water losses due to evaporation and diversions are assumed to be equalized by ground-water seepage and inflows of small, unmeasured tributaries.

4. Water temperature. The estimated applicable range is ±3°C of the following 1974 low-flow measurements: RM 86.5–52.6 = 20°C, RM 52.6–45.0 = 21°C, RM 45.0–37.0 = 22°C, RM 37.0–25.6 = 23°C, below RM 25.6 = 23.5°C.

5. Channel geometry. The model is applicable at morphologic conditions not markedly different from those occurring during 1973–1974. For example, isolated dredging or filling would probably not cause significant differences. In contrast, a 5-ft deepening of the Portland Harbor would probably invalidate predictions made by the present model and necessitate the collection of new channel-geometry data in that segment.

6. Waste loadings:

a. Applicable character. Predominantly effluents from secondary biological treatment and contributions from NPS's.

b. Model parameters:

(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 summertime water temperatures in the affected river segment are very close to 20°C.

(3) Benthic-oxygen demand. Simulated as an oxygen-demanding load distributed between RM 12.8 to 5.2. The total load was estimated to be 29,000 lb/d (table 4). 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.

7. Algal photosynthesis and respiration. DO produced and consumed by algae were taken to be in balance over the 81.5-mi modeled stretch of river. Between RM's 86.5 and 13, this assumption is supported by primary production data and by DO mass balance computations made with preliminary versions of the model. However, between RM's 13 and 5, algal respiration may, in fact, exceed photosynthetic oxygen production (see "Benthic Oxygen Demand Impact" section under "Planning Implications" in this report and also Rickert and others, 1977).

8. Atmospheric reaeration. Calculated on a segment-by-segment basis using the Velz (1970) method. The additional reaeration at Willamette Falls (RM 26.5) is simulated by

adding 13,400 lb/d of DO to profile computations. This addition is consistent with measurements made above and below the Falls during 1974 low-flow conditions.

SUPPLEMENT B—MODEL BOUNDARY POINT (RM 86.5) WASTE LOADINGS FOR SELECTED STREAMFLOWS

Computation of DO profiles over the selected range of stream flows (fig. 6) required use of assumptions for calculating the boundary point waste input loadings. The need for assumptions resulted because no loading measurements have been made across the entire range of selected flows. This supplement describes how the model input loadings were determined for both the point and NPS components of BOD_{ult} and NOD.

POINT-SOURCE BOD_{ult} LOADING

Point source loadings of BOD_{ult} at RM 86.5 were calculated by direct flow routing of each source and, thus, involved no major assumptions. To accomplish the flow routing, the time-of-travel from the source to RM 86.5 was determined from existing information. Next, the measured summertime BOD_{ult} load from each source was decayed at a temperature-corrected rate (based on $k_r = 0.06$/d at 20°C) for the determined travel time. Finally, the residuals of each source at RM 86.5 were summed to provide the model input loading. The same procedure was followed for each investigated flow.

NPS BOD_{ult} LOADING

Determination of the NPS BOD_{ult} loading at RM 86.5 was based on the assumption that for conditions represented by the flow range of 5,000–10,000 ft^3/s at Salem, the NPS loading of individual upstream tributaries is effectively constant. The assumption is based on observation that (1) in-river BOD_{ult} concentrations in major tributaries above point-source discharges are very low (approximating natural background levels), (2) the major tributaries are shallow with bottoms that produce significant amounts of biological materials, and (3) during summer low-flow conditions, precipitation is usually nil or very low for an extended period of time and, hence, little or no overland flow enters upstream tributaries or the main stem of the Willamette.

For summer, low-flow conditions, the rationales behind the assumption are (1) the NPS BOD_{ult} loading in major upstream tributaries is mostly stream generated, (2) the amount generated depends on the total surface area of stream bottoms covered by water, and (3) that the total surface areas of individual stream bottoms do not change appreciably for tributary flows which represent cumulative Salem flows in the range of 5,000–10,000 ft^3/s. The rationales are consistent with measured data and field observations, and they support the occurrence of a condition in which constant tributary loads of NPS BOD_{ult} would be produced.

On the basis of the stated assumption, NPS BOD_{ult} loads at measured points in tributaries were individually flow routed to RM 86.5 at determined times of travel. As with the point-source routing, the rate of decay was a temperature-corrected coefficient based on $k_r = 0.06$/d at 20°C.

As noted above, actual loading data at RM 86.5 were collected over the Salem flow range of 5,900–6,800 ft^3/s. For the latter streamflow, the total flow-routed load (point plus NPS) at RM 86.5 was checked against the measured in-stream load. The values were almost identical (see fig. 4 in Circular 715–J).

It might be expected that the contribution of reservoir water to the low flows of major tributaries would exert a controlling influence on the loading of NPS BOD_{ult} at RM 86.5. However, distances from reservoir discharge points to measurement locations are deemed sufficient to permit stream-bottom biology to damp any small differences in NPS BOD_{ult} loadings (from above to below a reservoir) that might occur as a result of reservoir influences.

Between the flows of 5,000 and 10,000 ft^3/s, it is possible that the described assumption would not hold at the higher flows, such as those above 8,000 ft^3/s. If this were so, the probable direction of failure would be an increased loading with flow owing to (1) increased contribution of nonbase-flow water and (2) increased scour of in-stream growths. This deviation from the assumption at the higher flows would result in lessened impacts of reservoir low-flow augmentation than those predicted. In other words, in figure 6, the DO profile predicted for 10,000 ft^3/s might show higher DO levels than those that would actually occur.

Analysis of stream morphologies and field observations in the shallow reaches above RM 50 suggests that the assumption would not hold at a flow of 3,260 ft^3/s (see figs. 6 and 7). The WIRQAS Model can be confidently applied down to 5,000 ft^3/s and possibly to 4,000 ft^3/s. However, at severe drought flows, the channel conditions, other physical factors, and several self-purification characteristics in the reach above RM 50 are thought to differ considerably from those existing at flows between 5,000 and 10,000 ft^3/s. Factors that probably change significantly include stream widths, water temperatures, sedimentation rates, and the opportunity for renewed contact between flowing water and the bottom growths. However, for lack of a better method, the BOD_{ult} loading at RM 86.5 for the flow of 3,260 ft^3/s (figs. 6 and 7) was computed in a manner similar to all other curves. Therefore, as noted in the text (see "Impact of Low-Flow Augmentation"), the resulting curves at 3,260 ft^3/s are viewed as estimates of the DO levels that would actually occur.

POINT AND NPS NOD LOADINGS

Flow routing could not be used to determine NOD loadings at RM 86.5 because no ammonia-N decay data were measured on the upper Willamette River and the upstream tributaries.

The approach used was based on measurements which showed an ammonia-N concentration of 0.16 mg/L at RM 86.5 during the 1974 calibration studies (flow=6,760 ft^3/s). Prior to and during this period, measured concentrations of ammonia-N in major upstream tributaries (above point sources) averaged about 0.04 mg/L. In the absence of decay rates to permit routing, the assumption was made that 0.04 mg/L of the measured 0.16 mg/L at RM 86.5 represented an NPS contribution, whereas the remaining 0.12 mg/L was a point-source contribution.

POINT-SOURCE NOD LOADING

For the different discharge levels used in the control runs, point-source NOD loading at RM 86.5 was kept constant at the level computed for the calibration period (NOD=18,900 lb/d). It might be reasoned that point-source NOD reaching RM 86.5 would vary in some direct manner with flow because, the higher the flow, the shorter the time of travel for ammonia decay. However, it is also possible that the rate of decay would increase with flow because the nitrification process occurs on the stream bottom and higher flows would increase the possibility of water-column turnover. In the absence of measured k_n rates, and because the two cited cases would counter one another, the choice was made to hold the point-source NOD loading constant across the investigated range of flows.

NPS NOD LOADING

The NPS NOD loading at different flows was computed on the assumption that the concentration of NPS ammonia-N remains constant at RM 86.5. The assumption, in turn, is based on 1974 summer, low-flow measurements of ammonia-N at sites above known point sources on the Middle Fork, McKenzie, and Santiam Rivers. Three to six samples were analyzed from each river. Individual concentrations varied somewhat from sample to sample, but, as previously noted, the average was about 0.04 mg/L for each river. Because these three tributaries contribute over 95 percent of the Willamette River summer flow at RM 86.5, the level of 0.04 mg/L was accepted as a reasonable background and, therefore, NPS concentration of ammonia-N at the model boundary point.

It is interesting to note that an average ammonia-N concentration of 0.03 mg/L was measured in the Clackamas River which drains the Cascade Range and enters the Willamette at RM 24.8. The controls that cause background ammonia-N levels of 0.03–0.04 mg/L are unknown, but the concentration does appear to be representative of regional, base-flow conditions.

Based on the stated assumption (NPS NOD concentration is constant), the NPS NOD loading at RM 86.5 was determined by multiplying the 0.04 mg/L concentration by the discharge selected for each predicted curve. At flows of 8,000–10,000 ft^3/s, the possibility exists that the NPS ammonia-N concentration would be lower than 0.04 mg/L. This possibility is based on the consideration that 0.04 mg/L represents the regional base-flow concentration in the range of 6,000–7,000 ft^3/s. If this were true, our calculated input loads of ammonia-N at RM 86.5 would be too high at the higher flows. This would mean that actual DO profiles would be slightly higher than predicted by the control curves.

SUPPLEMENT C— DECAY RATES FOR COMPUTING CARBONACEOUS OXYGEN DEMANDS

Carbonaceous oxygen demands in this report were computed assuming that all point and NPS BOD_{ult} decays in the river at $k_r = 0.06/d$ above RM 55.2, and at 0.03/d below this location. Circular 715–I describes how these two rates were determined through a combination of measurement and preliminary runs of the WIRQAS Model.

The assumption that point and NPS BOD_{ult} loads decay at the same rate is backed by the following reasoning. First, measured bottle BOD rates (k_1) for both municipal and industrial discharges to the Willamette River are low and in the same range as rates for tributary waters collected above all known point sources (Circular 715–I, table 5). Second, it would be expected that the oxidative character of organic materials from well-treated (highly oxidized) secondary effluents should approximate the oxidative character of organic matter in natural streams. Thus, the bottle rate data are consistent with intuitive reasoning that the natural organic matter of streams and the organics in well-treated secondary effluents should both be well on the way to biochemical stabilization.

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