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Surveillance & Analysis Division

EPA

The Application of a One-Dimensional Steady-State Estuary Water Quality Model To Grays Harbor, Washington

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APPLICATION OF A STEADY-STATE DISSOLVED OXYGEN MODEL TO LOW FLOW CONDITIONS IN GRAYS HARBOR, WASHINGTON

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FINDINGS AND CONCLUSIONS

A steady-state one-dimensional mathematical model of dissolved oxygen was evaluated under critical low flow conditions in Grays Harbor, Washington. The model was based upon the assumption that the equations of mass balance could be described by non-tidal advection, diffusion-like processes and first-order biochemical reactions.

Vertically and time-averaged salinities, collected during the EPA Region 10 survey of July 25-29, 1978, were used to calibrate the pseudo-diffusion coefficients, using a balance between diffusion-like processes and non-tidal advection. The computed salinity distributions had a minimum value at the upstream, or freshwater, boundary of the estuary, and a maximum at the ocean boundary. The computed distribution of the pseudo-diffusion coefficient had a relative maximum in the inner estuary. This relative maximum was similar to results found by other investigators and was attributed to the two-layer flow induced by density differences between the oceanic and the freshwater boundaries of the estuary.

Simulations of the tidally-averaged dissolved oxygen and carbonaceous biological oxygen demand in Grays Harbor were done using two different models of the portion of the estuary affected by waste discharge. One of the models was based upon the assumption that water quality characteristics were uniform across the estuary. The other model was based upon the assumption all point source discharges and freshwater run-off were confined to the main navigational channel, only. The mean and standard deviation for the difference between simulated and mean observed were, for the first model, 0.20 mg/l and 0.32 mg/l, respectively. The corresponding values, using the second model were 0.18 mg/l and 0.31 mg/l, respectively. Since the first model was based upon assumptions which, are more consistent with the available data, it was this model upon which the sensitivity analysis was based.

An important aspect of the analysis was determining the sensitivity of the mathematical model to the following factors:

1. Changes in the pseudo-diffusion coefficient
2. Changes in the reaeration rate
3. Changes in the magnitude of the sediment oxygen demand
4. Changes in boundary conclusions for dissolved oxygen and BOD
5. Changes in the BOD loading
6. Changes in the temperature of the receiving waters.

The results of this analysis indicated that the mathematical model was most sensitive to changes in the reaeration rate and the magnitude of the sediment oxygen demand. The model was affected somewhat less by changes in the pseudo-diffusion coefficient, the point source BOD discharge, the oceanic dissolved oxygen and BOD boundary conditions, and the deoxygenation rate. The model was least sensitive to the receiving water temperature profile, and the upstream, or freshwater, boundary conditions for dissolved oxygen and BOD.

Net production of dissolved oxygen by phytoplankton was assumed to be zero in all simulations. This was done because the available data may not have been representative of _in situ_ conditions. Additional studies of primary production should be performed to improve our knowledge of the dissolved oxygen budget of Grays Harbor.

The one-dimensional model was calibrated only for the flow occurring during the July 1977 survey. Application of the model to other flow regimes can be accomplished by estimating the pseudo-diffusion coefficients appropriate to the new regimes. Available data can be used for this, as well as correlations between pseudo-diffusion coefficients and freshwater flow developed in other studies.

INTRODUCTION

Conditions of extreme low river flows, which occurred in the Pacific Northwest during 1977, provided an opportunity to evaluate mathematical water quality models under critical conditions. Grays Harbor (Figure 1), an estuary on the coast of Washington, experiences water quality problems during such critical conditions. The National Pollution Discharge Elimination System (NPDES) permits, written for industries which discharge to the estuary, contain limitations based upon the freshwater discharge to the estuary. Because the estuary is water quality limited, it was the subject of a comprehensive water quality survey during the period, July 25-29, 1977, and a subsequent analysis of the data using mathematical models of water quality. Due to time and resource limitations, the models were limited to those which simulate temperature, salinity, dissolved oxygen and biochemical oxygen demand.

Two different modeling concepts were applied to the analysis of the data. The first, which is described in this report, was based upon the assumption that the estuary could be considered to be a steady-state, one-dimensional system, governed by processes of horizontal diffusion, non-tidal advection, and first-order biochemical reactions. The second, as described by Yearsley and Cleland (1979), is a dynamic, quasi-two-dimensional hydraulic and water quality model which accounts for diurnal variations of water transport and surface elevations, as well as diurnal variations in processes which drive biochemical reactions, such as solar radiation.

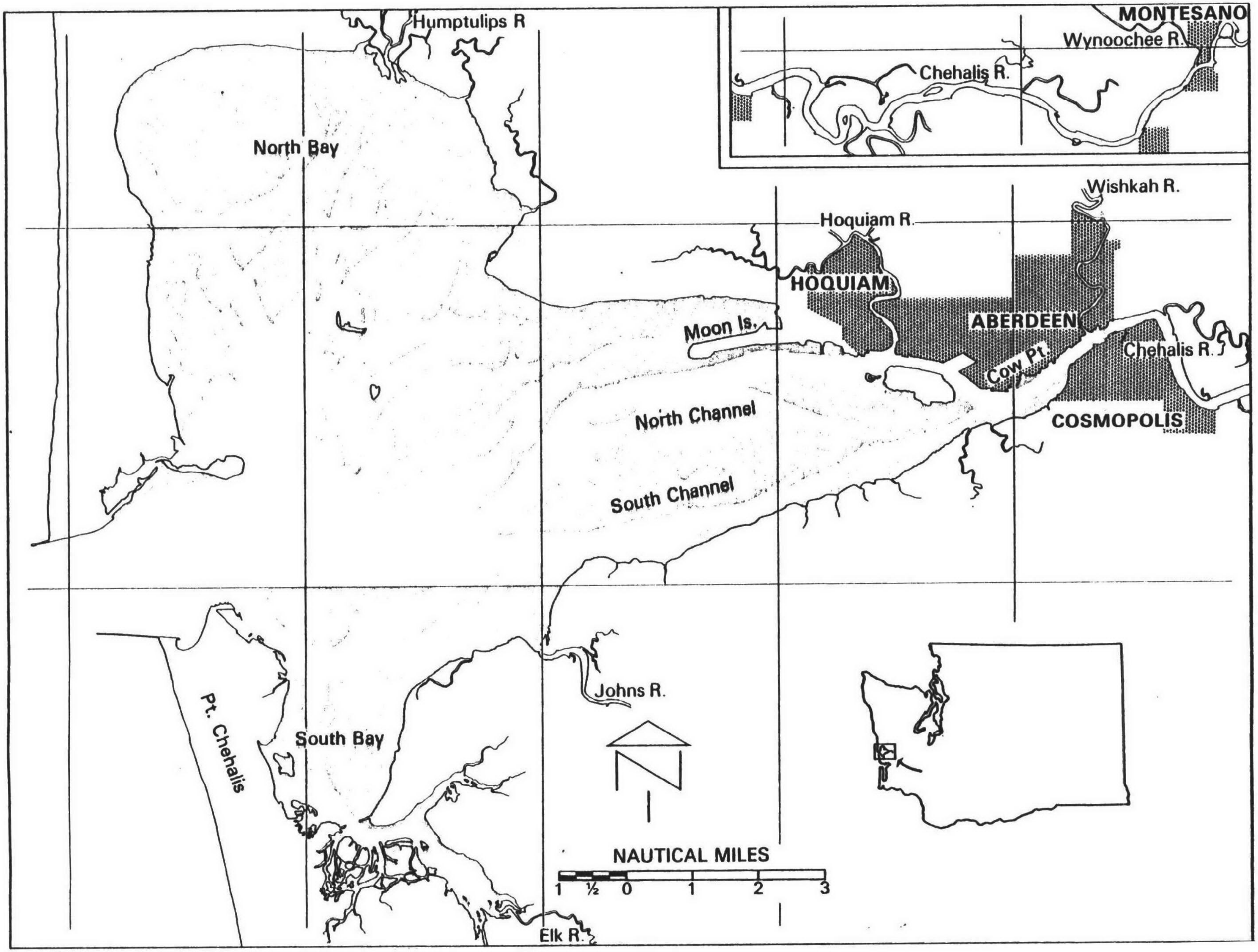


Figure 1. Grays Harbor and fresh water tributaries.

The intent of these model studies was to examine the processes which govern the distribution of dissolved oxygen in Grays Harbor and to provide the basis for comparing a simple steady-state model and a more sophisticated dynamic model. The final objective of the study was to improve our methods for evaluating and developing NPDES permits in Grays Harbor.

PREVIOUS INVESTIGATIONS

There have been a number of comprehensive field study programs in Grays Harbor and also a number of mathematical model studies. The first, and perhaps the most thorough field study was done by Ericksen and Townsend (1940). This study documented the severe water quality problem which had resulted from the discharge of high-strength organic wastes by the Grays Harbor Pulp and Paper Company (now owned by ITT/Rayonier). Subsequent field studies included the work of Orlob, Jones and Peterson (1951), Peterson (1953), Peterson, Wagner and Livingston (1957) and Beverage and Swecker (1969). With the exception of the report by Beverage and Swecker (1969), the principal objective of these studies was to monitor the impact of waste discharge upon water quality. The Beverage and Swecker (1969) study, in addition to dealing with water quality, provided useful information regarding the hydraulic characteristics of the estuary. Pearson and Holt (1960) examined the effects of oceanic upwelling upon the dissolved oxygen in Grays Harbor. Beverage and Swecker (1969) also did an extensive analysis of the character of the bottom sediments in Grays Harbor. Since 1971, ITT/Rayonier and Weyerhaeuser have monitored water quality in Grays Harbor at weekly intervals during the summer low flow. While this data is not published, it is available from the State of Washington's Department of Ecology.

Mathematical modeling in Grays Harbor was first reported by Callaway (1966), who applied a single, steady-state model to the analysis of waste loading and oceanic upwelling. This work was extended by Yearsley and

Houck (1973) to include the effects of sediment oxygen demand. Lorenzen et al (1976) developed a dynamic water quality model of the estuary, making extensive use of the estuary hydraulic model developed by the firm, Water Resource Engineers, Inc. (Shubinski, McCarty and Lindorf (1965). All of these studies provided the basis for the work described in this report and the report of Yearsley and Cleland (1979).

WATER QUALITY DATA

An intensive water quality sampling program was conducted in Grays Harbor (Figure 1) during the period July 25-29, 1978, by the EPA Region 10. The sampling program included measurements of temperature, salinity, dissolved oxygen and nutrients from major industrial and municipal sources, tributaries discharging to Grays Harbor and the waters of Grays Harbor, proper. A description of this data collection program is given by Yearsley (1979).

The data required for this study included vertical and time averages of temperature salinity, dissolved oxygen and biochemical oxygen demand in the estuary receiving waters and the discharge rates of these constituents from point sources and tributaries.

MODEL DEVELOPMENT

The mathematical model chosen for this study was a steady-state, one-dimensional model. The processes which determines the mass balances in this model are non-tidal advection, diffusion-like processes and biochemical reactions, where appropriate. There are a number of models of this type described in the literature. AUTOQUAL, developed by Crim and Lovelace (1973), was chosen for this study because it was a well-documented and tested software package.

AUTOQUAL is based upon a system of discrete volumes called junctions, which communicate with each other through a system of channels. The model assumes that all junctions are fully mixed, with properties represented as point values at the center of the junctions. A complete description of model development is given by Hess (1978).

Model Geometry and Data

Model geometry for (Figure 2) Grays Harbor was defined with the Highway 107 bridge south of Montesano adopted as the upstream boundary. Distances were measured seaward along the Chehalis River channel in nautical miles up to nautical mile 11 near Aberdeen. From there, distances were measured as a straight line to the center of the navigational channel at Point Chehalis. All water quality, point source, and tributary data are referenced to this river mile system. For purposes of simulation, the estuary was partitioned into 30 segments, one

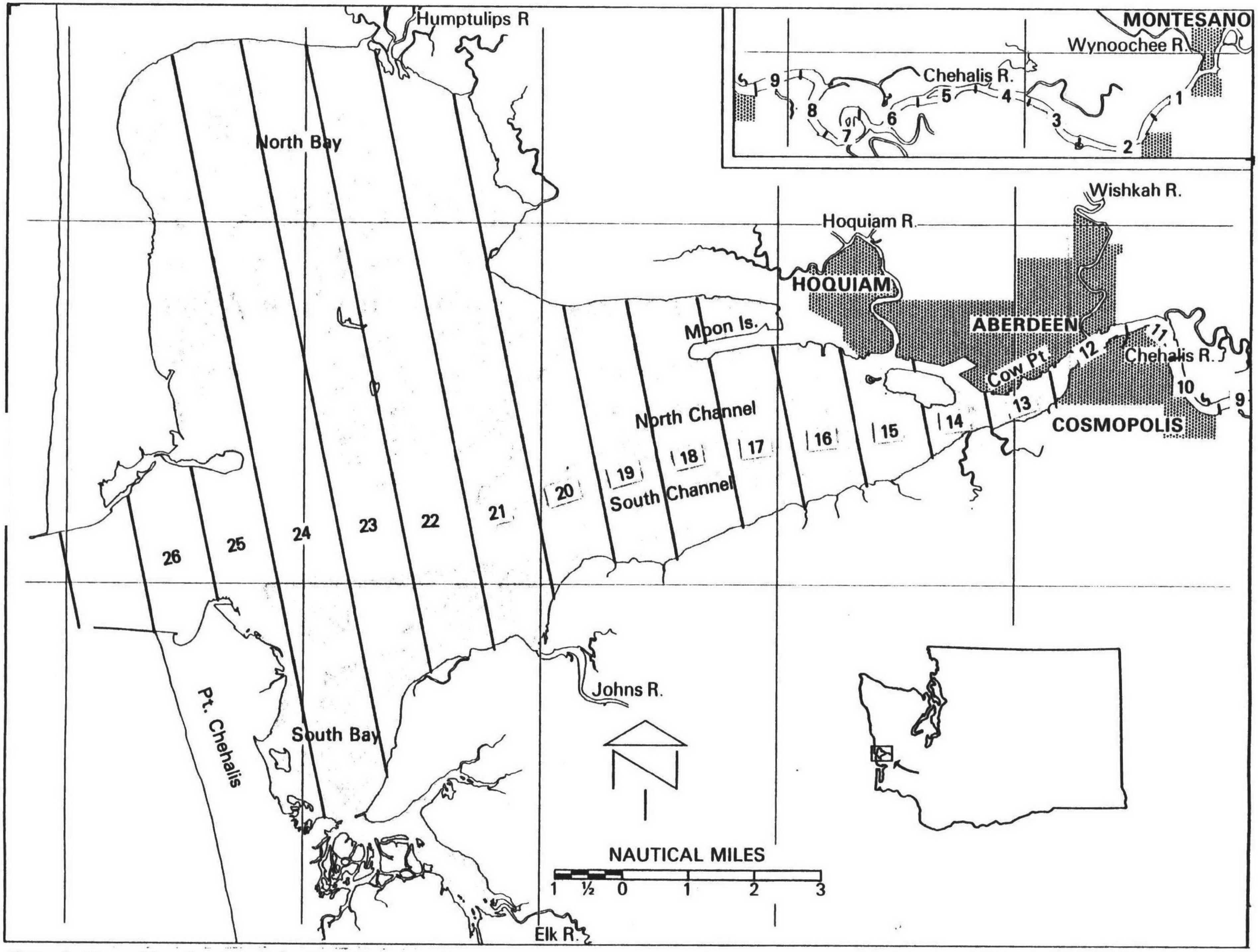


Figure 2. Channel-junction system for Grays Harbor based upon entire estuary geometry

nautical mile long, beginning at nautical mile 0. Twenty seven of these segments are within Grays Harbor while three are in the open ocean. The three segments defined in the ocean were used to establish the ocean boundary conditions. Two channel-junction systems were defined for Grays Harbor.

Initially the estuary was segmented as it appears in Figure 2. Starting at nautical mile 0 the estuary was segmented along the length of the channel until nautical mile 11 was reached. From nautical mile 11 to the ocean segments were defined across the estuary's entire width. A second channel-junction system was defined as it appears in Figure 3. Here the channel junction system is identical to that in Figure 2, except that beyond mile 14 only the North Channel of the estuary is included in the segments. This second configuration assumes that the main navigational channel carries all the freshwater discharge, as well as all the point source waste discharges.

The basic input data required by AUTOQUAL are described by Crim and Lovelace (1973). For a detailed description of how these data were input, see the AUTOQUAL users manual (Crim and Lovelace (1973)). Segment widths and depths were computed from output from the WRE hydrodynamic as calibrated by Yearsley and Cleland (1979).

Hydraulic geometry was required for both systems at mean tide. The geometry used for each system is given in Tables 1 and 2 .

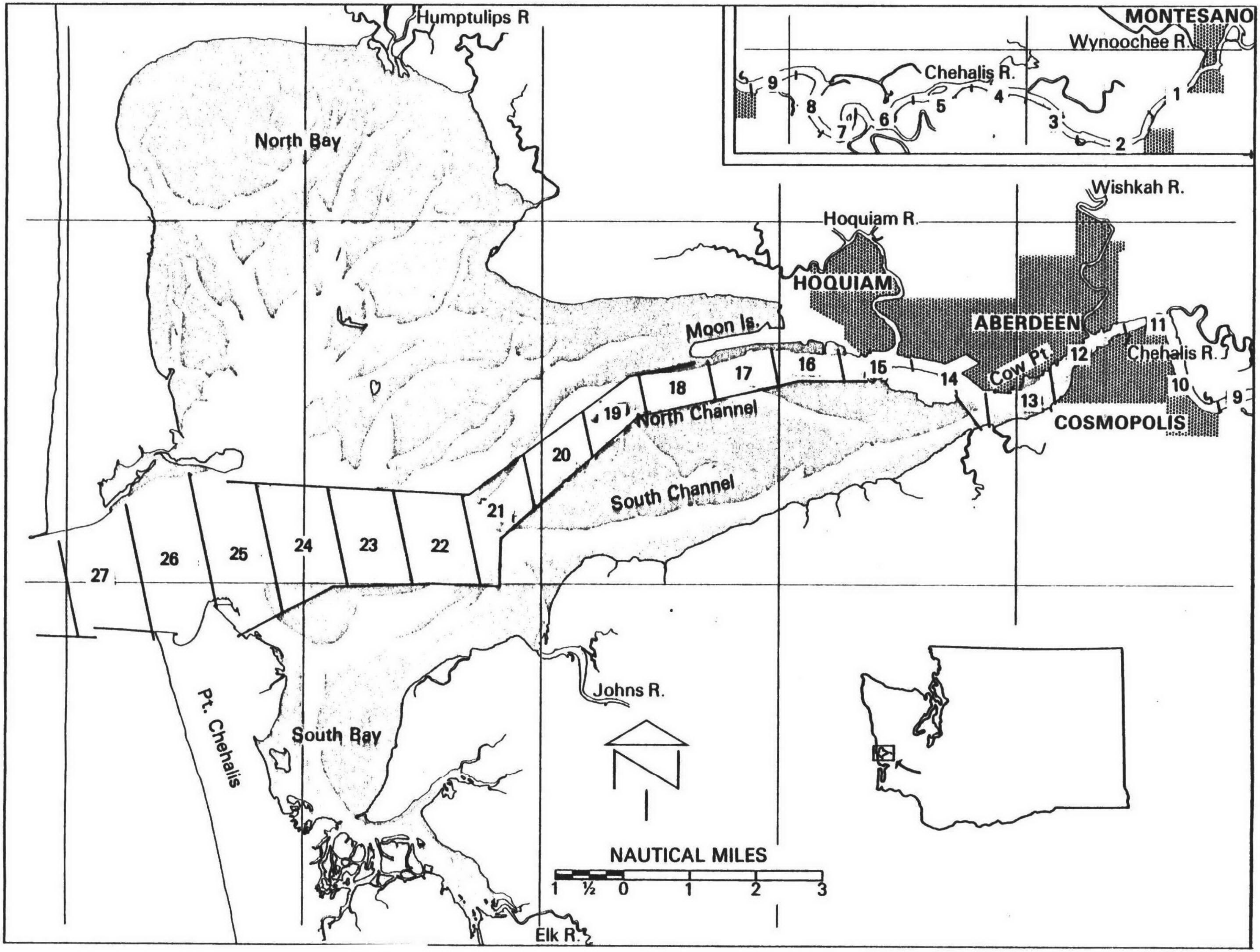


Figure 3. Channel-junction system for Grays Harbor based upon main channel geometry

Point Sources and Freshwater Tributaries

Municipal and industrial waste loading data were based on discharge reports obtained from the Washington Department of Ecology and on data collected by EPA Region 10 during the July 25-29 1977 survey. Arithmetic averages of data collected during the period, July 25-29 1977 were used to determine loadings for input to the model.

The discharge from freshwater tributaries in Grays Harbor was obtained from the USGS. Water quality characteristics were obtained from data collected during the July 25-29, 1977 field study.

Estimates of mean values of water quantity and quality for the point sources and freshwater discharges to Grays Harbor are shown in Table 3.

Rate Constants, Water Temperature and Saturation D.O.

Values of temperature, salinity, dissolved oxygen, and biological oxygen demand used in the analysis were arithmetic averages of observed data collected during the survey (Yearsley (1979)), as shown in Table 4. BOD rates computed from samples collected in Grays Harbor during the July 1977 survey are shown in Table 5. The reaeration rates in each segment, j, were calculated using the equation developed by Langbein and Durum (1967):

$$K_{2j} = \frac{7.62\ V_j}{D_j^{4/3}} \quad (1)$$

where,

K_{2j} = the reaeration coefficient, days^{-1} (base e), in segment, j,

V_j = the river root-mean square velocity, feet/second, in segment, j,

D_j = the channel depth, feet, in segment, j.

The river root-mean square velocity, V_j, at each segment, j, was determined kinematically:

$$V_j = \frac{Q_j}{A_{xj}} + \frac{\sqrt{2}}{4}\frac{W \Delta H\ A_{sj}}{A_{xj}} \quad (2)$$

Table 1. Geometric characteristics used in steady state model for Grays Harbor (entire estuary):

Distance from Montesano (nautical miles)	Segment Depth (feet)	Channel Width (feet)
1	11.5	380.2
2	12.7	478.8
3	12.9	504.9
4	14.3	624.4
5	14.6	728.8
6	16.3	832.3
7	18.4	939.1
8	20.8	826.4
9	21.3	955.8
10	20.9	1074.0
11	20.4	1134.3
12	21.5	1097.1
13	23.8	2115.5
14	20.7	3885.5
15	11.6	6901.0
16	11.4	10546.3
17	11.8	11740.1
18	15.3	13592.8
19	13.7	16405.4
20	10.4	23937.8
21	9.9	32090.4
22	11.6	34879.0
23	16.3	41285.8
24	16.8	45719.7
25	21.0	29288.0
26	30.0	10290.7
27	47.0	8476.0

Table 2. Geometric characteristics used in steady-state model for Grays Harbor (North Channel):

Distance from Montesano (nautical miles)	Segment Depth (feet)	Channel Width (feet)
1	11.5	380.2
2	12.7	478.8
3	12.9	504.9
4	14.3	624.4
5	14.6	728.8
6	16.3	832.3
7	18.4	939.1
8	20.8	826.4
9	21.3	955.8
10	20.9	1074.0
11	20.4	1134.3
12	21.5	1097.1
13	23.8	2115.5
14	22.7	3260.9
15	21.0	1465.0
16	18.9	1974.7
17	16.9	3047.0
18	22.6	2891.8
19	21.6	3864.6
20	23.1	4045.5
21	24.6	5523.1
22	28.1	7300.3
23	30.1	8392.5
24	29.7	9921.3
25	29.6	13343.5
26	30.0	10290.7
27	47.0	8476.0

Table 3. Average water quality and quantity of point source discharging to the Chehalis River and Grays Harbor, July 25-29, 1977:

Source	Distance Montesano (nautical miles)	Flow (c.f.s.)	Dissolved Oxygen (mg/l)	Carbonaceous BOD (ultimate) (mg/l)
Chehalis River	0.0	628.0	9.8	2.7
Wynooche River	0.5	210.0	9.3	0.7
Weyerhaeuser Co.	8.5	1.2	6.7	25.8
Wishkah River	11.5	115.0	7.2	2.4
Aberdeen STP	12.3	3.5	5.9	150.0
Weyerhaeuser Co.	13.4	33.6	3.8	200.0
ITT/Rayonier	14.2	45.5	3.2	107.0
Hoquiam River	14.3	108.0	5.6	2.6
Hoquiam STP	16.2	2.6	8.5	89.5

Table 4. Mean values of temperature, dissolved oxygen and salinity at various locations in Grays Harbor, as measured during the period July 25-29 1977:

Distance from Montesano (nautical miles)	Temperature (C)	Dissolved Oxygen (mg/l)	Salinity (ppt*)
0.0	--	--	0.4
2.4	18.9	9.3	0.6
4.8	19.0	8.3	1.9
6.4	19.0	7.5	4.6
7.8	18.8	6.7	7.0
8.9	18.5	6.3	10.7
11.6	18.0	5.6	16.1
13.2	17.9	5.8	19.7
14.2	17.5	6.1	21.7
16.2	17.0	6.0	24.5
20.0	15.2	6.7	27.4
21.9	14.4	7.6	28.5
24.5	12.9	7.1	--
27.0	--	--	29.3

Table 5. BOD rate constants for Grays Harbor, computed from July 1977 field data:

Distance from Montesano (nautical miles)	BOD Rate Constant (base e) (days^{-1})
2.4	0.13
7.8	0.14
11.6	0.12
13.2	0.17
14.2	0.13
16.2	0.21
18.8	0.25
20.0	0.24
24.5	0.25

where,

Q_j = the freshwater flow, cfs, in segment, j,

Ax_j = the cross-sectional area, square feet, segment, j,

W = the tidal frequency, 1/seconds,

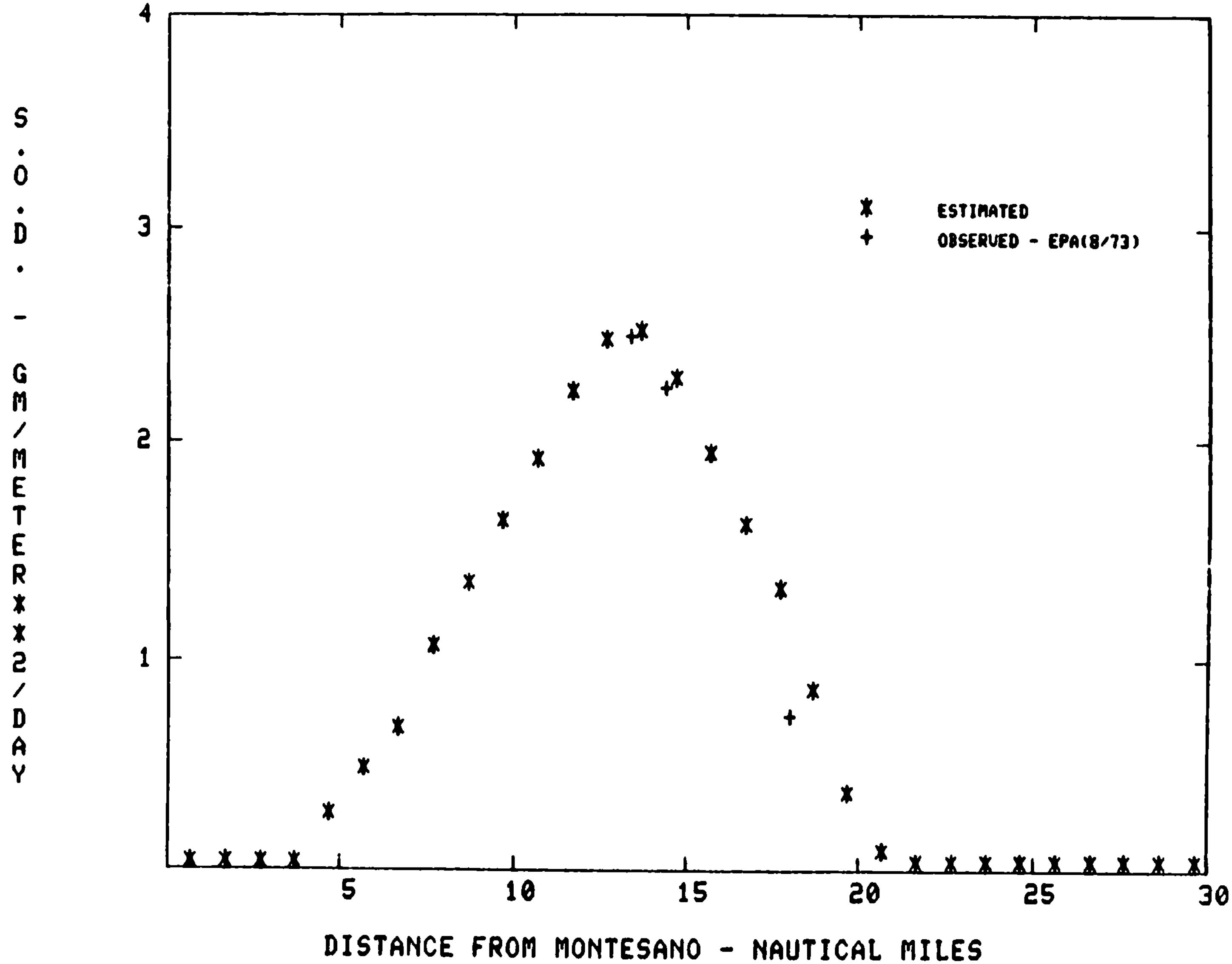
As_j = the surface area of the tidally influenced part of the estuary landward of segment, j, square feet,

ΔH = the amplitude of the tide, feet

Sediment Oxygen Demand

Sediment oxygen demand was estimated, as described by Yearsley and Houck (1973), by combining the results of benthic respirometer data (Kreizenbeck (1973)) and carbon content analysis of bottom material samples reported by Beverage and Swecker (1969). The benthic respirometer data consisted of three readings taken at nautical miles 13.5, 14.5, and 17.5. Carbon analysis data was available from nautical miles 6.5 to 27.5 from both the North and South Channels. It was assumed that distribution of carbon in the sediments was the same during the carbon content and the respirometer studies. It also was assumed that sediment demand was proportional to carbon content thus their distributions should be similar. The ratio of sediment oxygen demand to carbon content was calculated at nautical mile 13.4. This ratio was then used to estimate the distribution of sediment demand for the rest of the estuary. Estimated and observed sediment oxygen demand is plotted in Figure 4.

FIGURE 4. ESTIMATED AND OBSERVED SEDIMENT OXYGEND DEMAND IN GRAYS HARBOR, WASHINGTON.



The North Channel is dredged on a regular basis. Dredging operations were conducted in 1976, and were under way at the time of the July 1977 survey. The tacit assumption in distributing sediment demand on the basis of carbon content measurements made seven years earlier is that sediment materials tend to assume the same steady state distribution after each dredging in a time frame which is small relative to the interval between dredgings.

The Pseudo-Diffusion Coefficient

The basic assumption upon which the model is formulated is that the processes in an estuary can be described as a one-dimensional balance between diffusion-like processes, advection and first-order biochemical/physical decay. The determination of the coefficient characterizing the diffusion-like process is a key element in this analysis. This coefficient, which we shall call the pseudo-diffusion coefficient, includes the effects of a number of processes such as eddy diffusion, gravitational mixing and other forms of dispersion. Since the diffusion term becomes the repository for several complex processes not explicitly stated elsewhere in the nontidal models, the determination of the pseudo-diffusion coefficient based on theoretical considerations becomes extremely difficult if not impossible. Thus, its determination usually rests on an analysis of the distribution of some conservative tracer such as dye or salinity. Implicit in such an analysis is that the estuarine transport processes not specified explicitly by the model are expressed in the observed distribution of the tracer. Furthermore, it is assumed that this information can be incorporated into the diffusion coefficient. Stommel (1953), and O'Connor (1961), respectively, used salinity as a tracer to determine pseudo-diffusion coefficients for tidally averaged models. The same general procedures were followed in determining coefficients at mean tide for Grays Harbor. The tidally averaged form of the convective-diffusion equation for salinity, S, is:

$$\frac{\partial (SA)}{\partial t} + \frac{\partial (u_f SA)}{\partial x} = \frac{\partial \left(AE \frac{\partial S}{\partial x} \right)}{\partial x} \tag{3}$$

If we assume steady state conditions, Equation (3) may be solved for the pseudo-diffusion coefficient:

$$E = \frac{u_f S}{\frac{\partial S}{\partial x}} \tag{4}$$

Note that $Q_f = U_fA$ is the freshwater flow. Since salinity is usually defined as a function of x by a series of discrete observations, the finite difference form of Equation (4) is generally used. Because observations for Grays Harbor were not available for each of the 30 segments defined, a smoothing and interpolating function was needed. The function used was required to capture at least the first and second order changes of salinity with x, be continuous on at least the interval between observation points, and have a first derivative which is continuous between and at observation points. The class of n^{th} degree polynominals provided a convenient set of functions having these characteristics. In addition, these functions are continuous over their entire domain, thus Equation (4) may be used in its derivative form. Polynominals of degree three through six were fitted, using least squares analysis, to the harmonically smoothed salinity data. Polynominals of degree four appeared to best preserve the higher order characteristics of the data and provide suitable smoothing. Using the polynominal fits, the determination of the pseudo-diffusion coefficients was then a simple process for most portions of the estuary. However, near both the upstream and seaward boundaries $\frac{\partial S}{\partial x} \rightarrow 0$, making the right-hand side of Equation (4) an undefined quantity. In addition, neither the 4th degree polynominal nor it first derivative were reliable close to the beginning or ending data stations (nautical miles 2.4 and 24.5 respectively). The diffusion coefficients in these regions were determined by extrapolation of the well-defined values in the estuary interior and knowledge of the general diffusion characteristics at the boundaries. At the upsteam boundary it is expected that diffusive-like transport should approach a small value,

FIGURE 5. PSEUDO-DIFFUSION COEFFICIENT FOR ENTIRE CHANNEL AND MAIN CHANNEL SIMULATIONS IN GRAYS HARBOR, WASHINGTON.

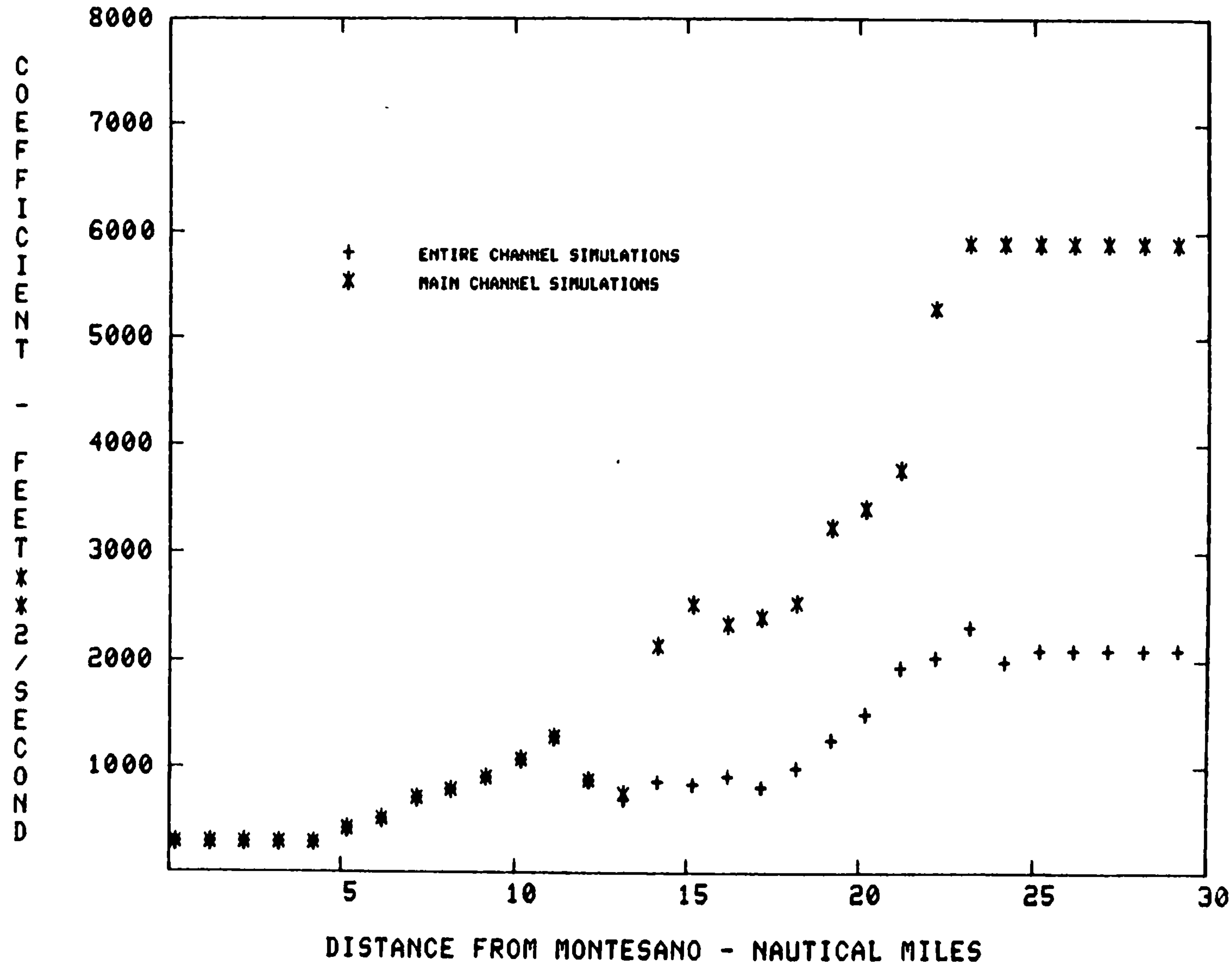
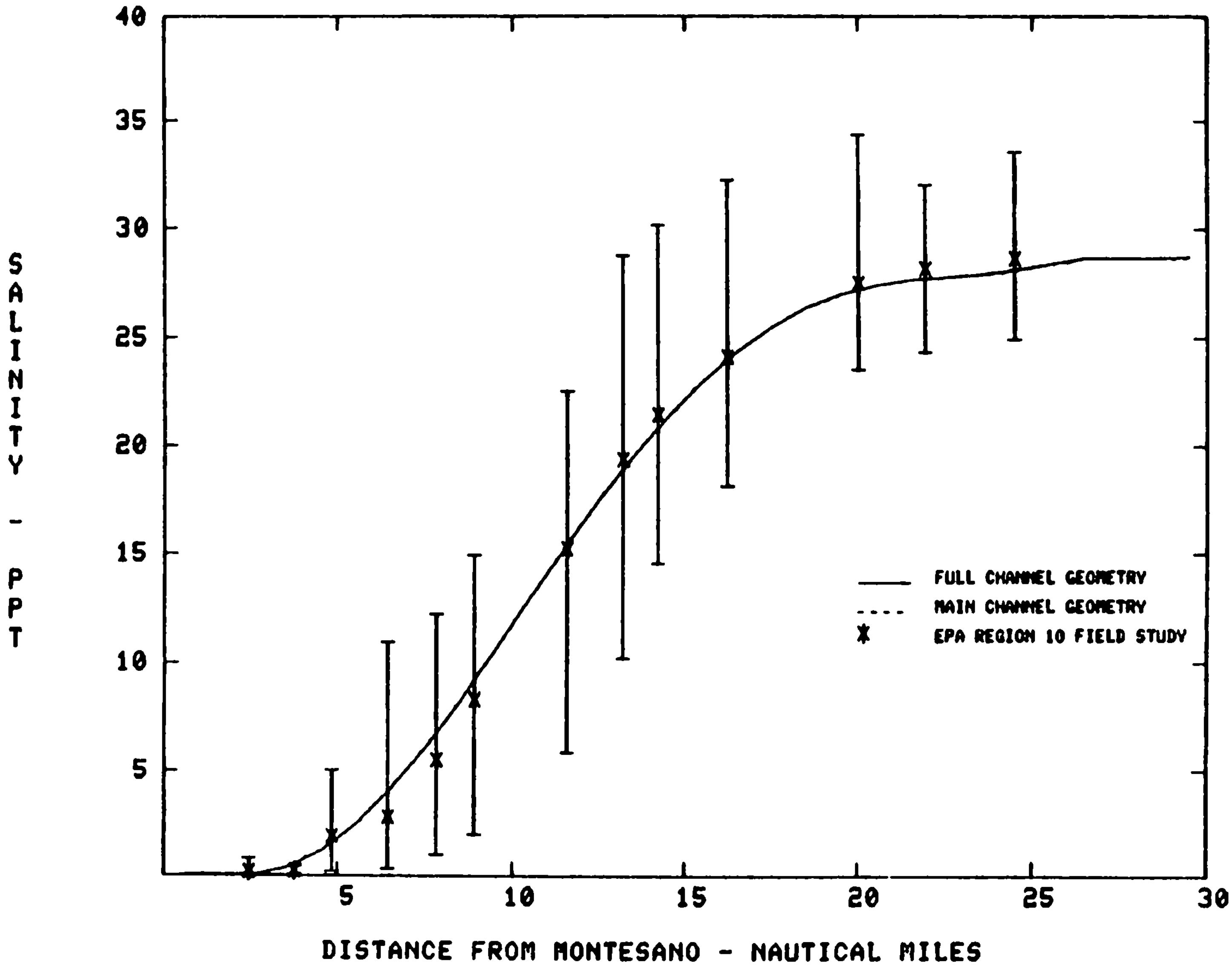


FIGURE 6. COMPARISON OF SIMULATED AND OBSERVED SALINITY IN GRAYS HARBOR FOR FULL CHANNEL AND MAIN CHANNEL GEOMETRIES.



since the magnitude of tidal action and salinity gradients decrease in the upstream direction. Near the seaward boundary the observed salinity profile becomes flat, approaching the ocean value of salinity, indicating that this portion of the estuary is well-mixed. In addition, it would be expected that the intensity of mixing due to tidal action should increase as the seaward boundary is approached. Thus, the diffusion coefficient near this end of the estuary would be expected to become large. Using these characteristics of diffusion as a guide, pseudo-diffusion coefficients were estimated near both boundaries by trial and error fits to the observed salinity profiles. The calculated pseudo-diffusion coefficients and simulated salinity profiles for both the complete and the partial estuary cross-sections are presented in Figures 5 and 6.

Plots of the pseudo-diffusion coefficient versus distance all reveal the same general relationships, each with a distinctive maximum approximately 10 nautical miles downstream of Montesano. These plots show a resemblance to a relationship postulated by WRE (1974). WRE (1974) suggests that the pseudo-diffusion coefficient may be thought of as the aggregate of three major processes, each of which predominate in different portions of the estuary. Since the maximum in Figure 6 occurs where density induced mixing predominates, it was hypothesized that this mixing mechanism was responsible for the observed maximum in the coefficients calculated for Grays Harbor.

Observed and Simulated Dissolved Oxygen Profiles

Observed dissolved oxygen profiles used for comparison with simulation results were derived from data collected during the July, 1977 survey. The arithmetic mean of dissolved oxygen measurements from each station was used to define the tidal average at that station.

Dissolved oxygen and carbonaceous biological oxygen demand (BOD) were simulated using cross sections extending the full width of the estuary (see Figure 2). Both of these parameters were also simulated for the model configuration which used the main navigation channel geometry past nautical mile 14 (see Figure 3). The resulting simulations are compared with the arithmetic mean of the observed values in Figures 7 and 8. The mean and standard deviation of the difference between simulated and observed dissolved oxygen concentrations for the full channel cross-sections are 2 mg/l and ± 0.51 mg/l, respectively. The corresponding values for the difference between simulated and observed concentrations of dissolved oxygen, using the main channel geometry, are 0.18 mg/l and ± 0.43 mg/l, respectively.

However, the assumptions upon which the main channel geometry model is based are not consistent with our knowledge of the hydrography and hydrodynamics of the North and South Channel of Grays Harbor. The hydrographic data (Yearsley (1979)) indicates that the water quality of the South Channel is similar to that of the North Channel. Hydrodynamic studies by Brogden and Fisackerly, (1973), using a physical model of Grays Harbor, show that the flow in the South Channel is similar to that in the North Channel. For these reasons it was difficult to justify using the main channel geometry without further analysis. As a result, the following discussion of sensitivity is based upon the model with the full channel geometry.

Primary Production

One of the assumptions upon which the Base Run (Figure 7) is based is that there is no net photosynthetic production of oxygen in Grays Harbor. During July 1977 the University of Washington Department of Oceanography measured primary productivity in Grays Harbor using the ^{14}C method (Yearsley 1979). The results of this study indicate that the average net production of dissolved oxygen varied from 0.37 grams O_2/meter^2/day to 8.13 grams O_2/meter^2/day.

There are two questions regarding these productivity data which make it difficult to incorporate the data into the dissolved oxygen budget. The first being that the samples were incubated at temperatures equal to the warmest temperatures in Grays Harbor duing July 25-29, 1977. This was 5°C to 7°C higher than the temperatures in outer Grays Harbor where the maximum productivity was measured. Winter et al (1975) suggest that these higher temperatures will result in overestimates of the production rate. The maximum specific primary production rates (ratio of carbon fixed per unit volume per unit time to chlorophyll a per unit volume) during July 1977 are two to three times higher than those observed in Puget Sound (Winter et al (1975)) and five to seven times higher than those observed in Grays Harbor by Westley and Tarr (1965).

The second question is related to the amount of grazing done by zooplankton. The University of Washington data suggests that chlorophyll _a_ degradation products in Grays Harbor were greater, in general, in Grays Harbor during July 1977, than in oceanic surface water (W. Peterson, personal communication). While these degradation products could be resuspended material from the bottom, they can also be the product of chlorophyll digested by zooplankton or other organisms.

As a result of these uncertainties, we chose not to incorporate the productivity data into the simulations. The model predicts the average dissolved oxygen in Grays Harbor quite well, given the assumption of no net production of dissolved oxygen by phytoplankton. However, until we have more complete knowledge of primary production levels in Grays Harbor we must treat these results with the appropriate caution.

FIGURE 7. COMPARISON OF SIMULATED AND OBSERVED D.O. IN GRAYS HARBOR FOR FULL CHANNEL AND MAIN CHANNEL GEOMETRIES.

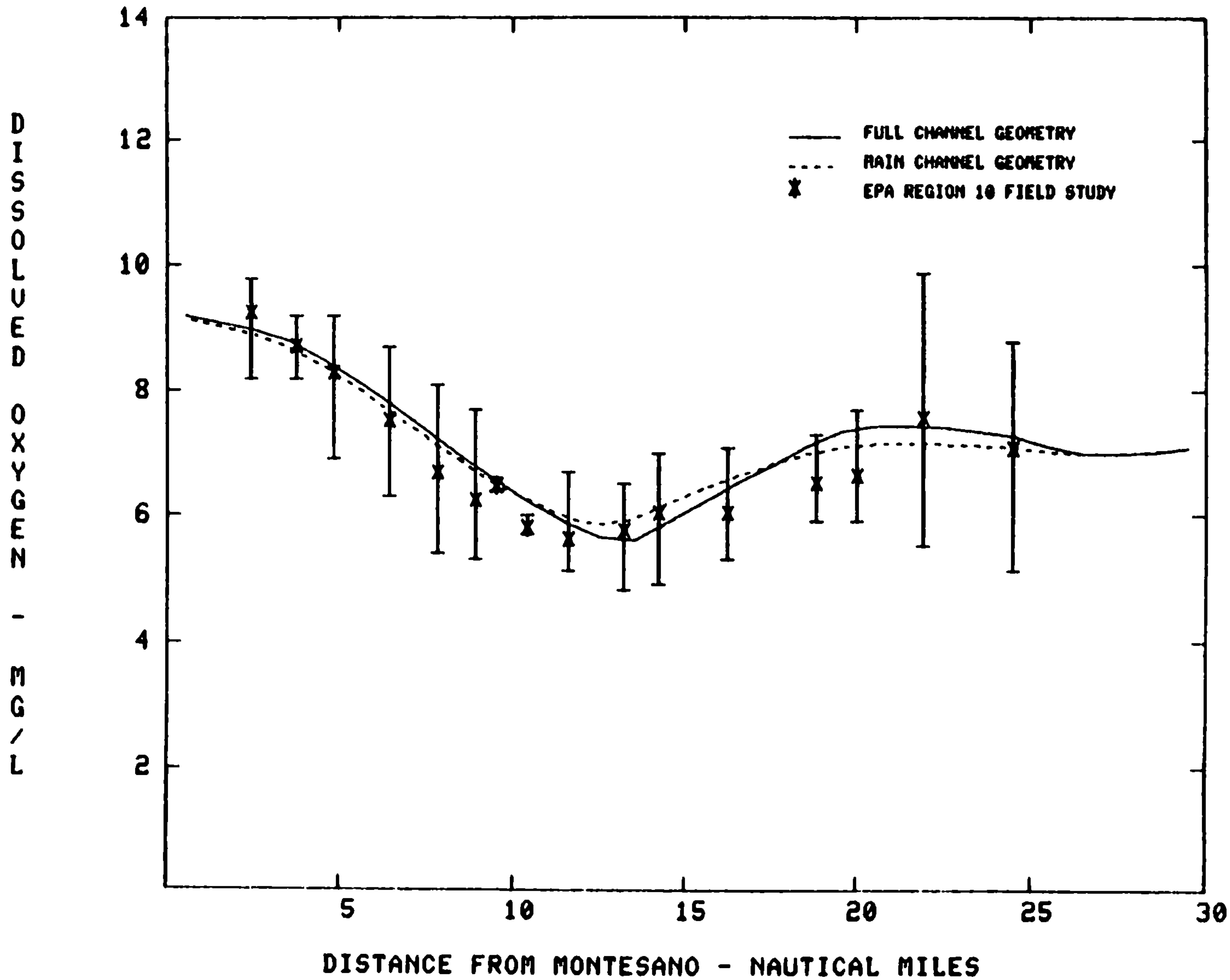
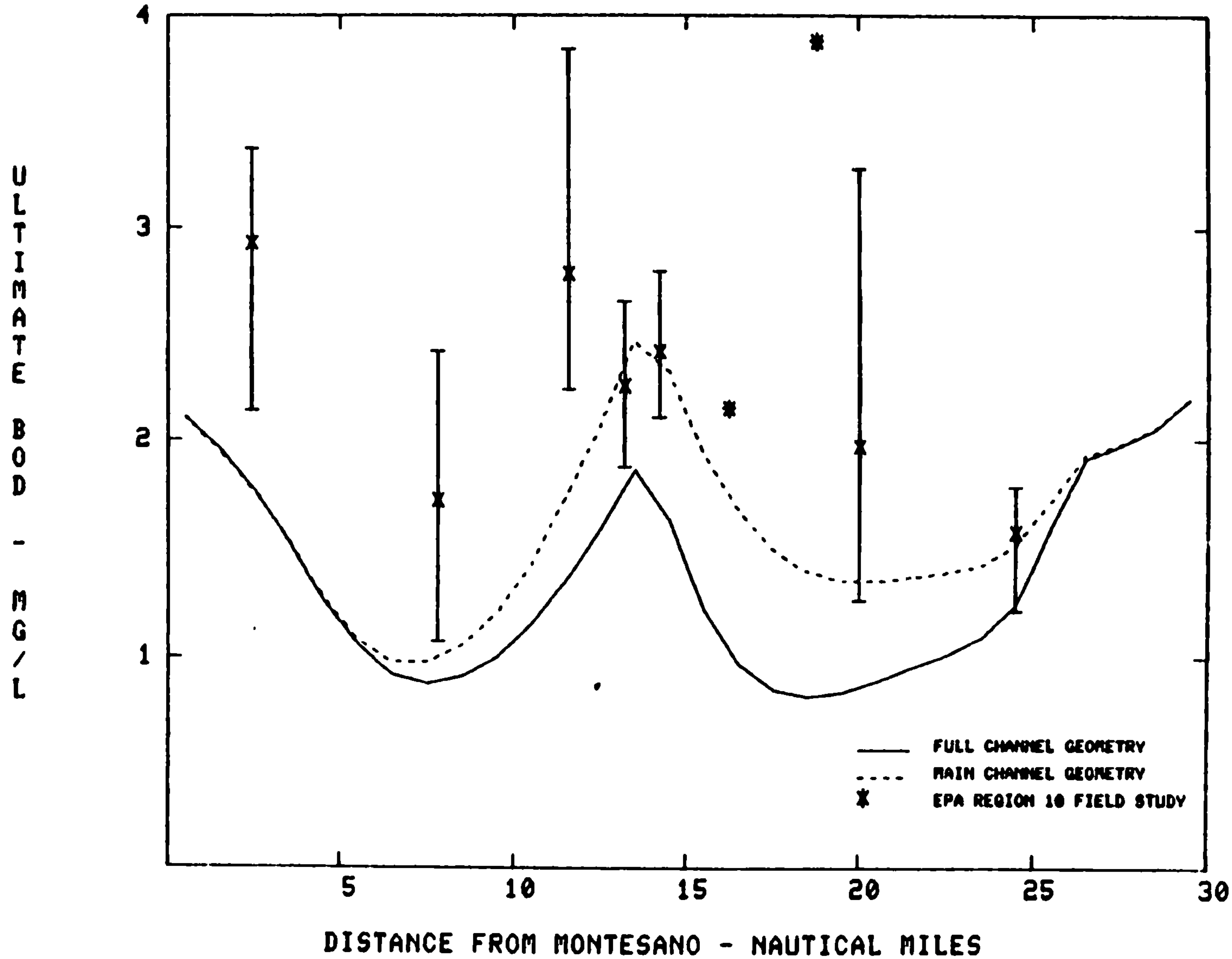


FIGURE 8. COMPARISON OF SIMULATED AND OBSERVED BOD IN GRAYS HARBOR FOR FULL CHANNEL AND MAIN CHANNEL GEOMETRIES.



SENSITIVITY ANALYSIS

Simulated dissolved oxygen responses to model inputs, parameters, boundary conditions, and channel geometry are presented as a series of plots comparing the observed response to the simulated profile for mean tide (referred to as "Base Run"). The plots appear as Figures 9 through 18.

Response of the simulated dissolved oxygen to changes in the pseudo-diffusion coefficient is shown in Figure 9. For large values of diffusion the dissolved oxygen sag is less than the base runs, but more of the deficit is transported upstream. In addition, the increased diffusion causes the system to approach well mixed conditions in the outer harbor, thus increasing the influence of the seaward boundary. The opposite is observed to be true of decreased values of diffusion.

Dissolved oxygen simulations in Grays Harbor are very sensitive to variations in the reaeration rate (Figure 10). Doubling the reaerations uniformly throughout Grays Harbor results in a minimum dissolved oxygen 1.0 mg/l higher than the calibration on base case. Halving the reaeration rate uniformly results in a 1.4 mg/l decrease in the minimum dissolved oxygen.

Temperature of the receiving water has only a moderate influence on the dissolved oxygen simulation, as shown in Figure 11. A 15 percent change in water temperature results in less than a 5 percent change in the predicted minimum dissolved oxygen.

The simulated dissolved oxygen are not very sensitive to changes in the deoxygenation rate, K_1. A 100 percent uniform increase in this rate gives rise to less than a 5 percent decrease in the simulated dissolved oxygen (Figure 12). Halving the base deoxygenation rate causes less than a 5 percent increase in the simulated dissolved oxygen.

Figures 13 and 14 examine the model response to sediment oxygen demand and BOD discharge. Figure 13 indicates a substantial response to over most of the 16 nautical miles where estimates indicate a significant demand exists (see Figure 4). A strong response to sediment oxygen demand is understandable, since it exerts it effects directly on the dissolved oxygen system. Figure 14, shows that the response to point sources of BOD is significant but is not as large as that observed for sediment oxygen demand, even though the total demand from sediment oxygen demand and BOD are comparable at 57500 and 72600 lbs/day, respectively.

This is due, principally, to the fact that sediment oxygen demand acts directly and instantaneously upon the water column, while the BOD is exerted on a time scale which is the order of the reciprocal ($1/K_1$) of the deoxygenation rate. Because of this a certain amount of the BOD is not exerted, but is transported out of the estuarine system.

Figures 15 through 18 examine model response to the landward and seaward boundary conditions. The effect of the landward boundary condition for BOD is minimal, showing its maximum response in the reach 5 to 8 nautical miles downstream of the boundary (Figure 15). The response to DO is more significant (Figure 16), but the majority of the response was confined to points 7.5 nautical miles from the boundary and landward. The magnitude and position of the dissolved oxygen sag was virtually unaffected by either of the landward boundary conditions.

Model response to ocean BOD was examined by doubling and halving the value adopted for the Base Run. As Figure 17 demonstrates, the response is significant not only in the outer harbor but at points considerable distances upstream. The same is true of model response to ocean dissolved oxygen (Figure 18). The values examined reflect the range of values for ocean dissolved oxygen. According to Pearson and Holt (1960), 3.0 mg/l typifies the effect of upwelling of deoxygenated water at the ocean boundary, while the upper end of 8.9 mg/l is the saturated value of oxygen at oceanic salinity and temperature. Simulation results indicate a significant impact in the outer harbor. However, a 4.0 mg/l decrease in the dissolved oxygen at the entrance gives rise to only a 0.2 mg/l decrease of the simulated minimum dissolved oxygen in the inner harbor.

FIGURE 9. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO THE PSEUDO-DIFFUSION COEFFICIENT, E0.

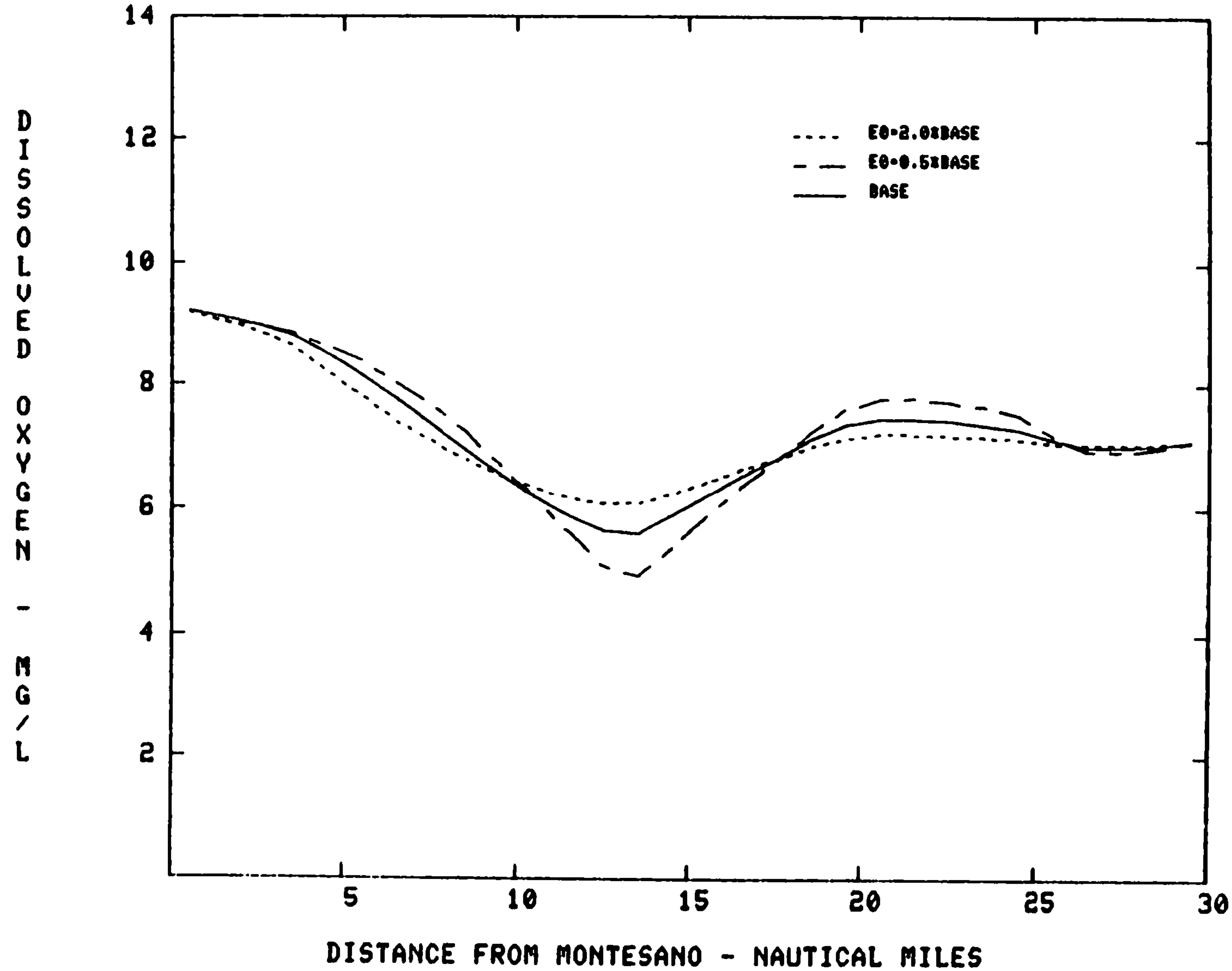


FIGURE 10. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE REAERATION RATE, K2.

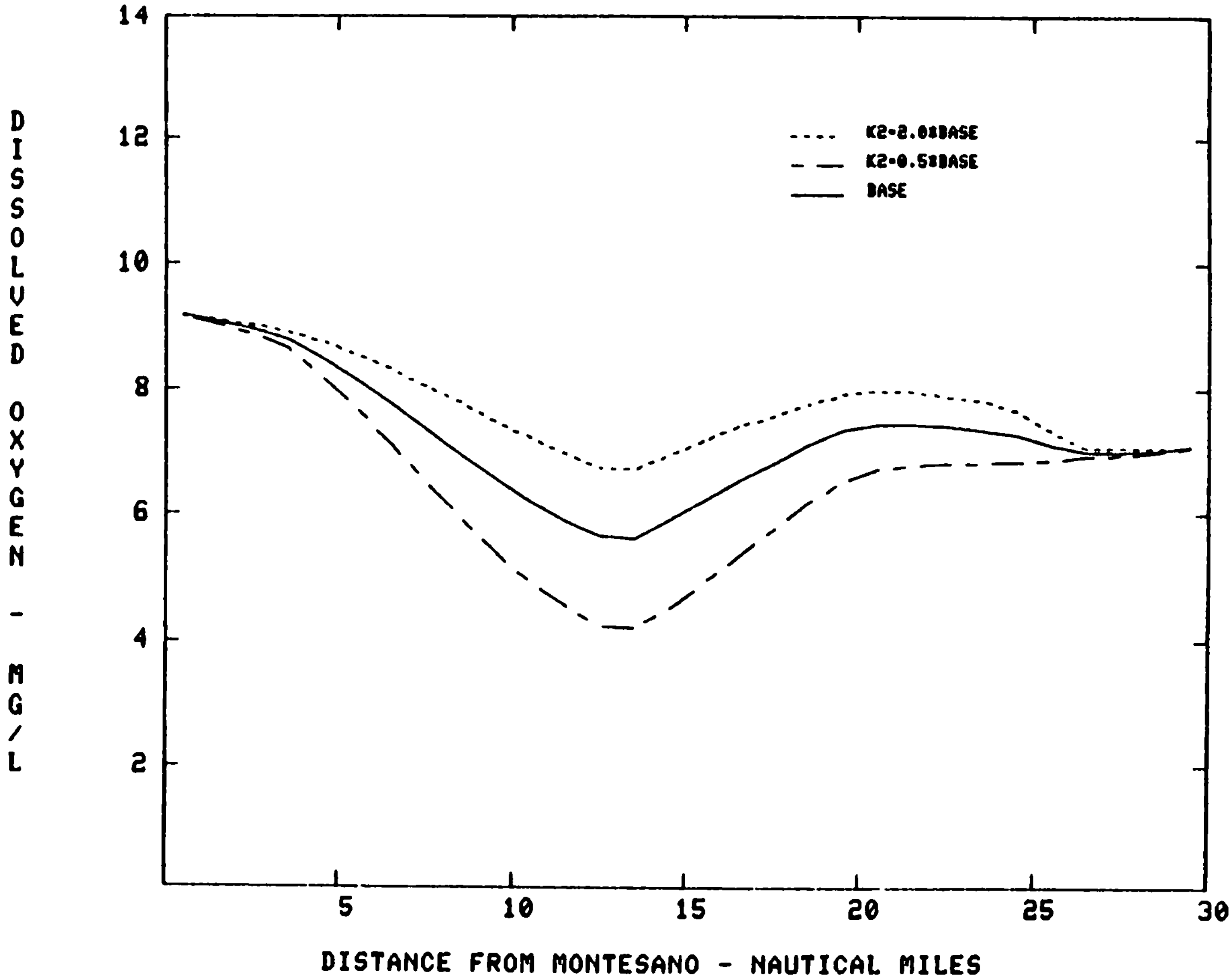


FIGURE 11. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE DEOXYGENATION RATE, K1.

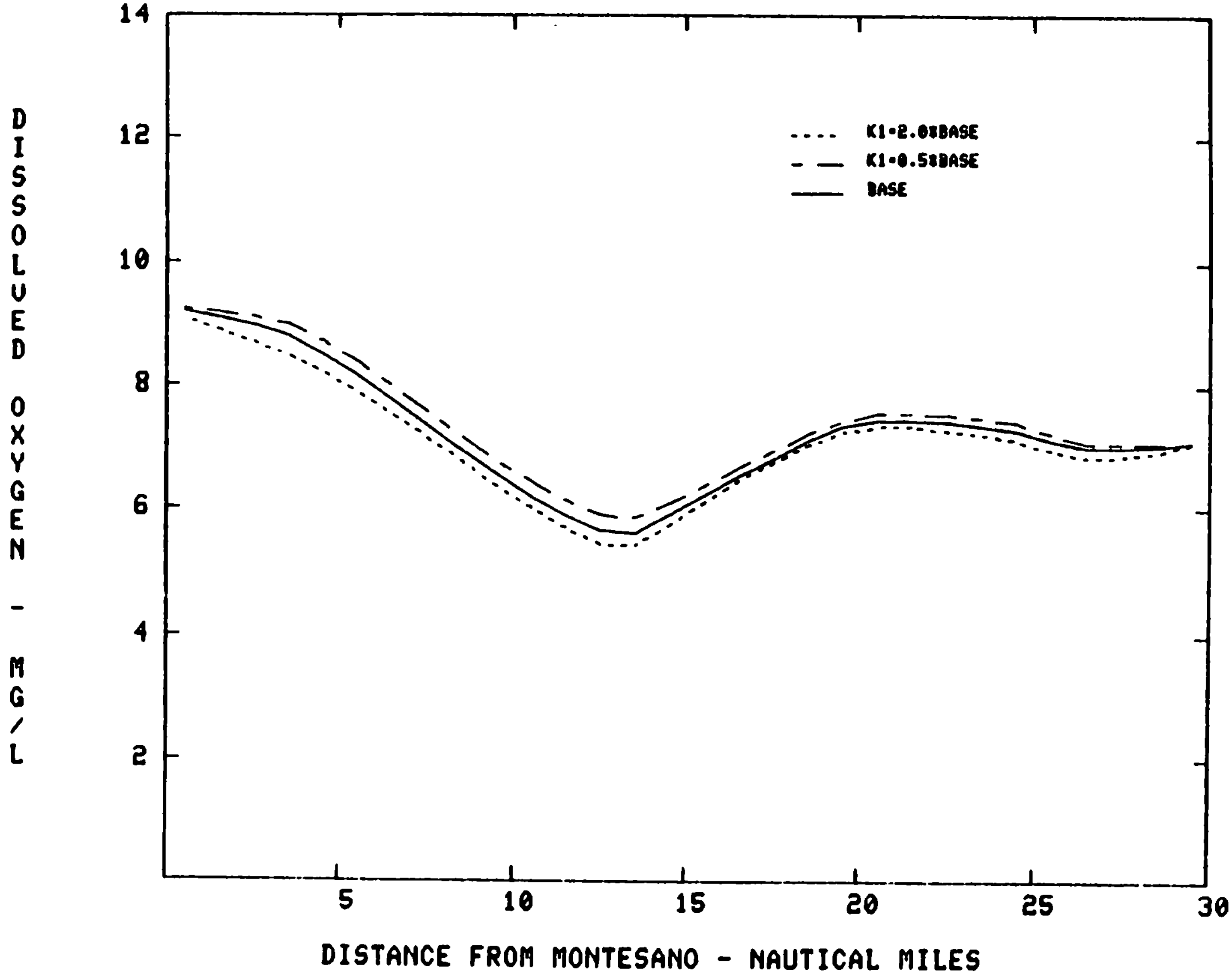


FIGURE 12. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE AMBIENT WATER TEMPERATURE.

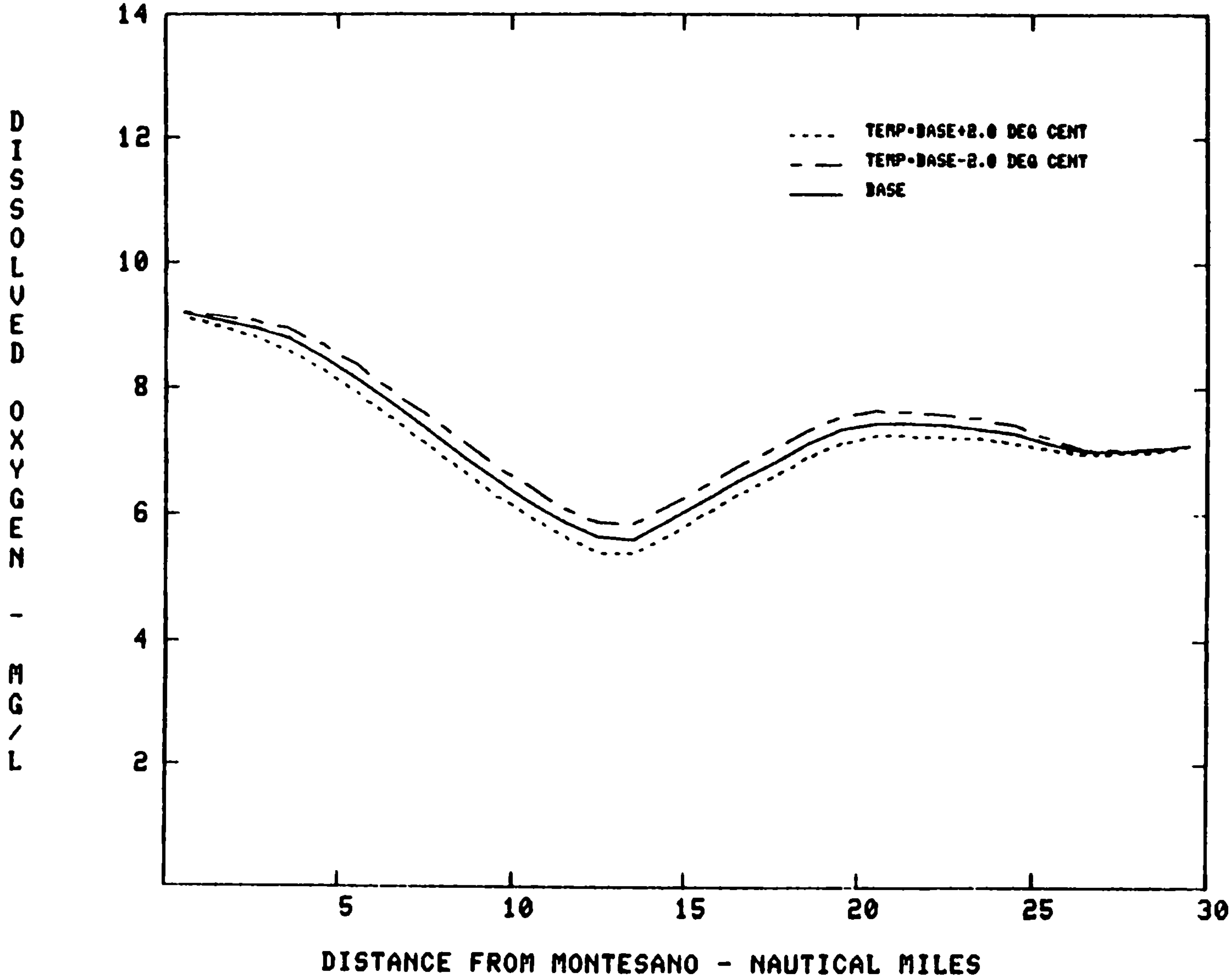


FIGURE 13. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN SEDIMENT OXYGEN DEMAND.

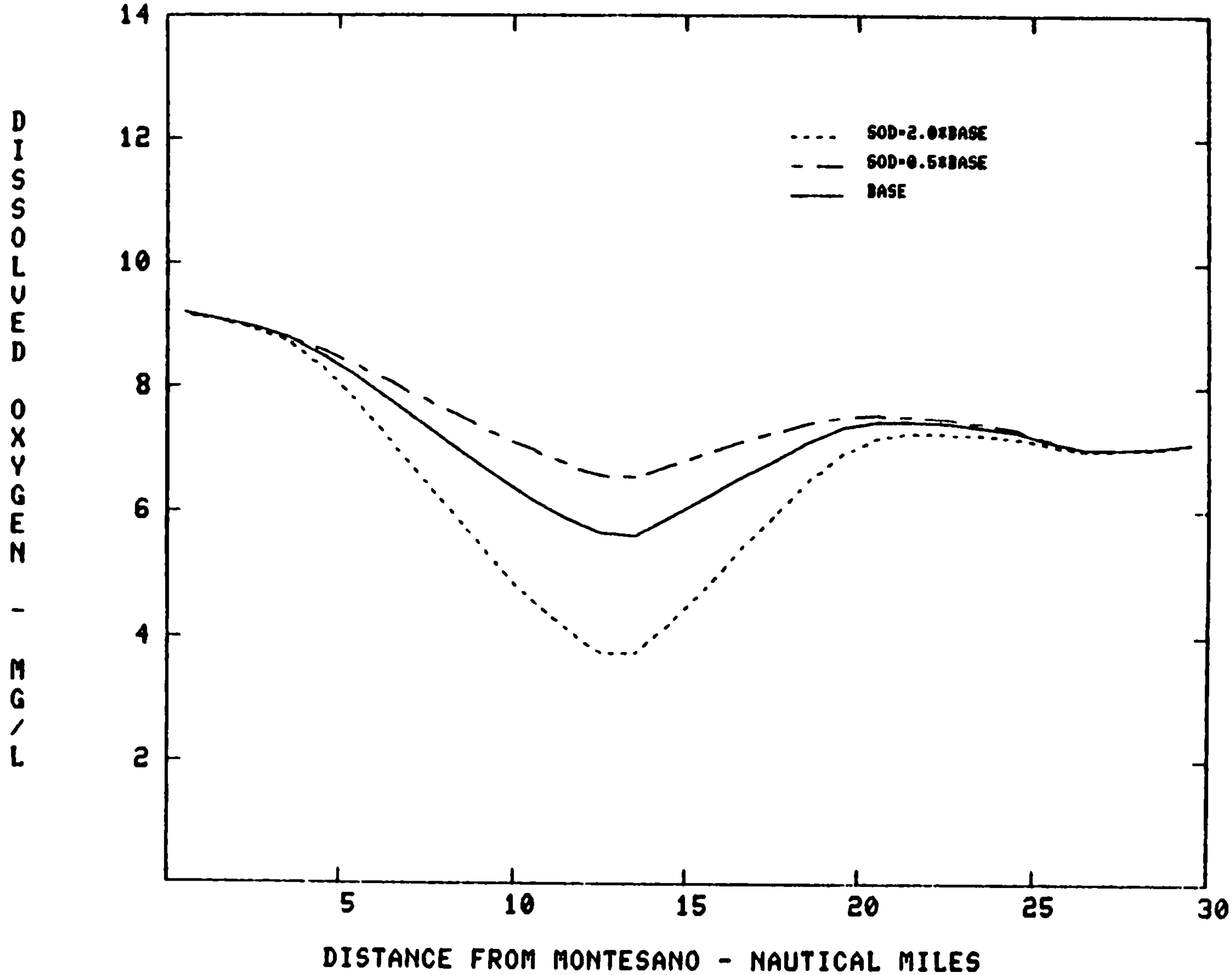


FIGURE 14. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO THE REMOVAL OF B.O.D. AND S.O.D.

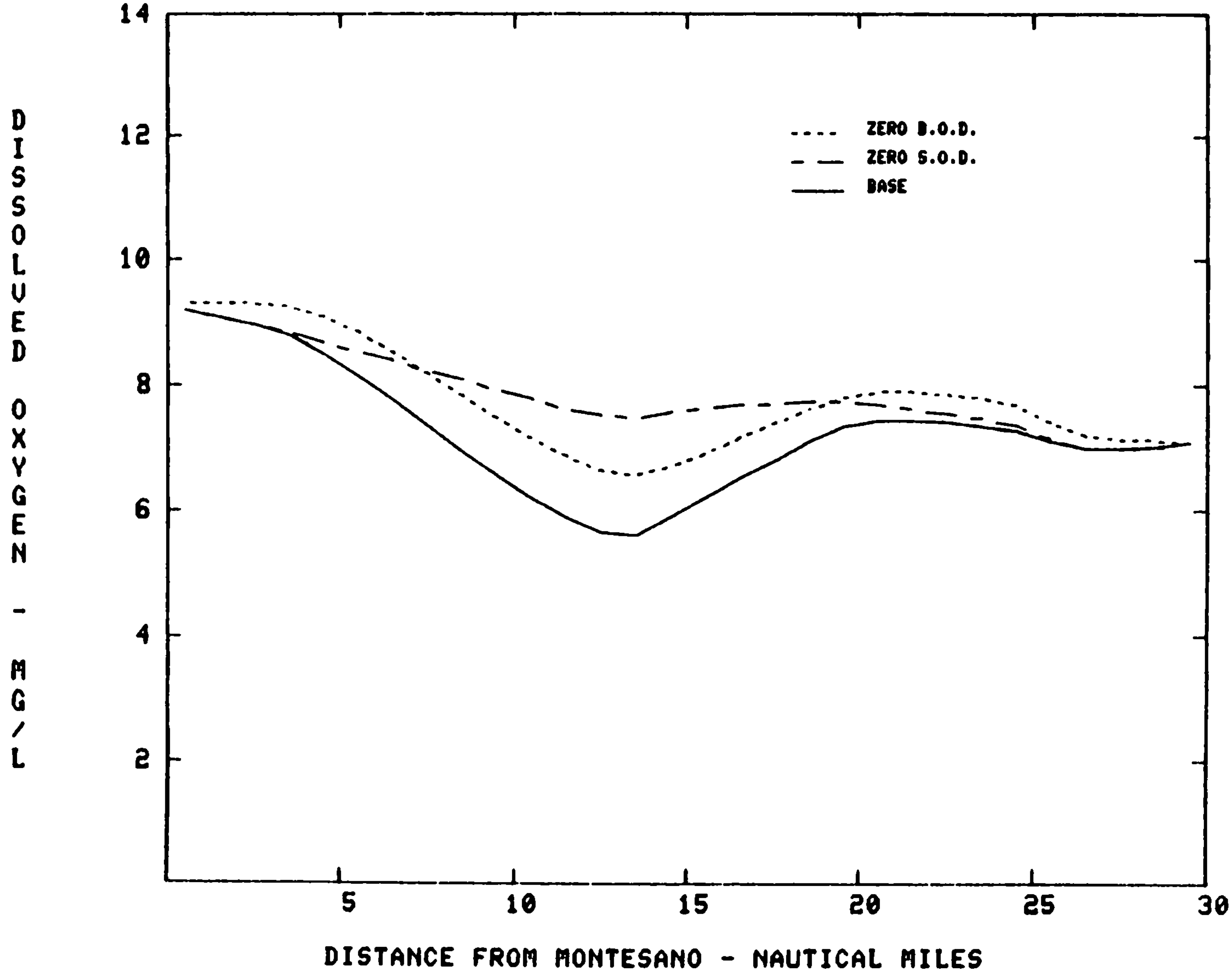


FIGURE 15. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE UPSTREAM B.O.D.

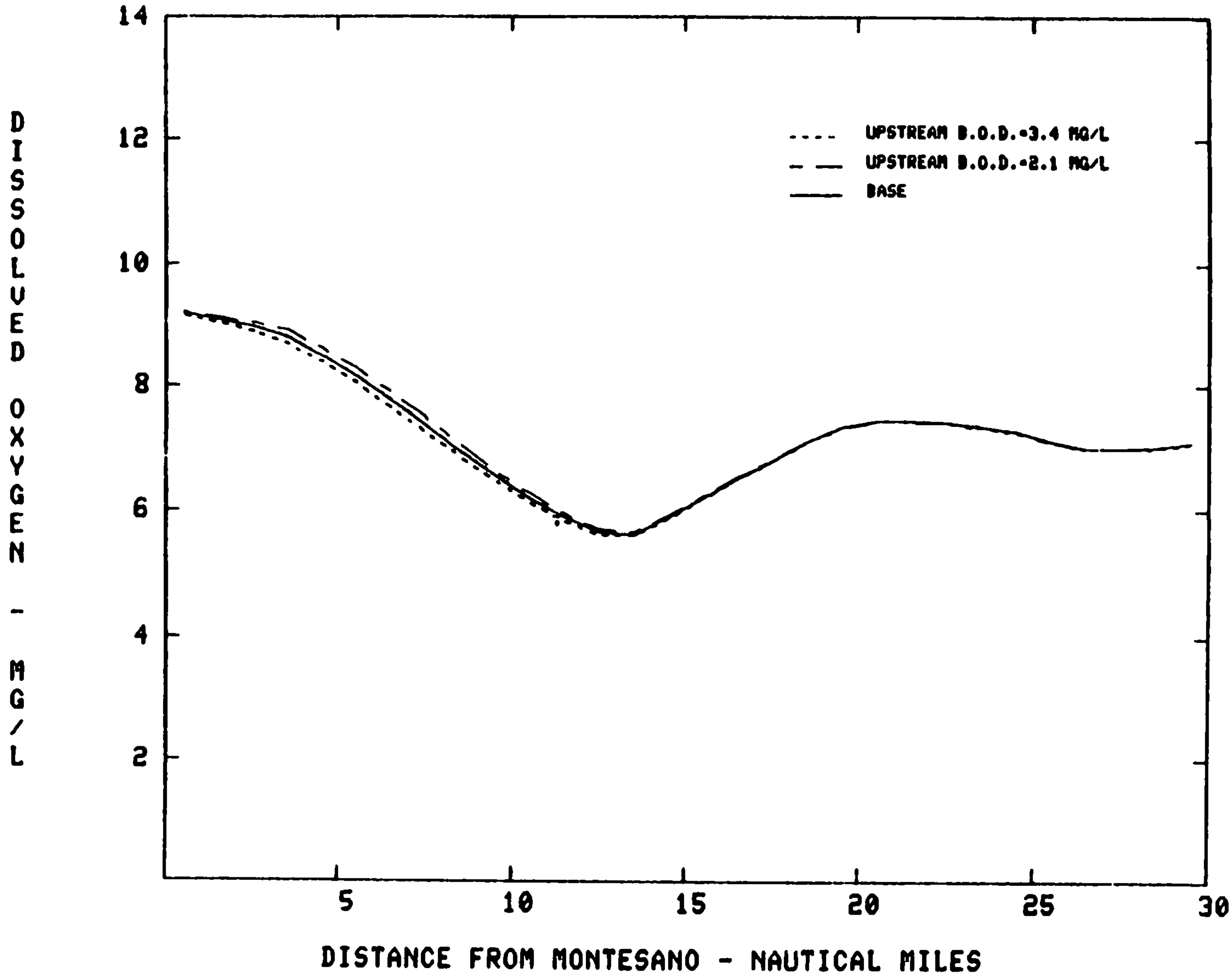


FIGURE 16. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE UPSTREAM DISSOLVED OXYGEN.

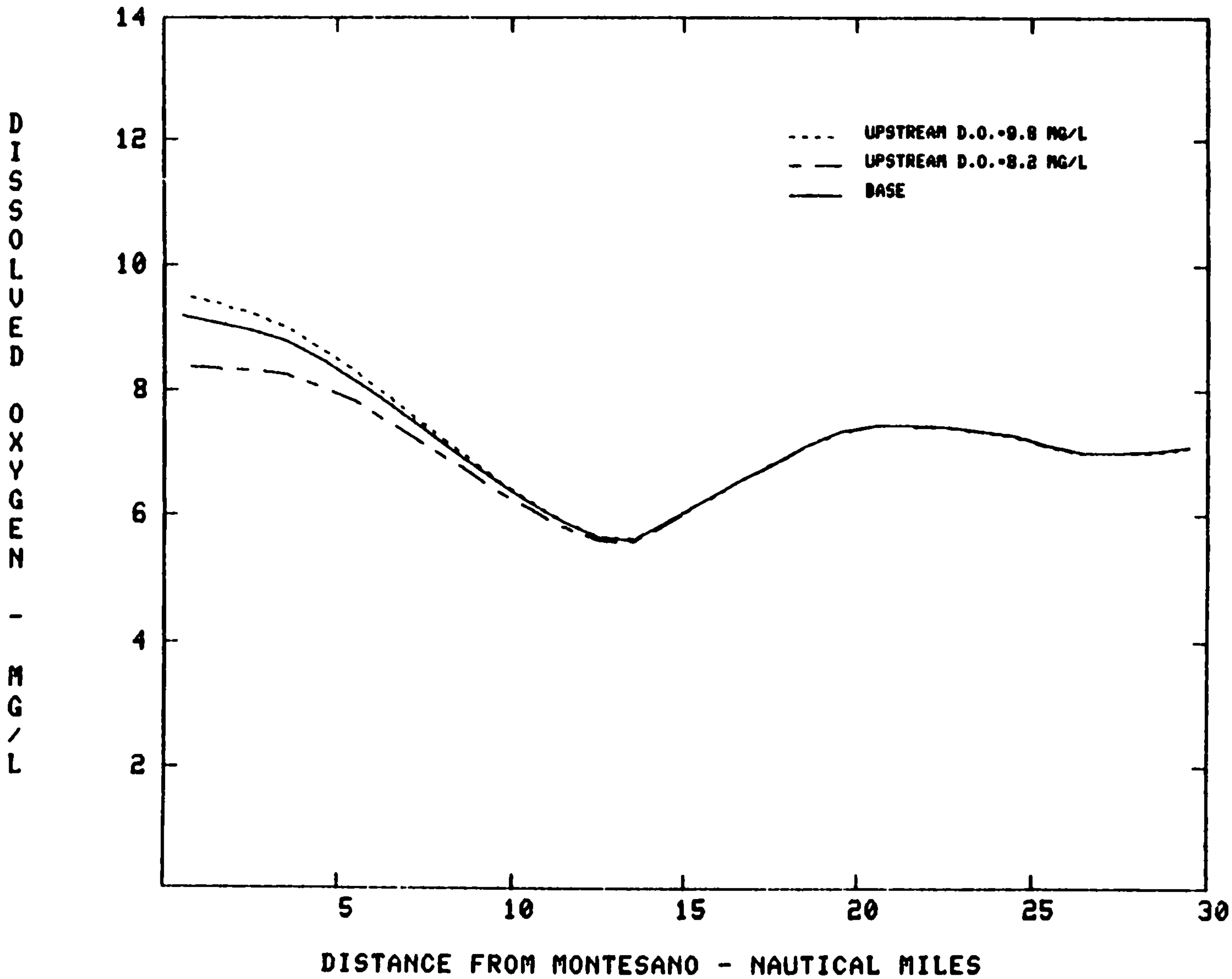


FIGURE 17. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE OCEAN B.O.D.

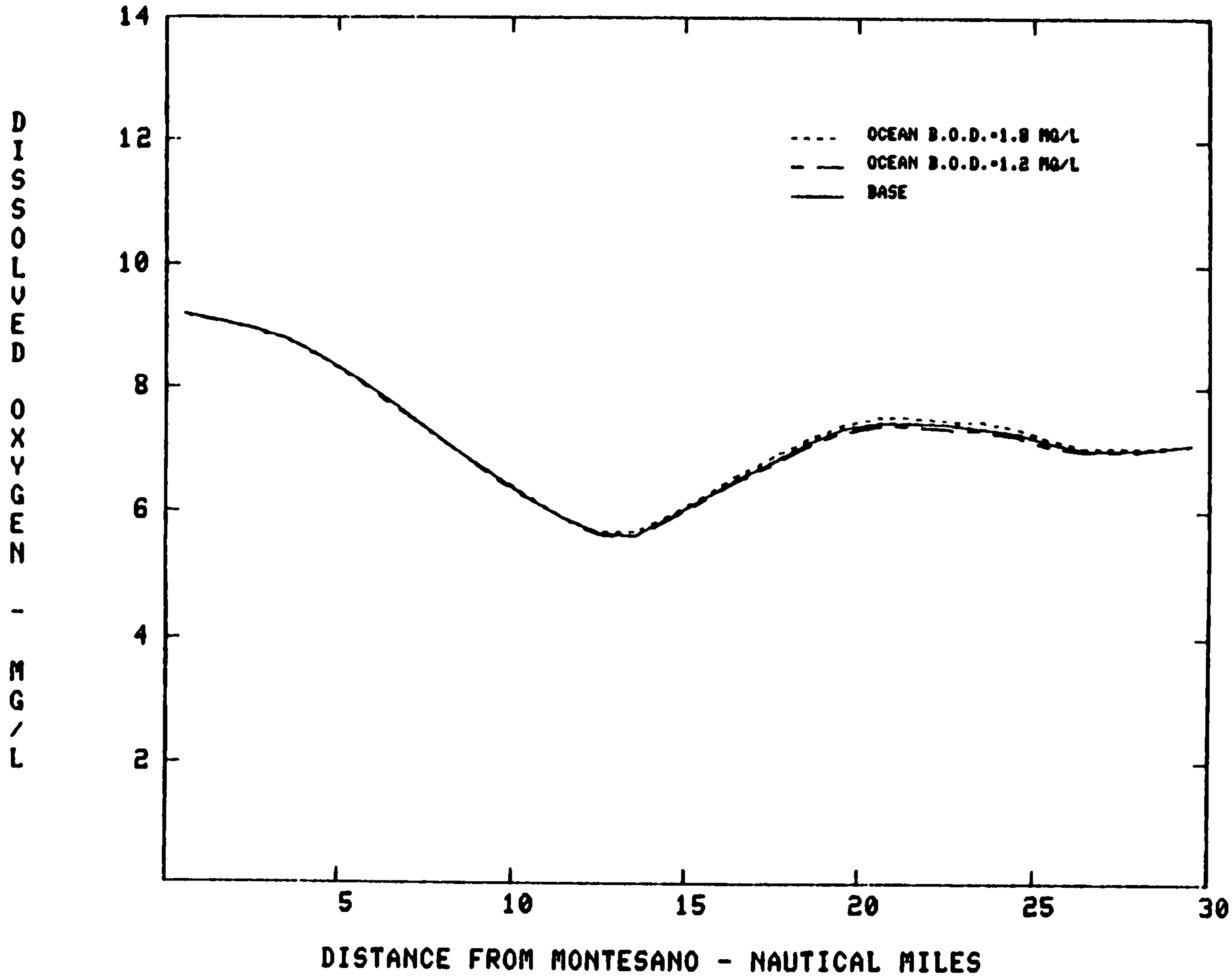
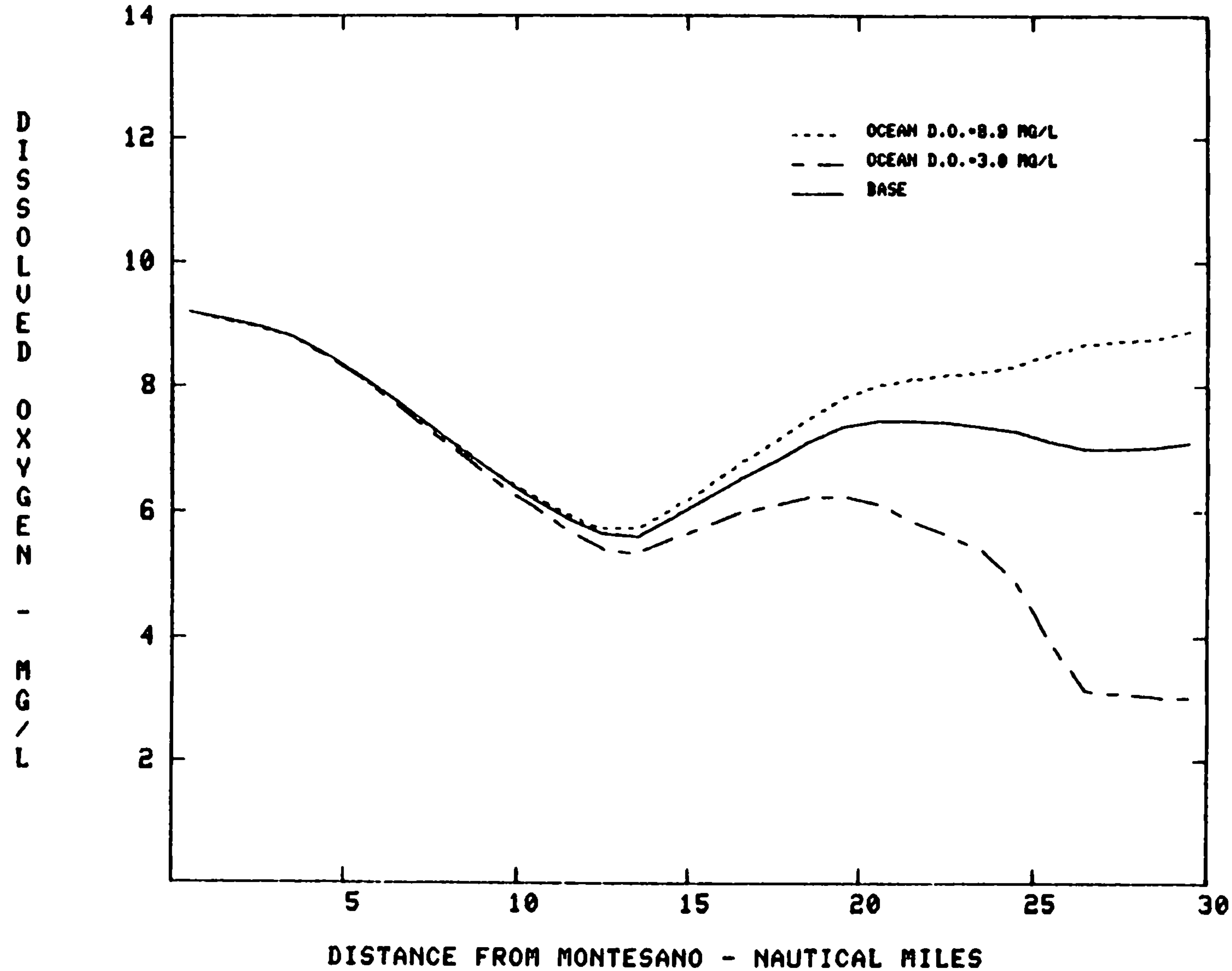


FIGURE 18. SENSITIVITY OF THE STEADY-STATE DIFFUSION MODEL OF GRAYS HARBOR TO CHANGES IN THE OCEAN D.O.



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