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A ONE DIMENSIONAL MATHEMATICAL MODEL OF SANTOS ESTUARY, SANTOS, BRAZIL

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by

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THESIS

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May 31, 1977

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CHAPTER I

INTRODUCTION

NEED FOR STUDY

The municipal area of Greater Santos, Brazil is located in one of the most industrialized areas in Latin America. Santos lies on the coast of the State of Sao Paulo, which produces about 60 percent of Brazil's total national industrial output (World Health Organization, 1974). The wastes produced by this concentration of industry have caused a steady decline in the water quality of the Cubatao River Basin, which includes the Santos estuary. The degree of waste treatment has fallen far behind the rate of industrial growth; few industries in the greater Santos area have any waste treatment facilities.

Recent industrial growth has been accompanied by an influx of people into Greater Santos. The population increased at annual rates of 4.86 and 4.69 percent during the decades of 1950/60 and 1960/70 to a present population of more than 612,000 (World Health Organization, 1974).

Santos is adjacent to the metropolitan area of Greater Sao Paulo, the capital of the state. With a population of 6,900,796 in 1970, this urbanized area is one of the fastest growing industrial areas in the world. It has become the industrial and commercial capital of South America. The recreational facilities of Santos attract many persons from the Sao Paulo area as well as from other parts of South America. Peaks of tourist activity occur during the months of January and Februar and to a lesser degree in July. This variable "floating" population is another factor which has a detrimental effect on the water quality of the area.

Water quality studies are currently being conducted in the Cubatao River, Santos estuary, and Santos Bay. However, a mathematical model is needed to aid the process of making water quality management decisions, such as the question of improving treatment methods in order to increase the quality of the water of the Cubatao River Basin.

OBJECTIVES

The overall purpose of this study was to provide a working one-dimensional mathematical model of water quality in the Santos estuary, which flows from the northern section of Santos to the east, and finally empties into Santos Bay. Specific objectives included: (1) adapting an existing model, QUAL-1, to this estuary; (2) developing the input for the model; (3) estimating the waste loading to the estuary; (4) determining the problems encountered in adapting a one-dimensional model to a stratified two-dimensional flow system; and (5) estimating water quality improvements resulting from increased treatment levels with future growth in the area.

SCOPE

Water quality data from previous field studies were used for calibration of the model. The main parameters used in this study were carbonaceous biochemical oxygen demand (CBOD) which is equivalent to BOD_5, nitrogenous biochemical oxygen demand (NBOD), dissolved oxygen (DO), and salinity. Due to the lack of information concerning waste discharges in the area, locations and quantities of waste loads had to be estimated to match the water quality of the estuary.

After calibration of the model, future growth and treatment levels were applied to predict improvement of water quality with treatment levels that could be expected for municipal and industrial discharges.

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CHAPTER II

LITERATURE REVIEW

INTRODUCTION

This chapter includes a description of QUAL-1, the model used in the simulation of the water quality of the Santos estuary. The main options of the program are summarized, and the basic equations and solution techniques that are used in the model are briefly described.

The second part of this chapter contains information concerning the demographic, economic, and climatological characteristics of the study area, and also a description of the Cubatao River Basin.

MODEL

Development

The original version of QUAL-1 was developed by W. A. White, R. J. Brandes, and Dr. F. D. Masch, in close collaboration with the Texas Water Development Board during the period September, 1969 to September, 1970.

Program Options

The version of QUAL-1 used in this study is made up of a set of interrelated water quality models capable of routing through a stream subsystem the following water quality parameters:

(1) temperature,
(2) biochemical oxygen demand (carbonaceous and nitrogenous) and dissolved oxygen, and
(3) one conservative material.

Any combination of these three models can be used in the simulation, but for this study only the BOD and DO and conservative material models were used to predict the water quality of the Santos estuary.

Several other options are available to the user. If desirable, the flow augmentation option can be used to determine the dilution water requirements necessary to meet a specified dissolved oxygen level. Another option exists for the addition of incremental runoff to the system. Steady-state or dynamic solutions are possible, and spatial and temporal descriptions of the water quality parameters can be included in the output from the model.

An additional subroutine was added to the model which produced a plot of observed and predicted values of dissolved oxygen, carbonaceous biochemical oxygen demand, and salinity.

Modification of Existing Program

One change was made to the model to provide for a better approximation of an estuarine system. In the subroutine HYDRAU, the dispersion coefficient is calculated for each reach. The original version of the equation as applied to systems whose transport is governed by advection is as follows:

$$D_L = 22.6\ (n)\ (U)\ (H)^{0.833} \tag{1}$$

where:

D_L= longitudinal dispersion coefficient, ft^2/sec,

n = Mannings roughness coefficient,

U = mean velocity, ft/sec, and

H = mean depth, ft.

This equation was replaced in the model by the equation for dispersion as applied to systems whose transport is governed by dispersion, as shown below:

$$D_L = U/n' \qquad (2)$$

where:

D_L= longitudinal dispersion coefficient, ft^2/sec,

U = mean stream velocity, ft/sec, and

n'= slope of semilogrithmic plot of salinity concentration versus distance downstream, ft^{-1} (base e).

The value of D_L was then used in calculations in the basic equation describing the mass transport of conservative and non-conservative constituents, assuming steady-state, non-uniform flow:

$$\underset{(i)}{A\frac{\partial C}{\partial t}} = \underset{(ii)}{\frac{\partial (AD_L\frac{\partial C}{\partial x})}{\partial x}} + \underset{(iii)}{\frac{\partial (AUC)}{\partial x}} + \underset{(iv)}{A"S"} \qquad (3)$$

where:

A = cross-sectional area of the stream, ft^2,

C = concentration of the constituent, mg/l, or temperature, ^oF,

U = mean velocity of the stream, ft/sec,

D_L= longitudinal dispersion coefficient, ft^2/sec,

t = some point in time, sec,

x = some point along the longitudinal axis of the stream (x-axis), ft, and

"S"= sources or sinks of a nonconservative constituent, mg/l, or termperature, ^oF.

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In the equation above, term (i) represents the temporal change in concentration, term (ii) represents the transport due to longitudinal dispersion, term (iii) represents the transport due to longitudinal advection, and term (iv) represents the sources or sinks if the constituent is nonconservative (Texas Water Development Board, 1971). This equation is solved by the model for CBOD, NBOD, DO, temperature, and salinity.

For BOD calculations the "S_{BOD}" term can be expressed as follows:

$$"S_{BOD}" = -(K_x + K_3)\ L \tag{4}$$

where:

"S_{BOD}" = net BOD (carbonaceous or nitrogenous) source or sink, mg/l/sec,
K_x = K_1 (CBOD) or K_4 (NBOD), BOD removal, day^{-1},
K_3 = BOD removal by deposition, day^{-1}, and
L = concentration of ultimate BOD (carbonaceous or nitrogenous), mg/l.

For DO calculations, the "S_{DO}" term can be expressed as follows:

$$"S_{DO}" = K_2\ (C_s - C) - (K_1 L_{CBOD} + K_4\ L_{\ NBOD} + K_5/H) \tag{5}$$

where:

"S_{DO}" = net DO source or sink, mg/l/sec,
K_2 = reaeration rate, day^{-1},
C_s = solubility of oxygen in water, mg/l,
C = concentration of DO, mg/l,
K_1 = CBOD deoxygenation rate, day^{-1},

L_{CBOD} = concentration of CBOD (ultimate), mg/l,

K_4 = NBOD deoxygenation rate, day^{-1},

L_{NBOD} = concentration of NBOD (ultimate), mg/l,

K_5 = benthic demand, grams $0_2/m^2$/day, and

H = mean stream depth, ft.

The program performs the necessary transformations of units to assure that the source or sink term is in the units of mg/l/second.

Assumptions

Major assumptions used in the development of the model are:

(1) the major transport mechanisms, advection and dispersion, are significant only along the main direction (longitudinal axis) of the stream; and

(2) the stream is flowing at nonuniform, steady-state conditions.

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STUDY AREA

Introduction

The city of Santos is located on the southeastern coast of the State of Sao Paulo, Brazil. The city lies at approximately 23° 57' south latitude and 46° 24' west longitude. The Santos estuary and its tributaries drain most of the adjoining area to the north and west of Santos, and the waters of the estuary flow through Santos Bay to the Atlantic Ocean. A map of the section of the estuary that was modeled in the study is shown in Figure 1.

Municipalities

Greater Santos is composed of six municipalities: Santos, Sao Vincente, Guaruja, Cubatao, Praia Grande, and Mongagua. Table 1 shows the population of these cities from 1950 to 1970. More than three-fourths of the resident population of the Greater Santos area for the year 1970 was concentrated in the cities of Santos and Sao Vincente, which border the estuary on the south.

Economy

The Santos area attracts many tourists from all parts of South America and the world. The beaches that border the bay along Santos and Sao Vincente and the ocean beaches of Praia Grande, Guarja, and Mongagua provide recreational opportunities throughout the year. The "floating" population associated with the tourist industry has a major effect on the economy of the area. Tables 2, 3 and 4 give a comparison of the estimated resident and "floating" populations of Greater Santos for the

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FIG. 1. LOCATION OF STUDY AREA

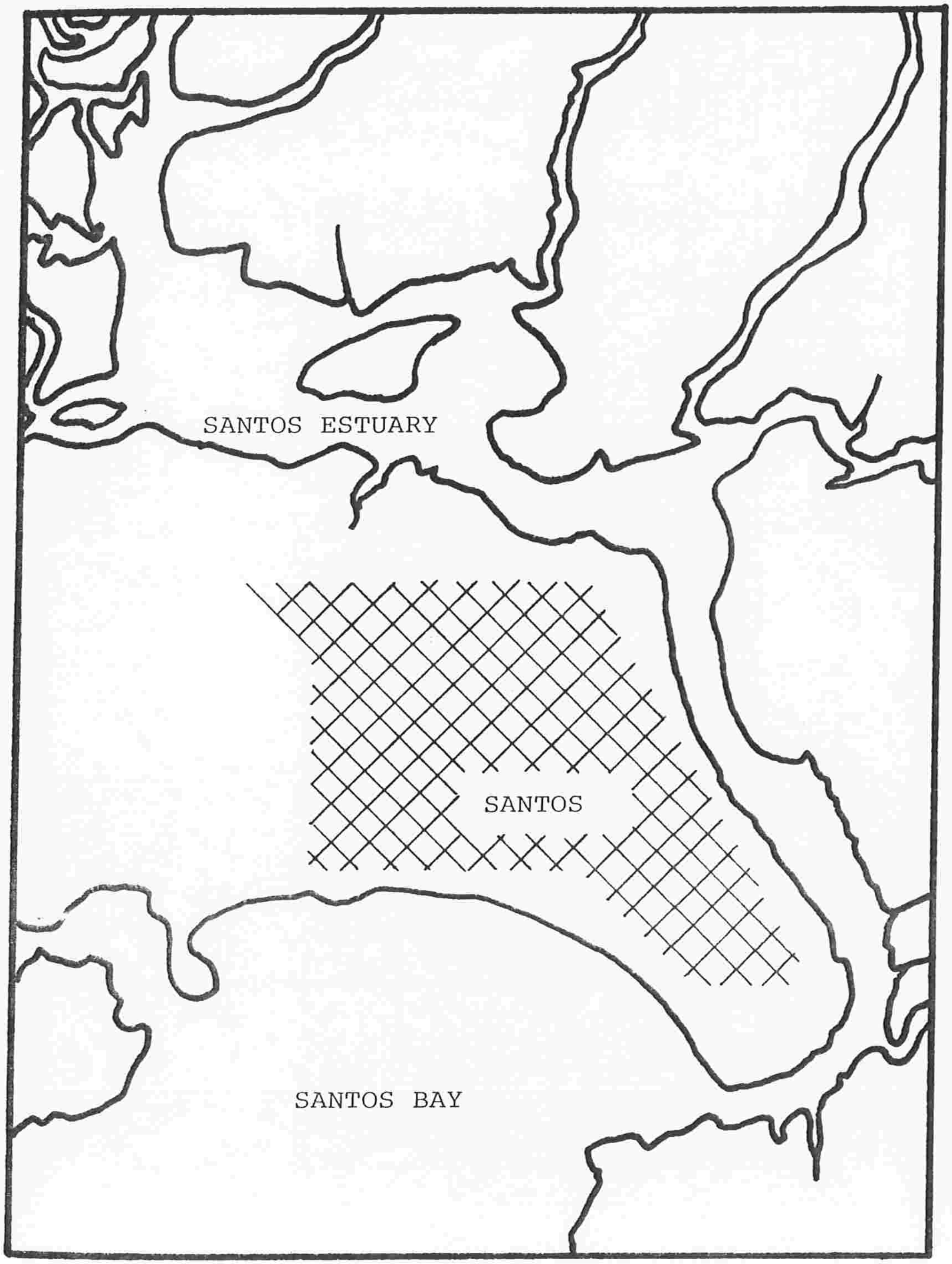

TABLE 1

RESIDENT URBAN POPULATION IN GREATER SANTOS

(1950/1970)

Municipality	1950		1960		1970	
	Absolute Numbers	Percent of Total	Absolute Numbers	Percent of Total	Absolute Numbers	Percent of Total
Santos	196,588	81.6	259,888	67.2	343,890	56.1
Sao Vincente	26,163	10.9	68,960	17.8	116,075	19.0
Guaruja	8,885	3.7	30,291	7.8	90,508	14.8
Cubatao	6,407	2.7	18,828	4.9	37,255	6.1
Praia Grande	1,915	0.8	7,412	1.9	19,757	3.2
Mongagua	819	0.3	1,621	0.4	4,683	0.8
TOTALS	240,777	100.0	387,000	100.0	612,168	100.0

Source: World Health Organization, 1974

TABLE 2

URBAN RESIDENT AND "FLOATING" POPULATION

IN GREATER SANTOS - 1970

Municipality	Resident Population	Percent of Total	"Floating" Population	Percent of Total	Total Population
Santos	343,890	71.1	139,578	28.9	483,468
Sao Vincente	116,075	59.1	80,462	40.9	196,537
Guarja	90,508	69.9	38,902	30.1	129,410
Cubatao	37,255	100.0	-00-	0.0	37,255
Praia Grande	19,757	11.5	151,592	88.5	171,349
Mongagua	4,683	16.7	23,329	83.3	28,012
TOTAL	612,168	58.5	433,863	41.5	1,046,031

Source: World Health Organization, 1974

TABLE 3

URBAN RESIDENT AND "FLOATING" POPULATION IN GREATER SANTOS - 1985 (ESTIMATE)

Municipality	Resident Population	Percent of Total	"Floating" Population	Percent of Total	Total Population
Santos	507,508	73.7	180,882	26.3	688,390
Sao Vincente	212,668	67.7	101,540	32.3	314,208
Guarja	250,523	78.7	67,702	21.3	318,225
Cubatao	81,741	100.0	-00-	0.0	81,741
Praia Grande	50,548	15.5	275,645	84.5	326,193
Mongagua	13,145	20.8	50,176	79.2	63,321
TOTAL	1,116,133	62.3	675,945	37.7	1,792,078

Source: World Health Organization, 1974

TABLE 4

URBAN RESIDENT AND "FLOATING" POPULATION IN GREATER SANTOS - 2000 (ESTIMATE)

Municipality	Resident Population	Percent of Total	"Floating" Population	Percent of Total	Total Population
Santos	724,177	76.4	223,153	23.6	947,330
Sao Vincente	344,207	73.7	123,063	26.3	467,270
Guarja	426,790	79.8	107,826	20.2	534,616
Cubatao	134,245	100.0	-00-	0.0	134,245
Praia Grande	100,213	16.5	506,796	83.5	607,009
Mongagua	28,651	23.7	92,254	76.3	120,905
TOTAL	1,758,283	62.5	1,053,092	37.5	2,811,375

Source: World Health Organization, 1974

years 1970, 1985, and 2000.

The industrial center of Greater Santos is located in the municipality of Cubatao. Inorganic and organic chemicals, pulp and paper, oil refinery, textile, fertilizer, plastics, and heavy metal wastes are included in the pollutants that are discharged to the Cubatao River Basin, and many smaller industries contribute to the pollutant loading of the area.

The harbors of Greater Santos provide an excellent place for national and international trade. A dredged channel enables access for twelve miles upstream from the point where the estuary enters the bay, and shipping and related port activities continue to grow each year.

Several factors enhance the development of industry in Greater Santos. The proximity of the city of Sao Paulo provides a large consumer base for the products of the area. The largest seaport in the nation is centered in Santos, and rail and highway links with other parts of the country make inland trade possible. The Henry Borden Power Plant provides a continuous source of electric power, and the Cubatao River gives an available fresh water source for the municipalities and industries of the area.

Factors that inhibit industrial growth also exist. These elements include a shortage of land for industrial development, flooding problems, and water pollution and flow variations in the Cubatao River due to power generation from the waters of the Billings Reservoir.

Climate

The climate of the Greater Santos region is hot and humid, without a distinct dry season. Due to its location in the Southern Hemisphere, the seasons of summer and winter are reversed from their expected order in the Northern Hemisphere. The average annual temperature is about 68^{o} F (20^{o} C), and the average yearly rainfall is approximately 79 inches (The New Encyclopaedia Britannica, 1976).

Cubatao River Basin

The freshwater portion of the Cubatao River is approximately fifteen miles long and drains 54 square miles of land area. The main flow of the river results from the discharge of water from Billings Reservoir during power generation. The reservoir is fed in part by the Tiete River, and this interbasin transfer of water comprises about 95 percent of the flow in the Cubatao River. The power plant flow used in this study was 2772 cubic feet per second.

Background flow in the Cubatao River is measured at a point approximately 1.5 miles upstream from the power plant discharge. The average flow at this point for the purposes of this study was 159 cubic feet per second, which was 5.4 percent of the total flow of the river.

The quality of the Cubatao River is poor after the flow from the power plant enters the stream. Anaerobic conditions have been documented in the 1,206 million cubic meter (319,000 million gallons) maximum capacity Billings Reservoir for a distance of nine miles upstream from the dam (World Health

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Organization, 1974). The water flows in pipes to the power plant as it drops approximately 700 meters (2300 feet) in a distance of about 2.5 miles, and the flow of the Cubatao River after the discharge is enriched in nutrients and deficient in dissolved oxygen (Rohlich, 1976).

The estuarine portion of the Cubatao River basin begins approximately 3.7 miles downstream from the power plant discharge. As can be seen in Figure 1, for a distance of three miles the river passes through a swampy area, and the flow is dissipated into several directions, all of which flow into the Santos estuary within a distance of two miles along the estuary.

The Santos estuary is 11.75 miles long and empties into Santos Bay. The Cubatao River is the major freshwater flow into the estuary, and several smaller streams enter along its length. The streams considered to be significant in this study were: Rio Mogi, Rio Quilombo, Rio Jurubatuba, Rio Sandi, Rio Diana, Rio S. Amaro, Rio do Meio, and Rio Icanhema.

A channel has been dredged in the upper sections of the estuary to allow passage to and from the industrial complex near the city of Cubatao. The channel begins approximately 6.75 miles upstream from the mouth of the estuary, and is five miles long. The dredged portion averages 10 meters (32.8 feet) in depth and extends 1.5 miles upstream from the last freshwater inflow of the Cubatao River.

CHAPTER III

METHODS

INTRODUCTION

The method used in the application of QUAL-1 to the Santos estuary consisted of: (1) segmenting the system to reproduce the geometric and hydrogeometric properties of the stream system; (2) defining the hydrologic inputs to the system; (3) defining the water quality inputs to the system; and (4) calibrating the model as closely as possible to existing data.

Two additional analyses were performed. After the model was calibrated, the sensitivity of the water quality output was investigated by varying certain inputs in order to determine the controlling factors of the system. Also, a prediction of water quality resulting from improved waste treatment was completed for the years 1985 and 2000.

SEGMENTATION

The first step in the application of QUAL-1 to the Santos estuary was to divide the system into reaches. Each reach contained at least one computational element, that was 0.25 miles in length. Depth profiles were constructed from data taken from a 1973 map of the Port of Santos, the most recent available (Defense Mapping Agency Hydrographic Center, 1973). Due to the shallow portions of the estuary on either side of the dredged channel and at the mouths of entering tributaries, measurements were considered insignificant if the depth was more shallow than one meter in those areas. From these depth profiles at each quarter mile point, average depths and cross-sectional areas for each computational element were calculated.

Similar characteristics of these two parameters were used in the division of the system into reaches. Average values of depth and cross-sectional area were then calculated over each reach using each quarter mile section as one data point. If necessary, these reaches were subdivided later to accomodate large flows that would cause erroneous depth and velocity computations by the program. Table 5 shows the division of the system into reaches, average depths and cross-sectional areas for each reach, and the flow and velocities that were estimated at the heads of each reach.

HYDROLOGY

Flow

An average flow of 2772 cubic feet per second for the power plant discharge and an estimated average flow of 159 cubic feet per second at the gauge on the Cubatao River were used in this study.

Flows for other tributaries to the estuarine system were estimated as follows. The area drained by the Cubatao River and its tributaries upstream from a gauge that is located 1.5 miles upstream from the power plant discharge was estimated by planimeter. The measured flow per unit area was computed to be 4.01 cubic feet per second per square mile. The remaining drainage area downstream from the gauge to the point of entrance into Santos estuary was determined, and the total freshwater flow for the Cubatao River was calculated. Drainage areas for other tributaries to the estuary were measured, and their freshwater

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TABLE 5

REACH INFORMATION

Reach	Upstream Mile at Beginning of Reach	Average Flow (cfs) Winter	Average Flow (cfs) Summer	Average Cross-Sectional Area (ft^2)	Average Depth (ft)	Average Velocity (ft/sec)
Zero*	12.00	1051.1	1043.7	-	-	0.020
One	11.75	1051.1	1043.7	53,900	32.8	0.020
Two	11.50	2030.5	2015.7	12,900	19.0	0.157
Three	11.00	2154.7	2139.9	11,300	22.2	0.191
Four	10.25	3134.1	3111.9	15,300	16.2	0.205
Five	8.75	3136.2	3114.0	41,000	18.9	0.077
Six	7.00	3231.1	3208.9	64,100	24.8	0.050
Seven	4.75	3258.4	3236.2	50,900	31.0	0.064
Eight	3.00	3269.7	3247.5	75,400	35.7	0.043
Nine	1.75	3280.9	3258.7	53,300	35.8	0.062
Ten*	0.00	5032.1	5009.9	-	-	-

*Outside boundaries of the study area.

flows were computed in like manner.

The municipalities of Santos, Sao Vincente, and Cubatao take their public water supply from the Cubatao River. To estimate the withdrawal from the River, a value of 50 gallons per capita per day was assumed as an average sewage flow rate, and this value was assumed to be 75 percent of the public water supply demand (Azevedo, 1975). These values yielded an estimate of 66.7 gallons per capita per day for withdrawal purposes. For summer conditions in the model, the resident and "floating" population figures were considered.

The undefined flow characteristics and channel boundaries of the Cubatao River prior to discharge into the Santos estuary made it necessary to split the flow into three sections. The flow was divided evenly between the three inputs after the background flow for the Cubatao River and the water supply withdrawal had been taken into consideration. Freshwater flows used as seasonal inputs for the model are listed in Table 6.

Several saline tributaries, including the Canal de Bertioga and Rio Casquiero, were not considered as inputs to the system. The net effect of the flow of tributaries of this type was considered as zero and not applicable to the simulation of time-averaged water quality as predicted by the model.

The first 0.5 mile of the Bay was represented by the last reach in the system. The volume of this portion of the Bay was 13.2 million cubic feet (989 million gallons), and the salinity was 32.1 parts per thousand. The amount of material in the Bay that was allowed to disperse into the estuary was controlled

TABLE 6

FRESHWATER INFLOWS

Freshwater Input	Mile at Which the Tributary Enters the Estuary	Drainage Area (Square Miles)	Flow (cfs) Summer	Flow (cfs) Winter
Rio Mogi	11.75	17	71.7	71.7
Rio Cubatao 1	11.75	54.0*	972.0	979.4
Rio Cubatao 2	11.50	-	972.0	979.4
Rio Quilombo	11.00	31.0	124.2	124.2
Rio Cubatao 3	10.25	-	972.0	979.4
Rio Jurubatuba	7.00	20.7	82.9	82.9
Rio Sandi	5.75	1.27	5.1	5.1
Rio Diana	5.25	5.82	23.3	23.3
Rio South Amaro	1.25	2.11	8.5	8.5
Rio do Meio	0.75	0.762	3.1	3.1
Rio Icanhema	0.50	0.707	2.8	2.8

*Includes the total drainage area of Rio Cubatao.

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by the dispersion coefficient in the last reach.

The average tide range was found to be 1.48 feet (Defense Mapping Agency Hydrographic Center, 1973). The amount of water exchanged on a tidal cycle was calculated by the following method. The average tidal velocity near the mouth of the estuary was found by using a value of 70 percent of the maximum tidal velocity over either the flooding or ebbing tide (Armstrong, 1976). The maximum ebbing tidal velocity was used in this study. The average velocity was then multiplied by the cross-sectional area at the mouth of the estuary to obtain a flow of 41,500 cubic feet per second. This figure was then multiplied by the period of one tidal cycle, six hours (Armstrong, 1976). A value of 893 million cubic feet (6680 million gallons) resulted from these computations.

The total volume of the estuary was found to be 2870 million cubic feet. Dividing the tidal volume by the total volume of the estuary yielded a result of 0.31 for the theoretical fraction of tidal volume in the estuary. Assuming an actual exchange of ten percent of this value as in other estuaries (Armstrong, 1976) only 3.1 percent of the estuary water is lost to the Bay.

Velocity and Depth Coefficients

Velocity is computed in QUAL-1 by the formula:

$$U = aQ^b \qquad (6)$$

where:

U = mean velocity in the stream, ft/sec,

Q = mean stream flow, ft^3/sec,

a = velocity coefficient, and

b = velocity exponent.

Absence of data prevented analysis of flow - velocity relationships, and therefore the exponent of the equation was assumed to have a value of unity. The inverse value of the cross-sectional area for each reach was used as input for the velocity coefficient.

Depth is calculated in QUAL-1 by the equation:

$$H = cQ^d \tag{7}$$

where:

H = mean stream depth, ft,

Q = mean stream flow, ft^3/sec,

c = depth coefficient, and

d = depth exponent.

Flow versus depth data were not available, and the exponent of the equation was assumed to have a value of one. The depth coefficient for the model was computed as the quotient of the average depth calculated and the average flow over the length of each reach.

WATER QUALITY

Introduction

The amount of water quality data available for the Santos estuary was small. Average values and ranges of observed data used in this study are given in Table 7.

Salinity

Salinity data were available at nine stations in the estuary (CETESB, 1976). Measurements were taken at one meter

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TABLE 7

SUMMARY OF WATER QUALITY DATA

		DISSOLVED OXYGEN							
		SUMMER			WINTER				
STATION	MILE	AVERAGE	80% CONFIDENCE LIMITS		AVERAGE	80% CONFIDENCE LIMITS		TEMP. °C	SALINITY PPT
1	11.25	3.1	1.8	4.5	2.4	0.0	4.9	25.7	24.5
3	10.25	3.9	3.7	4.1	4.5	3.2	5.7	23.0	26.3
4	9.75	3.6	2.1	5.0	4.9	4.1	5.7	25.1	--
5	9.00	3.8	2.6	5.0	4.6	2.7	6.5	25.4	--
7	8.75	4.0	3.0	5.0	4.9	3.2	6.6	25.7	24.7
9	7.75	4.3	2.0	8.6	4.5	2.9	6.1	26.0	26.4
12	6.50	3.4	2.8	4.1	4.3	2.8	5.8	25.7	28.2
13	5.50	4.3	3.4	5.2	4.6	3.4	5.7	25.7	26.6
15	4.25	4.2	3.6	4.8	5.0	4.5	5.5	25.7	27.8
16	2.25	4.0	1.5	6.5	5.2	4.5	5.9	26.0	27.1
17	1.25	6.0	4.5	7.4	5.4	4.5	6.4	26.0	--
18	0.00	5.2	4.4	6.1	6.0	4.8	7.3	26.0	31.5

TABLE 7 (CONTINUED)

SUMMARY OF WATER QUALITY DATA

STATION	MILE	CBOD SUMMER AVERAGE	SUMMER 80% CONFIDENCE LIMITS		CBOD WINTER AVERAGE	WINTER 80% CONFIDENCE LIMITS	
1	11.25	1.3	0.3	2.3	1.2	0.7	1.7
3	10.25	1.6	1.2	2.0	2.0	-0.2	4.1
4	9.75	1.5	0.8	2.3	1.5	1.1	1.9
5	9.00	1.4	0.5	2.2	0.9	0.6	1.1
7	8.75	1.1	0.1	2.1	0.9	0.5	1.4
9	7.75	2.0	0.9	3.0	1.2	0.2	2.2
12	6.50	1.4	0.8	1.9	1.0	0.6	1.4
13	5.50	2.7	0.1	5.3	1.2	1.0	1.4
15	4.25	1.8	1.1	2.4	1.0	0.6	1.5
16	2.25	2.1	-0.2	4.5	0.9	0.6	1.3
17	1.25	2.0	0.8	3.3	0.9	0.1	1.6
18	0.00	1.4	0.9	1.8	0.8	0.3	1.3

intervals starting at a depth of one meter and also a reading at a depth of 0.3 meters below the surface. Weighted average data over the entire depth at each station were used as input values for the calibration of the model. Average salinity readings ranged from 24.5 parts per thousand at mile 11.25 to 31.5 parts per thousand at the mouth.

The dispersion coefficient over the length of the estuary was then calculated. A plot was constructed of the natural logarithm of the salinity versus the distance downstream from the uppermost reach of the study area. The average velocity in feet per second over the study area was divided by the slope of the semi-logrithmic plot, after conversion of the slope from miles^{-1} to feet^{-1}. This yielded the dispersion coefficient in square feet per second.

Due to the intense salinity stratification in the estuary, salinity data were treated in three ways: (1) using the 0.3 meter depth salinity values only; (2) using a weighted average over the first five meters at each station; and (3) using a weighted average over the entire depth at each station. The results of these calculations are shown in Table 8. The dispersion coefficient computed using the weighted salinity data over the entire depth was used as a first approximation to the actual field conditions.

Temperature

Temperature data were available at twelve stations over the area of the estuary (CETESB, 1976). The data consisted of four pairs of samples at each station. One sample was taken

TABLE 8

DISPERSION COEFFICIENTS FOR SANTOS ESTUARY

Data Used	Slope of Semilogarithmic Plot (Base e) ft^{-1}	Dispersion Coefficient ft^2/sec	mi^2/day
0.3 meters below the surface only	1.91×10^{-5}	6.63×10^{3}	20.5
Weighted average over the top five meters	7.03×10^{-6}	1.12×10^{4}	34.7
Weighted average over the entire depth	3.24×10^{-6}	2.43×10^{4}	75.3

at the surface and another one meter from the bottom. The temperature data were grouped seasonally and averaged for each station; these station seasonal averages were then averaged over each reach.

Biochemical Oxygen Demand and Dissolved Oxygen

Carbonaceous biochemical oxygen demand (CBOD) and dissolved oxygen (DO) data were available at the same stations and depths as the temperature data (CETESB, 1976). Average seasonal values were calculated at each station, and these values were used to calibrate the model.

No nitrogenous biochemical oxygen demand (NBOD) data were available, but NBOD was regarded as an important parameter in the system and therefore was included in the simulation. The NBOD results as predicted by the model, however, cannot be calibrated or validated.

Reaction Rates

The reaeration rate (K_2) for the system was calculated using the equation developed by O'Conner and Dobbins in 1958 (Texas Water Development Board, 1971):

$$K_2^{20} = \frac{(D_m \ U)^{0.5}}{H^{1.5}} \tag{8}$$

where:

K_2^{20} = reaeration coefficient at 20°C, day^{-1},

H = mean stream depth, ft,

U = mean stream velocity, ft/sec, and

D_m = molecular diffusion coefficient, ft^2/day.

Tidal velocity measurements were substituted in the computation of the reaeration rates in place of the instream advective velocities that were calculated by the model. This made it necessary to use the option of reading in the hand-calculated rates as input for each reach.

Tidal velocity data existed at only three stations in the Santos estuary: 0.338 feet per second at mile 11.00, 0.676 feet per second at mile 6.50, and 1.35 feet per second at mile 1.75. A curve was fitted to the net tidal velocity versus the distance over the entire study area. Reaeration rates were calculated at the three stations, and the rates were plotted versus distance over the estuary. Average rates were computed over each reach, and these values served as input for the model.

The reaeration rate is influenced by temperature variation, and QUAL-1 corrects the K_2 value according to the following equation (Texas Water Development Board, 1971):

$$K_2^T = K_2^{20}\ 1.047^{(T-20)} \tag{9}$$

where:

K_2^T = reaeration rate at the desired temperature, day^{-1},
K_2^{20} = reaeration rate at $20^{\circ}C$, and
T = temperature, $^{\circ}C$,

Biological removal of CBOD from the estuary is estimated in QUAL-1 by the carbonaceous deoxygenation rate (K_1). A value of 0.5 day^{-1} (base e) at a temperature of $20^{\circ}C$ was used for the entire length of the Santos estuary. The model has the capacity to make the necessary corrections to the K_1 rate due to temperature variation in each reach. The equation that is used to perform the temperature correction in the model is (Texas Water Development Board, 1971):

$$K_1^T = K_2^{20}\ 1.075^{(T-20)} \tag{10}$$

where:

K_1^T = CBOD deoxygenation rate at desired temperature, day^{-1},

K_1^{20}= CBOD deoxygenation rate at 20^oC, day^{-1}, and

T = temperature, ^oC.

Biological removal of NBOD is controlled by the nitrogenous deoxygenation rate (K_4) in the model. A value of 0.1 day^{-1} (base e) at 20^oC was used for each reach (Thomann, 1972), and this value was corrected for temperature variation using the same equation as the carbonaceous deoxygenation rate.

Benthic oxygen demand was also routed in the model. A value of 2.0 grams per square meter per day was assumed for the reaches included from mile 7.00 to mile 11.75, and a value 0.5 grams per square meter per day was used for the reaches from mile 0.00 to 7.00 (Thomann, 1972). The scouring effect of increased tidal action in the downstream section of the estuary was assumed to cause the erosion of a constant bottom substrate, and therefore the smaller value was used.

The model included removal of biochemical oxygen demand due to settling (K_3). This rate of oxygen depletion was considered insignificant in the downstream reaches from mile 7.00 to the mouth of the estuary due to tidal action, but a value of 0.5 day^{-1} (base e) was used as input for the reaches included from mile 11.75 to 7.00.

CALIBRATION

Inputs

The inflows of freshwater tributaries calculated as noted above were located and placed at the appropriate milepoint in the model. From observations of regional maps and analysis of CBOD data, six other waste loads were considered to be significant in this study of the estuary.

Three canals, numbered from four through six, empty into the estuary at locations ranging from 2.25 to 3.25 miles above the mouth. Each of these canals was assigned a flow of 5.0 cubic feet per second.

The City of Itapema was assumed to have an untreated sewage discharge. Using an estimate of 50 gallons of sewage per capita per day (Azevedo, 1975), and an assumed population of 30,000, a value of 2.3 cubic feet per second was calculated.

Two other discharges were assumed to be present, due to the occurrence of two "peaks" at milepoints 7.75 and 5.50 in the summer CBOD curve as constructed from field data. These "peaks" were observed to a much lesser degree in the winter CBOD curves, and a flow of 5.0 cubic feet per second was estimated for each.

Water Quality

To approximate actual conditions, the only input used for salinity in the model was Santos Bay. A portion of the Bay was represented in the model by the last reach in the system. A large flow of high salinity water was entered as a waste load at the mouth of the estuary at the head of reach ten, and the

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salinity concentration profile was calibrated by controlling the dispersion in each reach. The calculated dispersion coefficient was used as a first approximation in the model.

Since the salinity concentration at the uppermost point of the estuary was specified as zero, an extra "dummy" reach was inserted in the model at mile 12.00. This reach, numbered as zero, was included in the simulation for the sole purpose of meeting the upper boundary condition at mile 11.75 for salinity, and simulation results in the reach were disregarded. The reach was assigned a low dispersion coefficient, and a small amount of the material in reach one was allowed to extend over the system boundary.

A temperature simulation was not attempted, although QUAL-1 has the capacity for such a procedure. Lack of meteorological data, such as ambient dry bulb and wet bulb temperature, barometric pressure, and wind velocity, prevented an accurate analysis of temperature variation, and the averaged seasonal values were used as input for the steady-state model.

Freshwater tributaries to the estuary other than the Cubatao River were assigned concentrations of 1.0 mg/l NBOD and CBOD each. Other untreated waste loads were assumed to have a value of 200 mg/l for both NBOD and CBOD.

The three flows of the Cubatao River and the waste load assigned as Santos Bay were used to further calibrate the model for CBOD. Various concentrations of equal parts of CBOD and NBOD were used as input for the Cubatao River for approximation of field data, and the Bay concentration was controlled to set the downstream boundary condition. These adjustments were a further attempt to estimate the waste loads which enter the estuary.

Dissolved oxygen was calibrated using the same methods as the CBOD data. Freshwater tributaries other than the flows of the Cubatao River were estimated to have a DO concentration of 7.0 mg/l of dissolved oxygen. The DO values of the Bay and the Cubatao River were then adjusted to approximate the field conditions.

SENSITIVITY ANALYSIS

Introduction

To determine the variables which had the greatest effect on calculated BOD and DO levels in the Santos estuary system, a sensitivity analysis was conducted. The analysis consisted of measuring the percent change in an output variable resulting from a known percent change in an input to the model. The equation for sensitivity used in this study is as follows:

$$\text{Sensitivity } (\%\ Y/\%\ X) = \frac{\frac{\Delta Y}{Y} \times 100}{\frac{\Delta X}{X} \times 100} \qquad (11)$$

where:

Y = output variable (dependent), and

X = input variable (independent).

Input Variables

Inputs that were selected for analysis were: (1) the concentration of BOD in the Cubatao River; (2) the BOD concentrations of the discharges that were estimated; (3) the DO concentration of the Cubatao River; (4) the reaeration rate (K_2); and

(5) the longitudinal dispersion coefficient (D_L).

Output Variables

The BOD analysis was included in order to determine which of the two waste loadings had the largest detrimental effect on the water quality of the estuary. Instream CBOD and DO concentrations were selected as output variables for study in the analysis of BOD sensitivity due to their importance in water quality management decisions.

The DO concentrations of the three flows of the Cubatao River were selected for analysis in order to evaluate the effect of oxygen concentration of the waste loadings in the area on instream DO levels.

The reaeration rate was selected for a sensitivity study due to the importance of oxygen in the estuarine system and the sparsity of tidal velocity data from which the rates were calculated. Dissolved oxygen was the only output variable studied as a function of the reaeration rate.

The effect of the use of the modified dispersion coefficient on the water quality simulation was investigated in the last sensitivity analysis. Percent change in salinity concentration was studied as the output variable.

Station Locations

The effects of these four variable inputs were studied at three locations in the estuary: (1) the head of reach four at mile 10.25; (2) the head of reach six at mile 7.00; and (3) the head of reach nine at mile 1.75. These stations were selected due to the varying effects of the input values upon the water quality of the estuary at an upstream, a downstream, and an approximately halfway point.

PREDICTION

Introduction

The relationship between future growth and increased waste treatment in the greater Santos area is largely unknown. To aid in the analysis of this relationship, the model was used to simulate possible water quality in the Santos estuary for the years 1985 and 2000. For the 1985 prediction, BOD removal levels and DO values associated with primary treatment were used; for the year 2000, secondary treatment levels were used as inputs for the model.

The present loading from industrial and municipal waste discharges to the Cubatao River and its tributaries was estimated by subtracting the loadings resulting from natural sources from the total loading at the mouth of the River. Percentages for BOD removal were applied to this loading as well as the two estimated waste discharges and the flow of sewage from the City of Itapema.

The loadings of CBOD, NBOD, and DO used in each prediction at the mouth of the Cubatao River were calculated by adding the natural loadings of these constituents to the loadings remaining after each level of treatment had been applied. Concentrations were determined after the public water supply demand had been subtracted from the combined flow of the power plant discharge and the background flow of the River. Equal concentrations of BOD were applied in each of the flows of the Cubatao River, but the DO level in the flow entering the estuary at mile

10.25 was kept at 1.0 mg/l lower than the DO levels in the other two sections of the River.

Each of the BOD concentrations in the canals was lowered to 20 mg/l for both predictions, and these values are consistent with loadings characteristic of urban runoff (Field, 1973).

Population estimates for the two years included the "floating" populations of the three cities of Santos, Sao Vicente, and Cubatao which draw their water supply from the Cubatao River. The figure used in earlier calculations for the public water supply (66.7 gallons per capita per day) was kept constant. A maximum annual growth rate for the City of Itapema was estimated as 4.0 percent, due to the estimated overall population increase of Greater Santos which was calculated to be 3.4 percent per year from 1970 through the year 2000.

Since the conditions for the highest degredation of water quality usually occur during periods of high temperature and low flow (associated with increased withdrawal for water supply), the summer seasonal model was used for prediction purposes.

1985 Prediction

Equal removal percentages of 30 percent for CBOD and NBOD were used for the waste discharges for primary treatment purposes. A DO concentration of 2.0 mg/l in each of the waste flows was assumed.

The BOD removal due to settling in the estuary was decreased by 80 percent to a value of 0.1 day^{-1} (base e). The benthic demands were reduced by 50 percent to figures of 1.0 and

0.25 grams of oxygen per square meter per day in the upper and lower reaches of the system, respectively.

2000 Prediction

For the prediction of secondary treatment, a percentage removal for CBOD of 85 percent and an effluent DO level of 3.0 mg/l were used in the waste loadings. The NBOD levels remained the same as in the primary treatment prediction. The CBOD deoxygenation rate over the entire length of the estuary was reduced by 50 percent to a value of 0.25 day^{-1} (base e) at $20^{\circ}C$, and all other inputs other than the withdrawal demand were unchanged from the 1985 prediction.

CHAPTER IV

RESULTS

INTRODUCTION

The mathematical model described in Chapter III was used in the Santos estuary to predict BOD and DO in 1985 and 2000 under several treatment regimens. First, however, the model had to be calibrated with existing salinity, CBOD, and DO data. The results of the calibration and prediction work are described below.

CALIBRATION

Salinity

Because salinity is considered a conservative material, it was calibrated first to "tune" the hydraulic characteristics of the model. The results of the salinity calibration are shown in Figure 2. The results of the calibration are considered good because at locations where salinity data existed, two-thirds of the predicted values were within 2.5 percent of the averaged field data, and all of the predicted values were within 5.3 percent of the weighted averages used for the calibration.

The average dispersion coefficient over the entire length of the estuary was calculated from calibration results to be 239,000 square feet per second (741 square miles per day). This value was approximately ten times greater than the value which was calculated from the semilogrithmic plot of salinity versus distance, one procedure for calculating this coefficient. This variation was due to the high dispersion in reaches six and seven, which averaged 640,000 square feet per second (2010 square

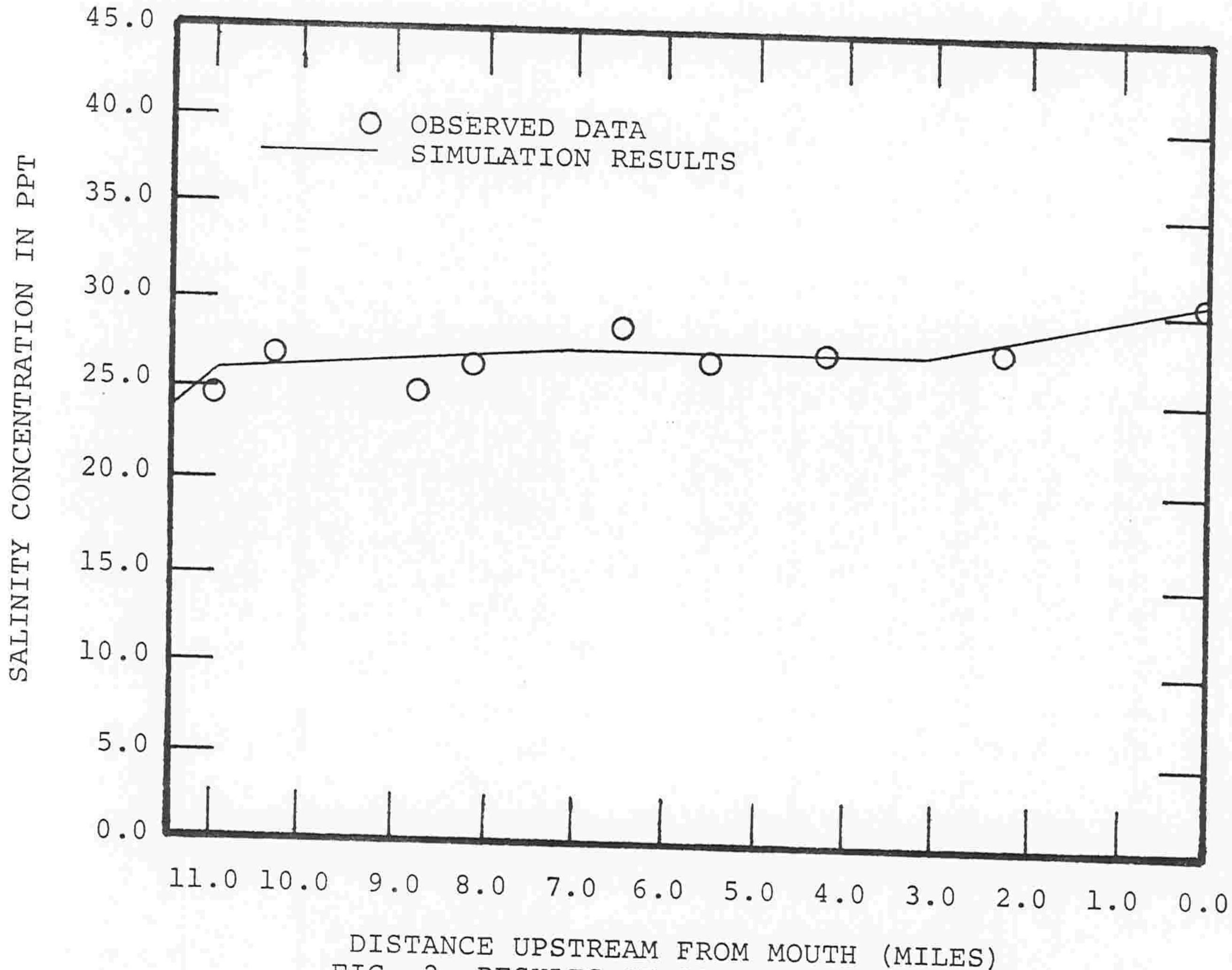

FIG. 2. RESULTS OF SALINITY CALIBRATION

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miles per day). The dispersion coefficient calculated, excluding reaches six and seven, was 3160 square feet per second (97.9 square miles per day) which was 30 percent greater than the expected value.

Biochemical Oxygen Demand

The results of the CBOD calibration for the winter and summer conditions are shown in Figures 3 and 4, respectively. The CBOD calibration was apparently good, since in both seasonal calibrations, all of the predicted values fell within the 80 percent confidence limits of the field data. This fit was forced, however, because the CBOD input values were increased until the desired levels of CBOD were obtained in the estuary. This was necessary because of the lack of waste input data, and this means that the CBOD data were considered the base data for the calibration. As will be discussed in the next chapter, some of these data are questionable and require that the results of this study be qualified. Nevertheless, a CBOD concentration of 5.0 mg/l in each of the flows of the Cubatao River was needed to achieve the desired results. Note that the field data and the model predictions show rather constant values throughout the estuary because of the high dispersion rates.

The NBOD concentrations predicted by the model for the winter and summer seasons are shown in Figures 5 and 6. Concentrations of 5.0 mg/l NBOD (corresponding to a total oxidizable nitrogen concentration of one mg/l) were used in the flows of the Cubatao River for the simulation. Since no field data existed for NBOD, a calibration could not be performed, but the results

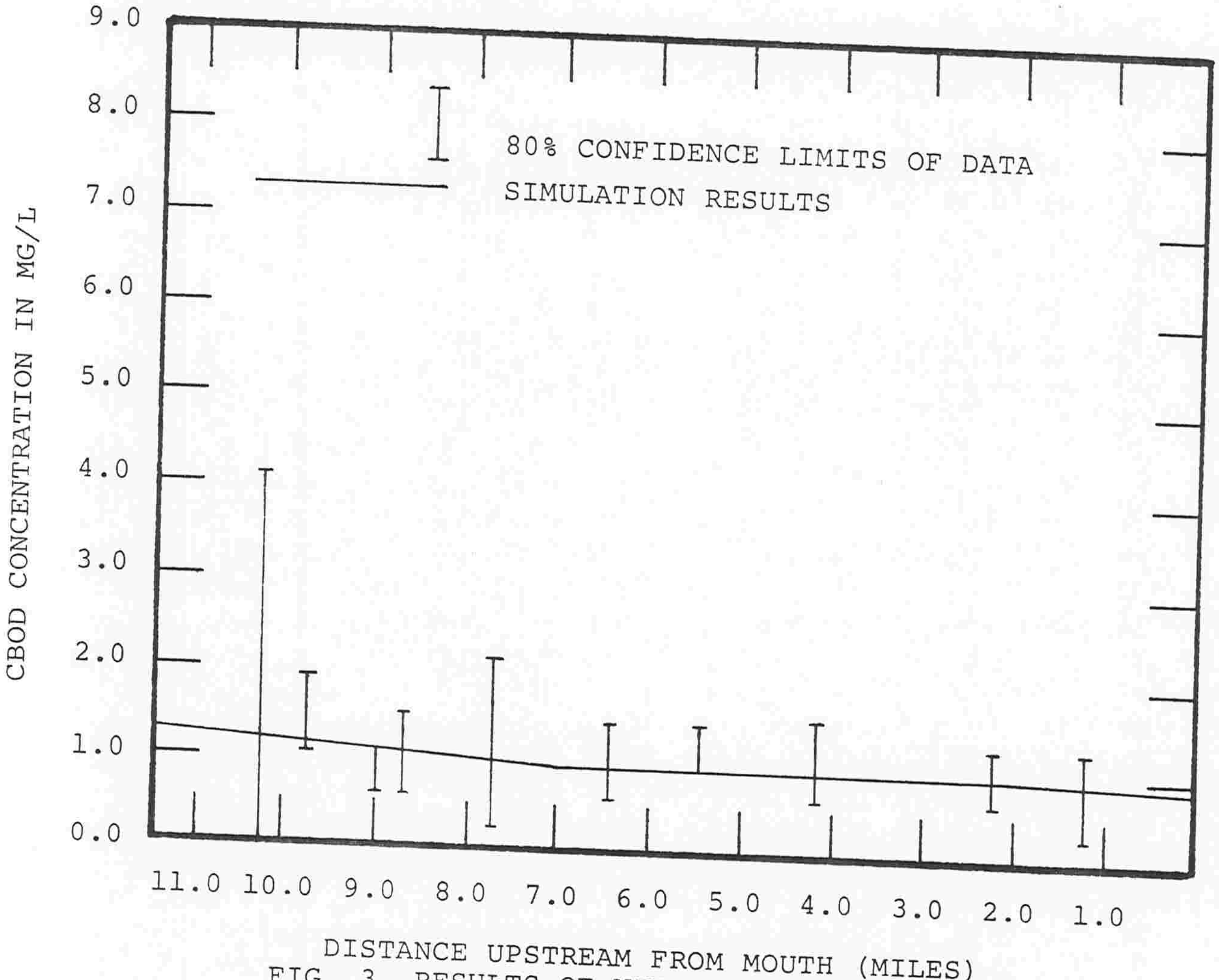

FIG. 3. RESULTS OF WINTER CBOD CALIBRATION

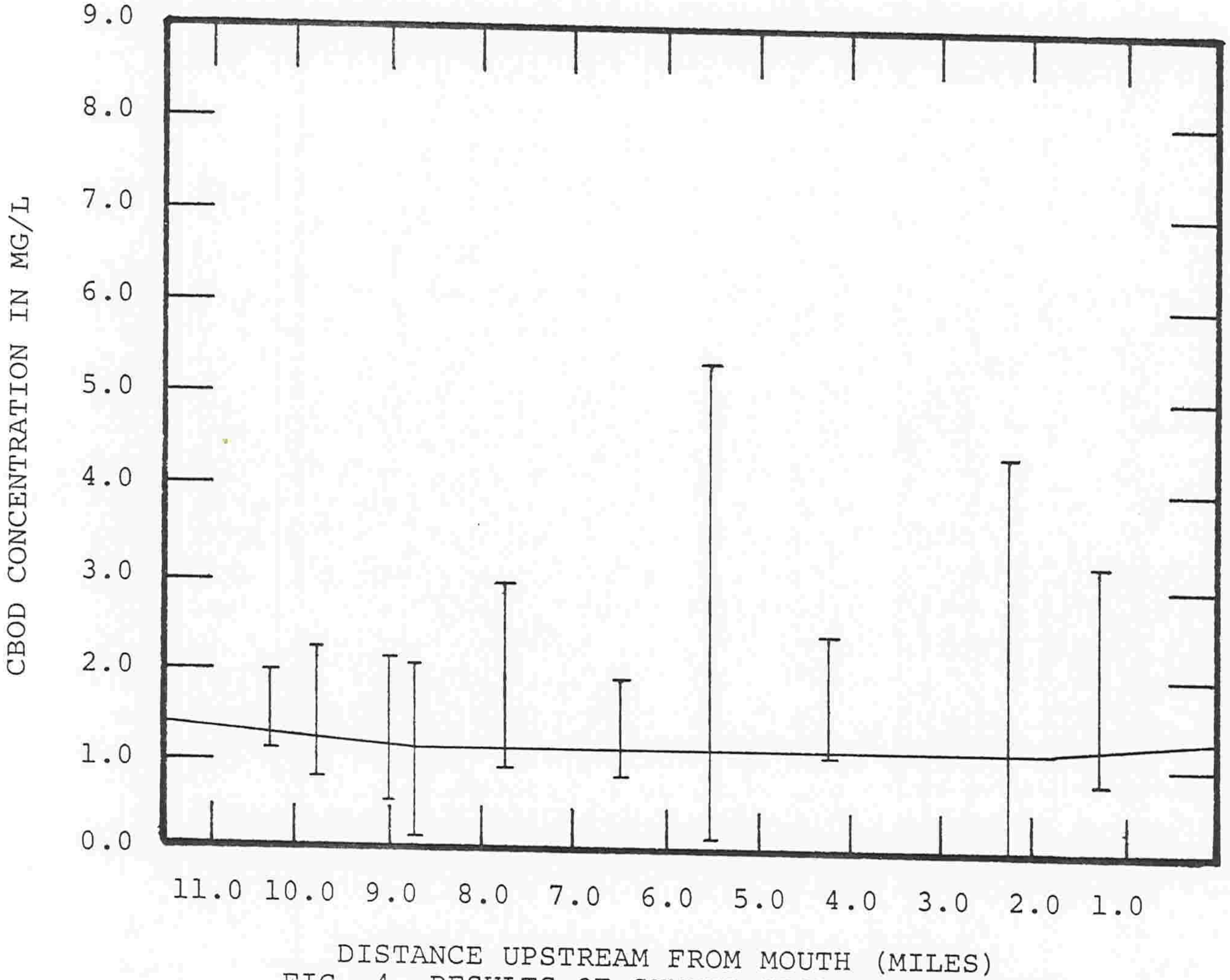

FIG. 4. RESULTS OF SUMMER CBOD CALIBRATION

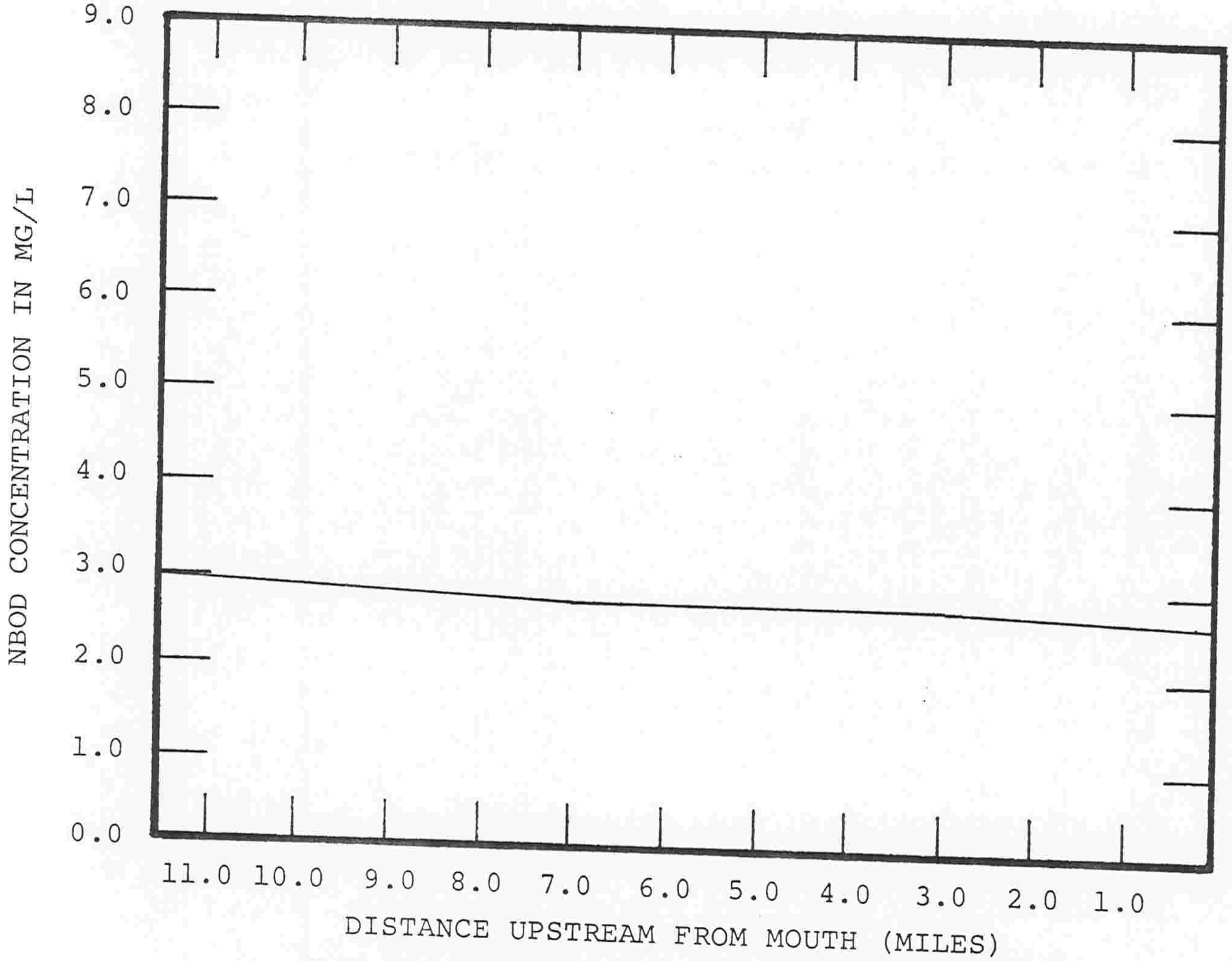

FIG. 5. RESULTS OF WINTER NBOD SIMULATION

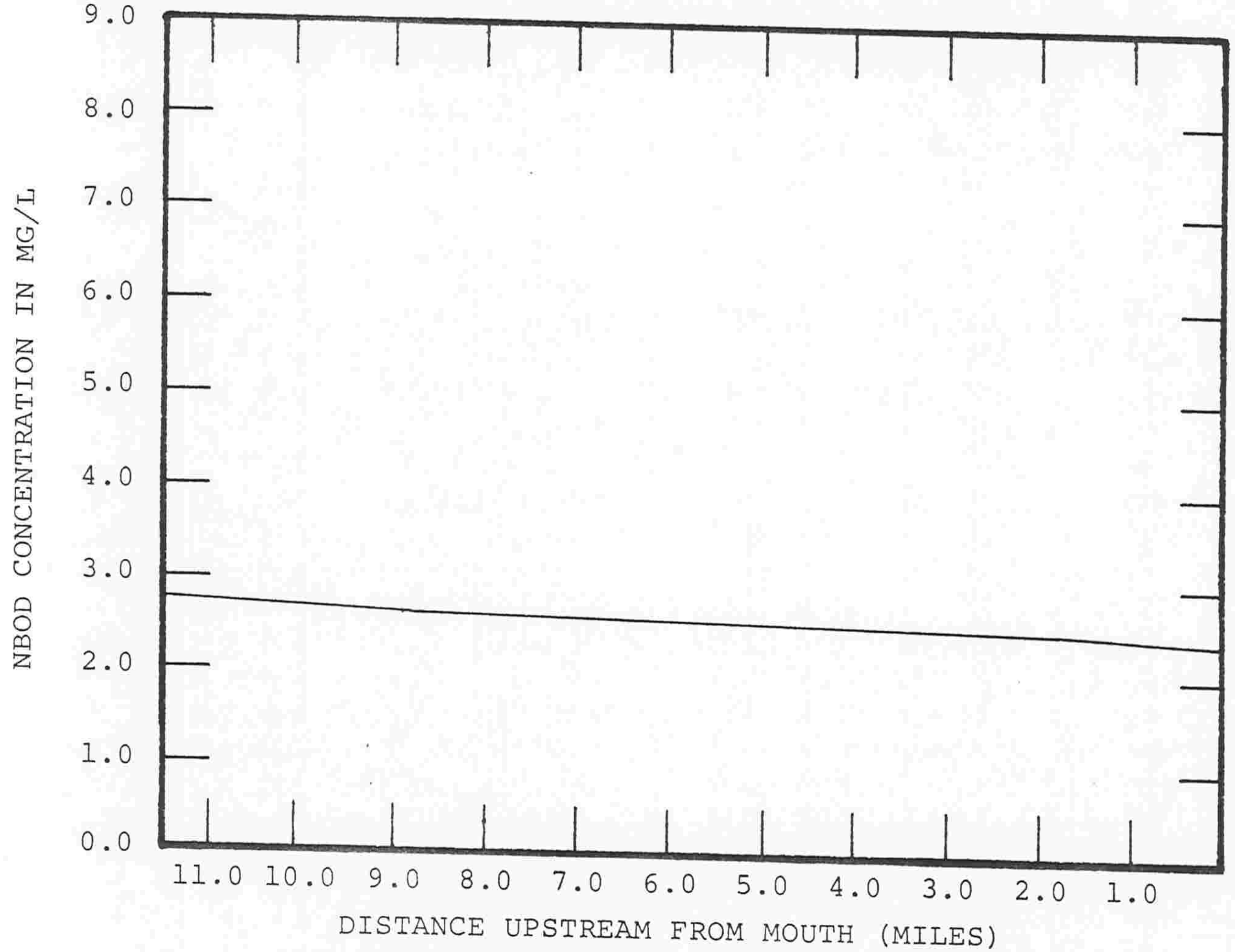

FIG. 6. RESULTS OF SUMMER NBOD SIMULATION

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are judged as reasonable.

Dissolved Oxygen

Dissolved oxygen profiles along the estuary for each of the seasonal calibrations are shown in Figures 7 and 8. Flows of the Cubatao River entering the system at miles 11.75 and 11.50 were assigned a DO concentration of 1.5 mg/l as described in the previous chapter. Due to its longer time of travel before entering the study area and consequent further uptake of oxygen, the remaining flow of the Cubatao River which enters the estuary at mile 10.25 was assumed to have a DO concentration of 0.5 mg/l.

The DO calibrations were considered good also, since only one value predicted by the model fell outside the 80 percent confidence limits of the observed data.

SENSITIVITY ANALYSIS

The results of the CBOD input - CBOD output, BOD input - DO output, and DO input - DO output analyses are shown in Figures 9 through 17. The graphs show a linear relationship between each two pairs of variables, and the slopes of the lines are summarized in Table 9.

The results of the K_2 input - DO output and the D_L input - salinity output analyses are shown in Figures 18 through 23. Since these graphs were not linear, constant slopes of the curves could not be computed.

These plots show that the BOD loading of the Cubatao River was the controlling factor of the system. For each percent change in the CBOD loading, an average change of 0.846 percent resulted in the instream concentrations of CBOD, and for

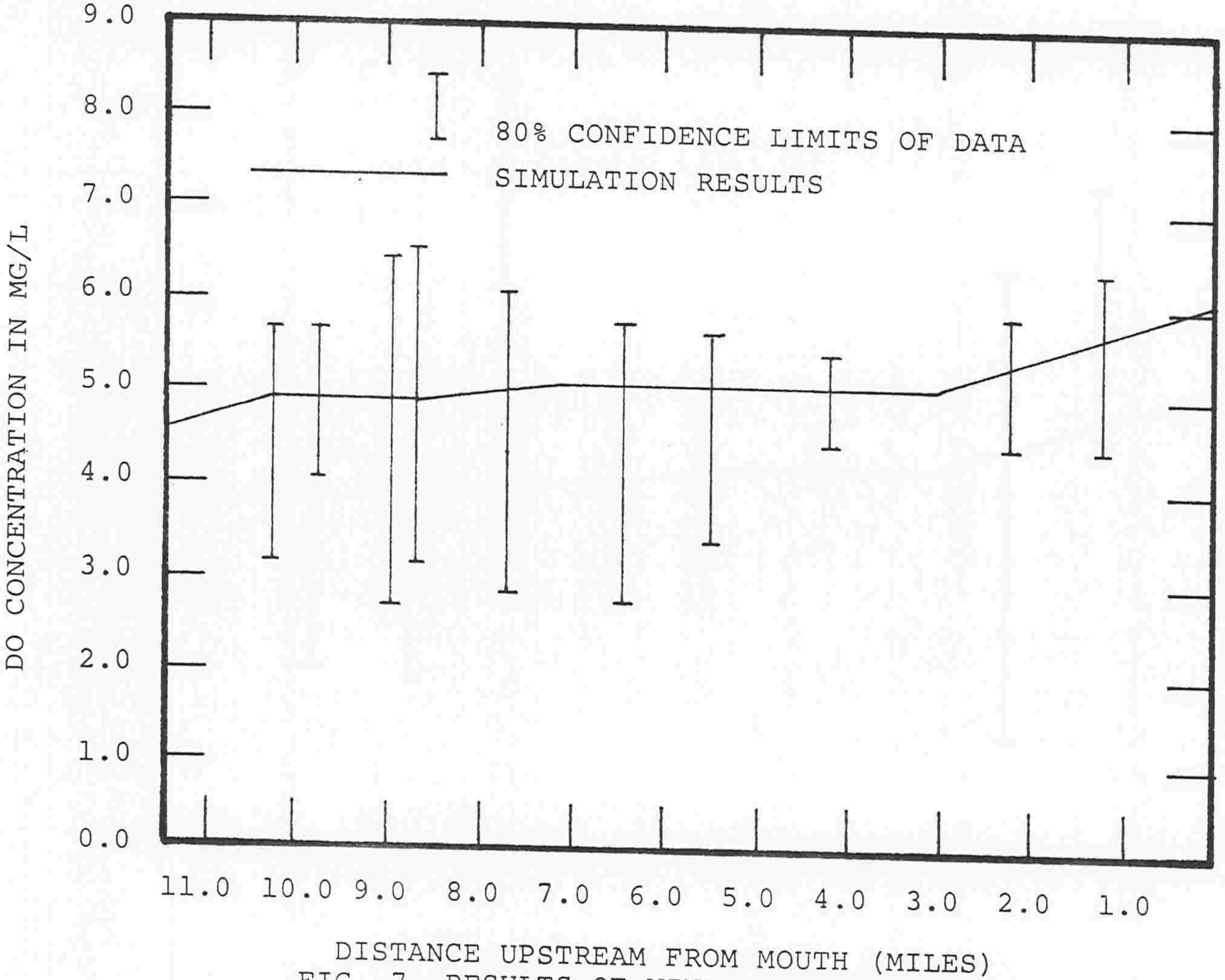

FIG. 7. RESULTS OF WINTER DO CALIBRATION

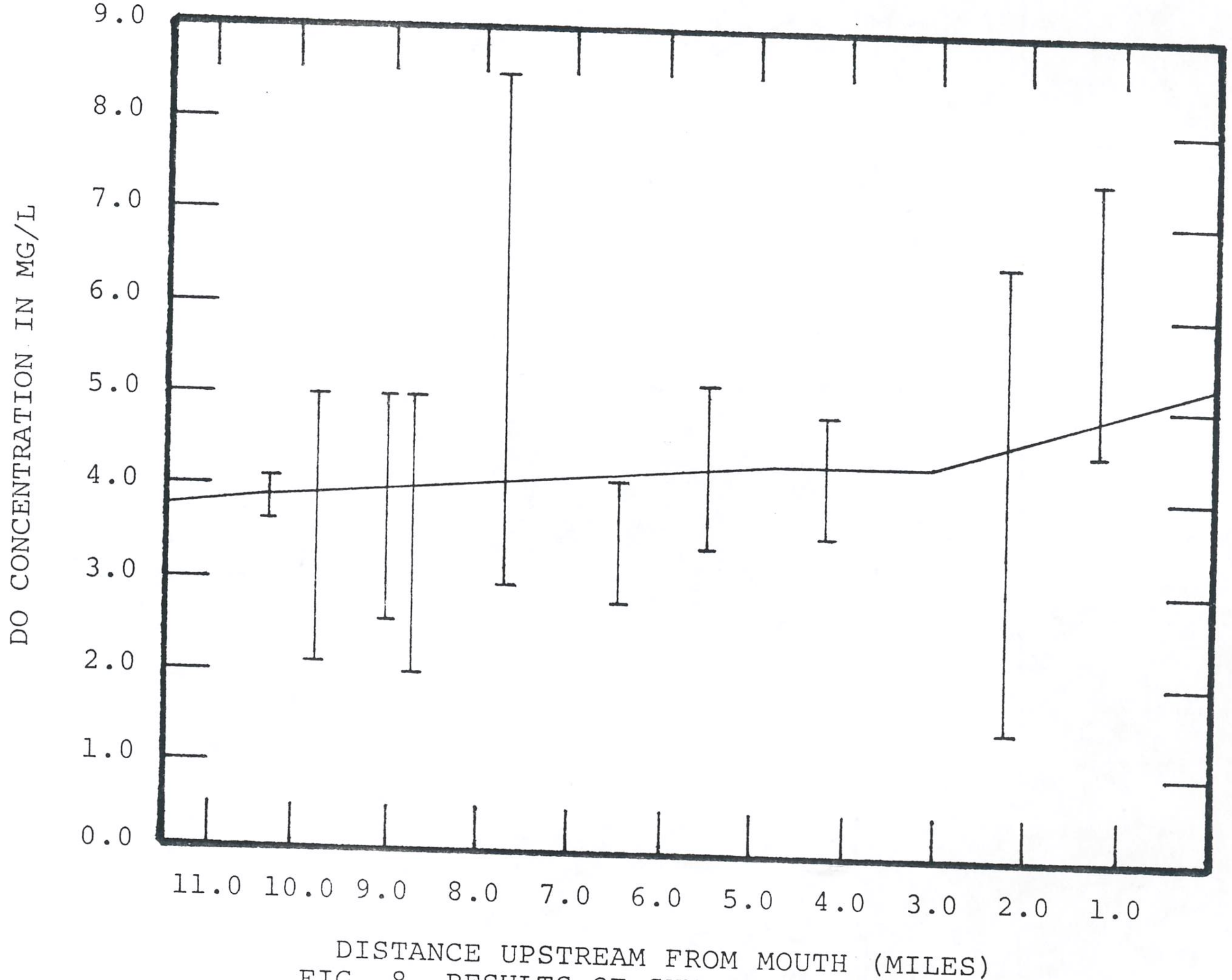

FIG. 8. RESULTS OF SUMMER DO CALIBRATION

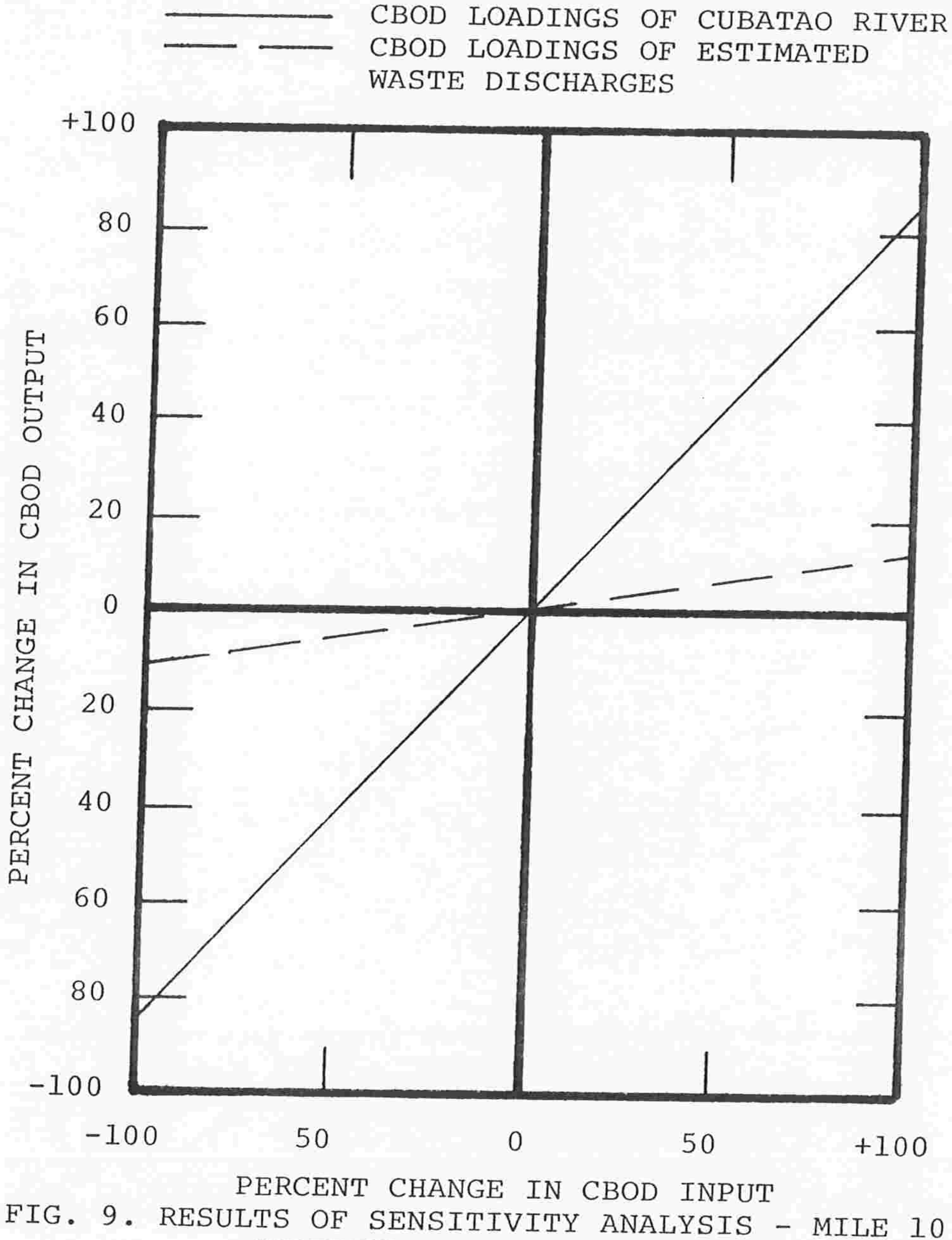

FIG. 9. RESULTS OF SENSITIVITY ANALYSIS - MILE 10.25:
INDEPENDENT VARIABLE - CBOD
DEPENDENT VARIABLE - CBOD

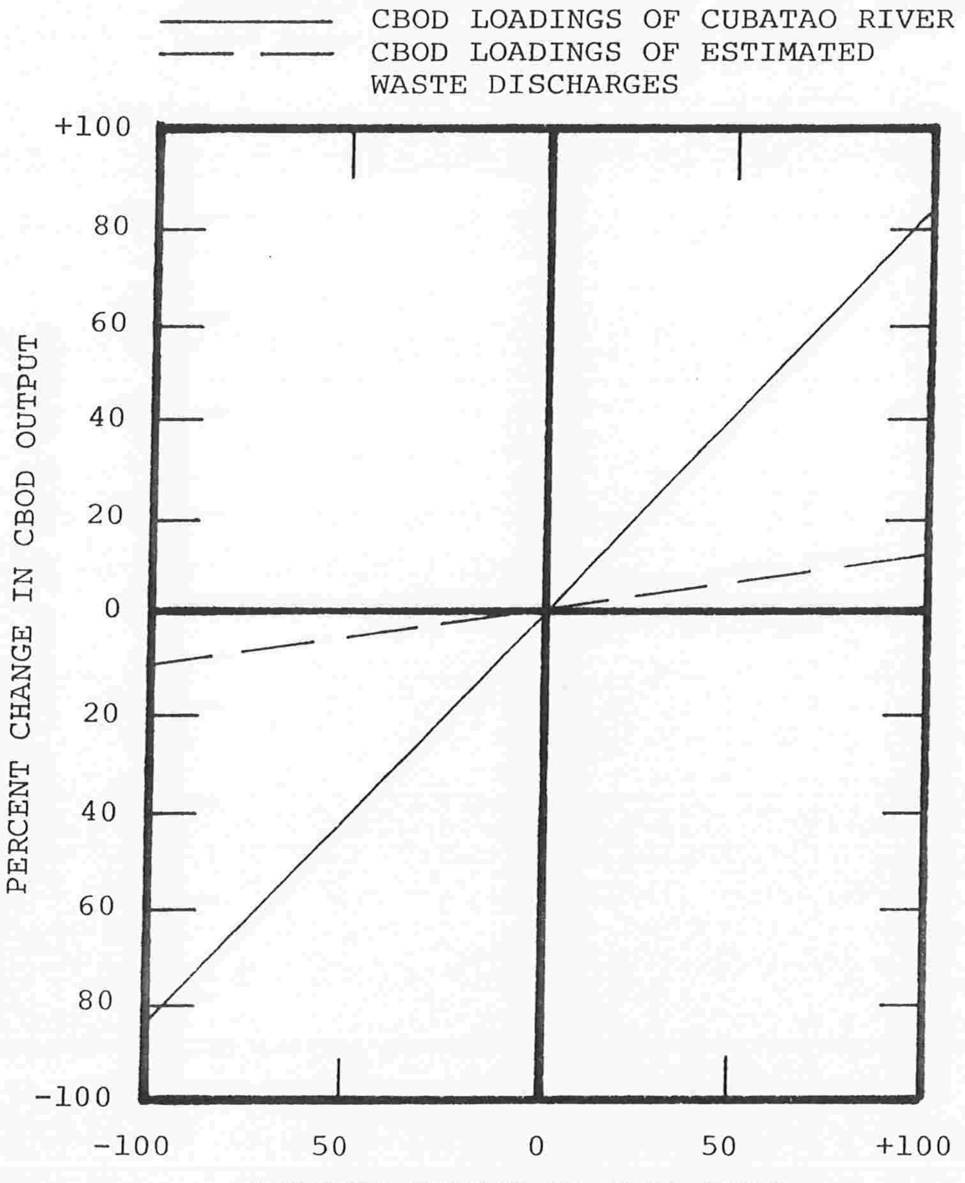

FIG. 10. RESULTS OF SENSITIVITY ANALYSIS - MILE 7.00:
INDEPENDENT VARIABLE - CBOD
DEPENDENT VARIABLE - CBOD

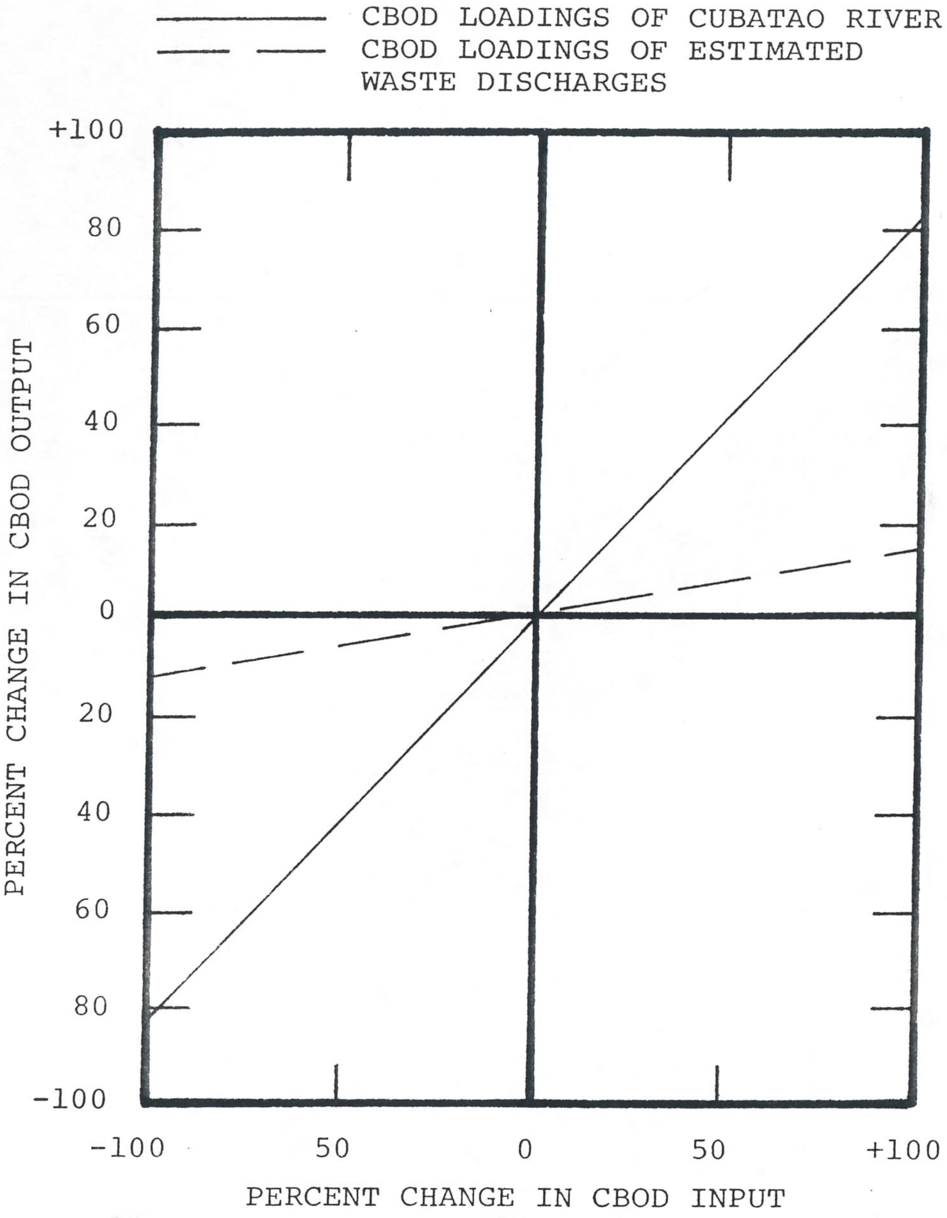

FIG. 11. RESULTS OF SENSITIVITY ANALYSIS - MILE 1.75:
INDEPENDENT VARIABLE - CBOD
DEPENDENT VARIABLE - CBOD

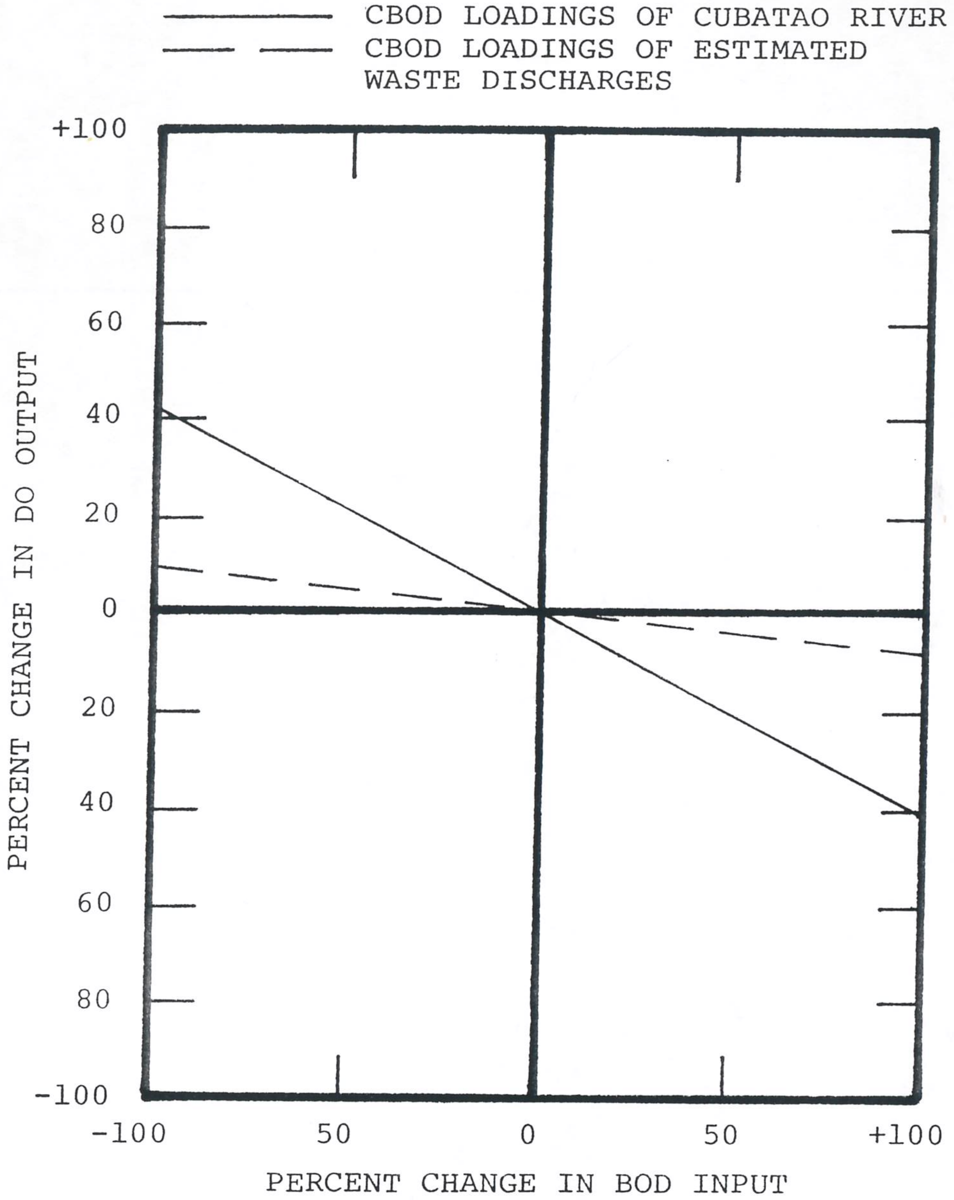

FIG. 12. RESULTS OF SENSITIVITY ANALYSIS - MILE 10.25:
INDEPENDENT VARIABLE - BOD
DEPENDENT VARIABLE - DO

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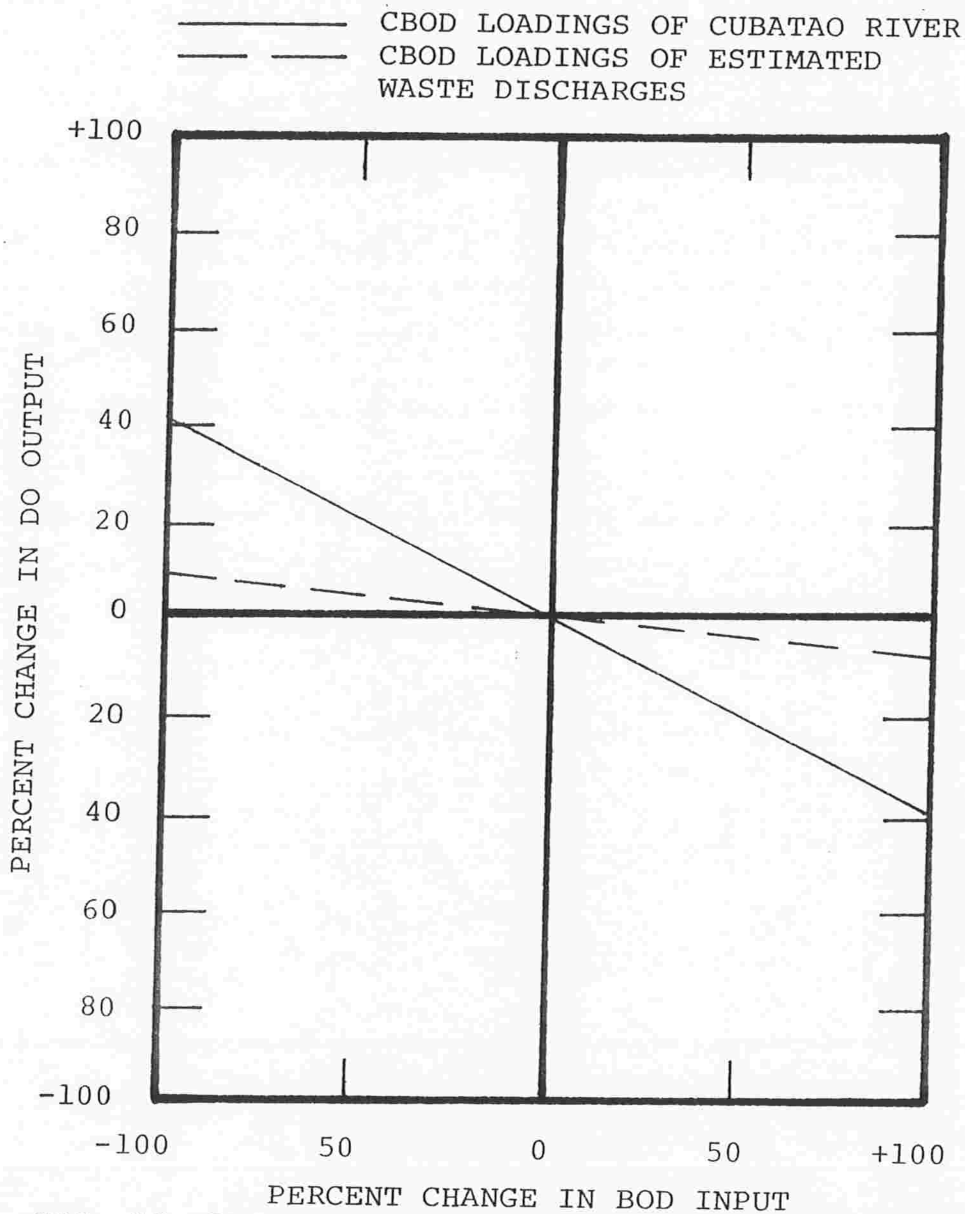

FIG. 13. RESULTS OF SENSITIVITY ANALYSIS - MILE 7.00:
INDEPENDENT VARIABLE - BOD
DEPENDENT VARIABLE - DO

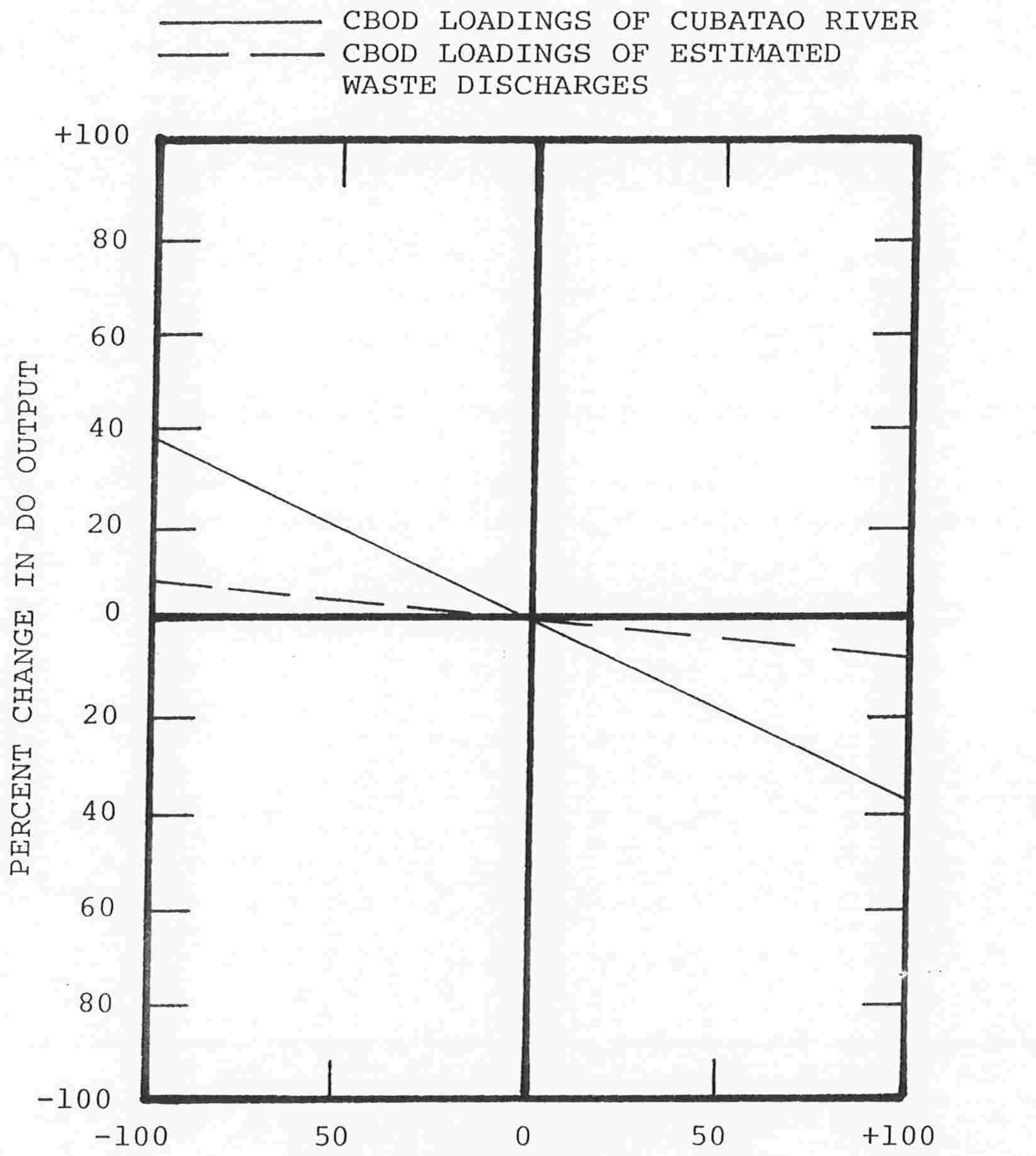

FIG. 14. RESULTS OF SENSITIVITY ANALYSIS - MILE 1.75:
INDEPENDENT VARIABLE - BOD
DEPENDENT VARIABLE - DO

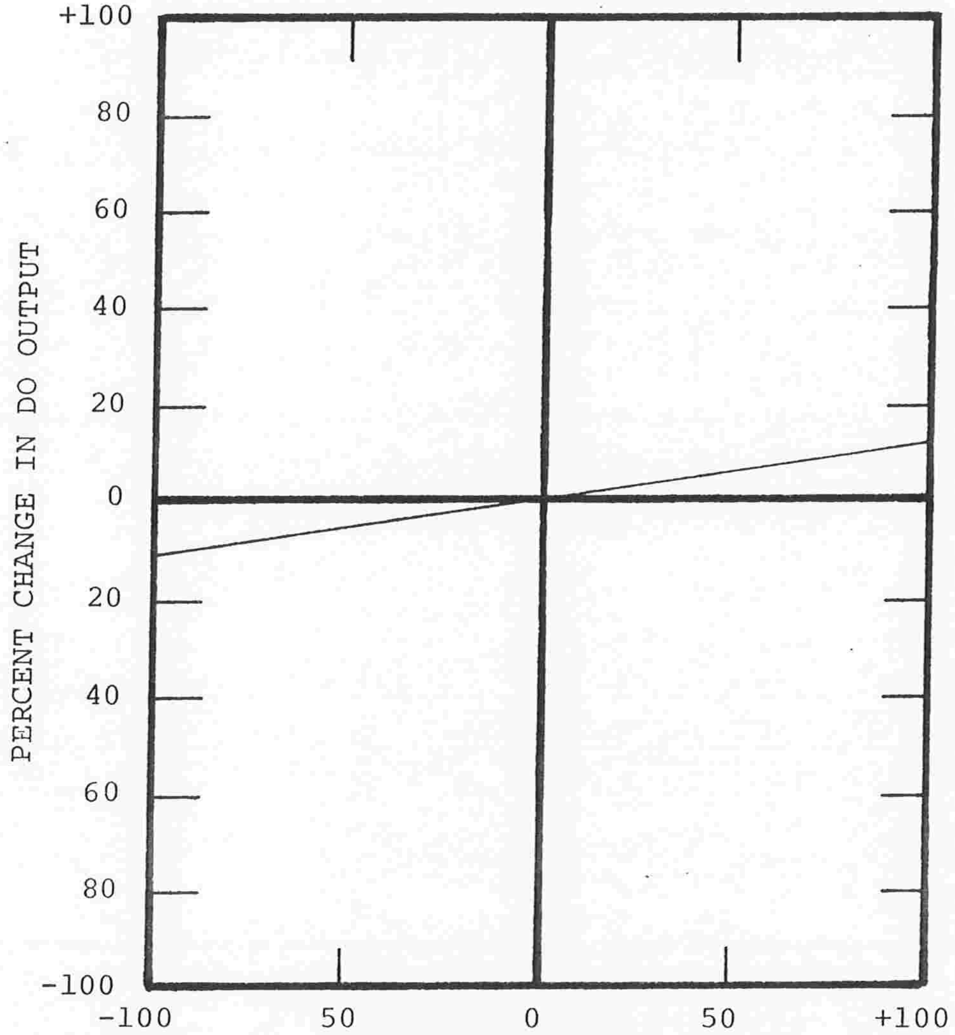

FIG. 15. RESULTS OF SENSITIVITY ANALYSIS - MILE 10.25:
INDEPENDENT VARIABLE - DO
DEPENDENT VARIABLE - DO

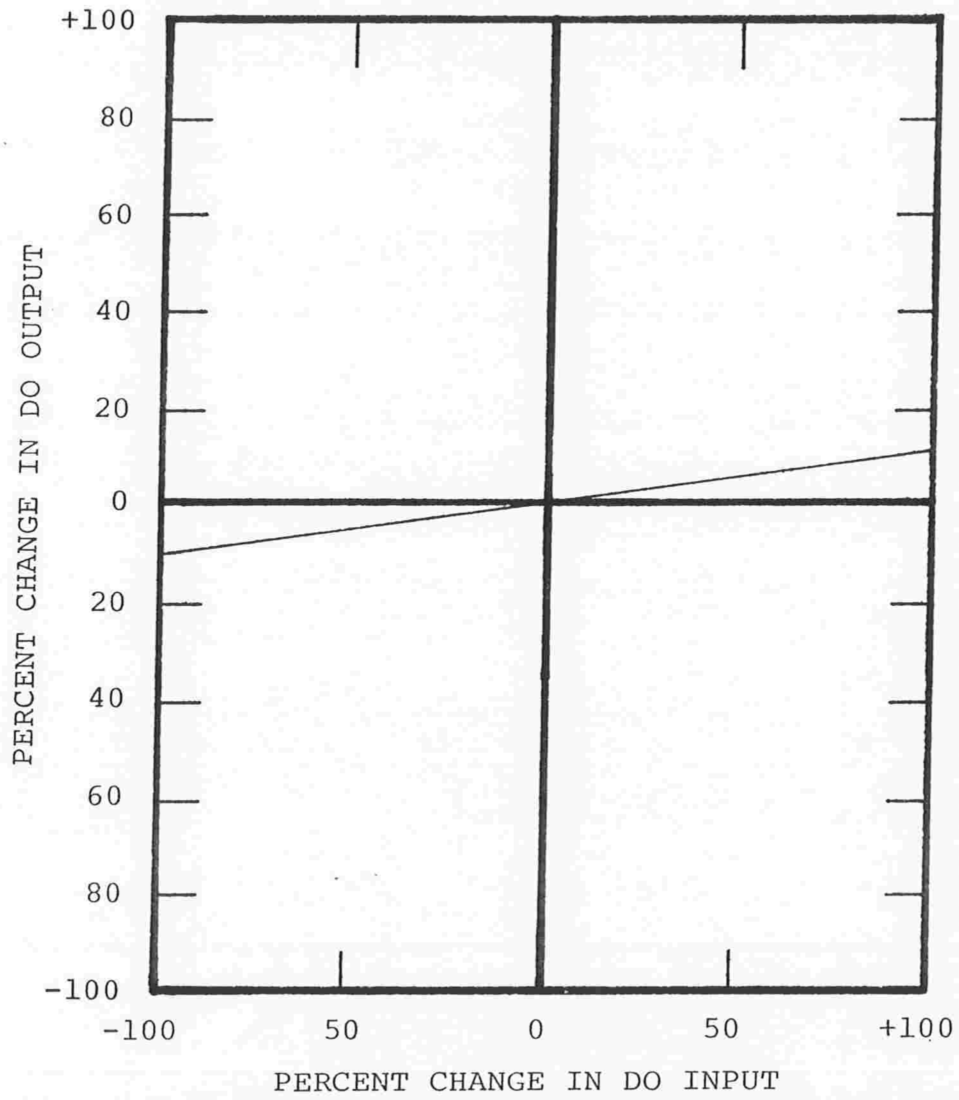

FIG. 16. RESULTS OF SENSITIVITY ANALYSIS - MILE 7.00:
INDEPENDENT VARIABLE - DO
DEPENDENT VARIABLE - DO

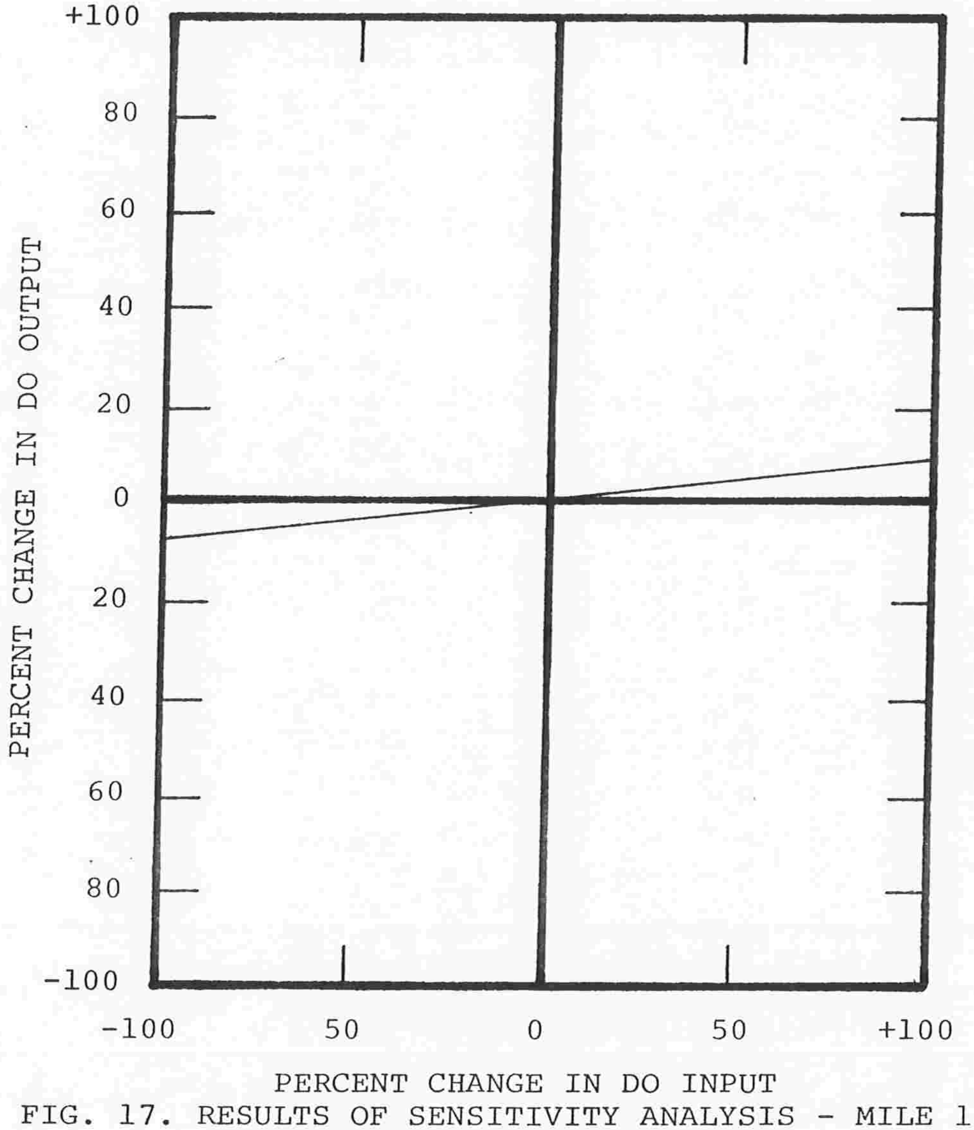

FIG. 17. RESULTS OF SENSITIVITY ANALYSIS - MILE 1.75:
INDEPENDENT VARIABLE - DO
DEPENDENT VARIABLE - DO

TABLE 9

LINEAR RESULTS OF SENSITIVITY ANALYSIS

Independent Variable	Dependent Variable	System Response $\frac{\Delta\%\text{ Independent Variable}}{\Delta\%\text{ Dependent Variable}}$		
		Mile 10.25	Mile 7.00	Mile 1.75
CBOD (Cubatao River)	CBOD	0.870	0.840	0.836
CBOD (Estimated Discharges)	CBOD	0.113	0.142	0.146
BOD (Cubatao River)	DO	-0.414	-0.400	-0.381
BOD (Estimated Discharges)	DO	-0.0630	-0.0613	-0.0584
DO (Cubatao River)	DO	0.105	0.0942	0.0885

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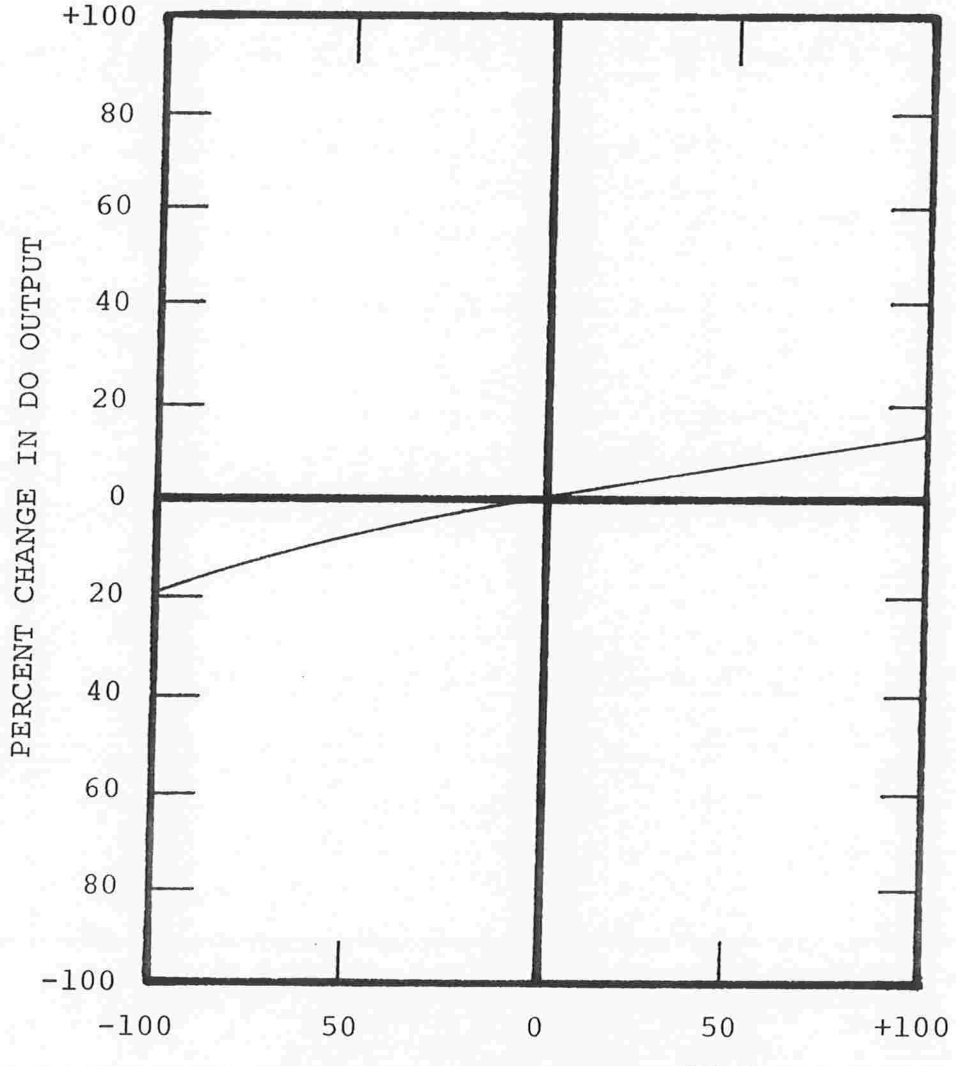
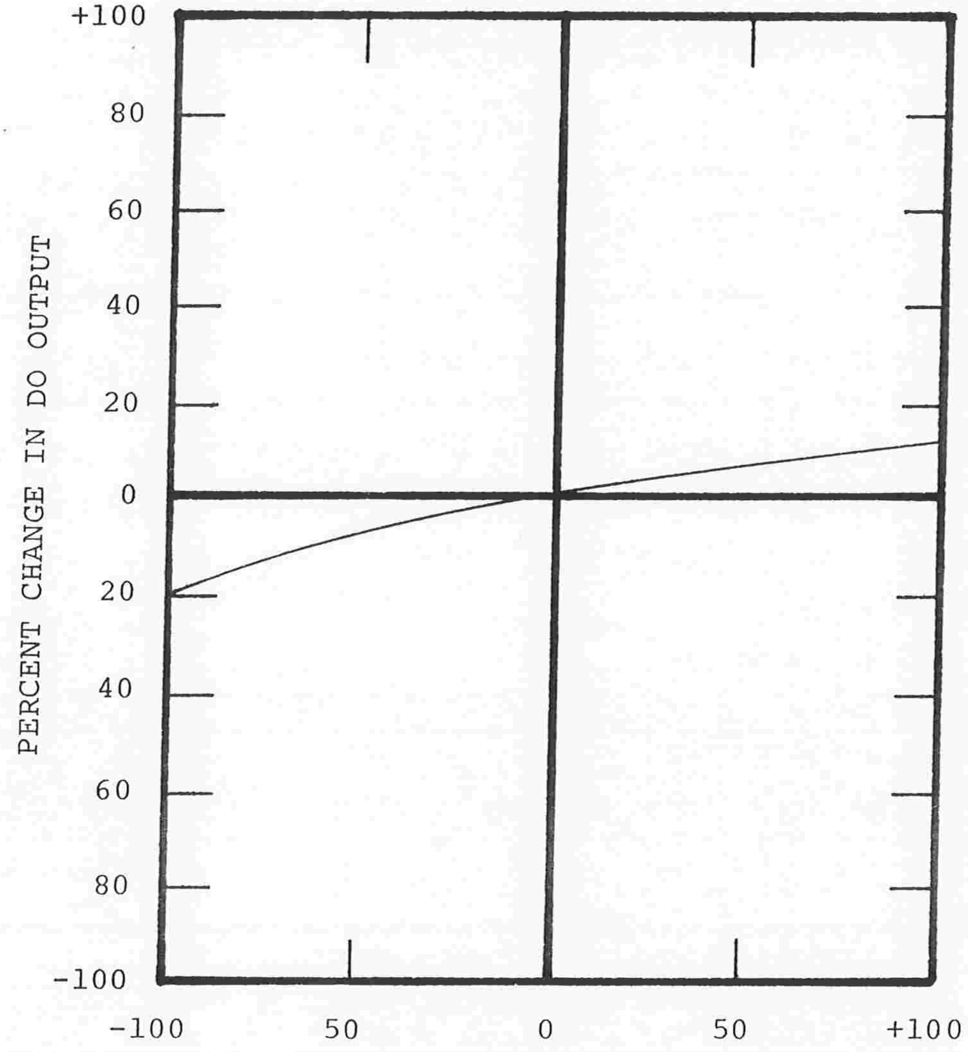


FIG. 18. RESULTS OF SENSITIVITY ANALYSIS - MILE 10.25:
INDEPENDENT VARIABLE - K_2
DEPENDENT VARIABLE - DO



PERCENT CHANGE IN K_2 INPUT

FIG. 19. RESULTS OF SENSITIVITY ANALYSIS - MILE 7.00:
INDEPENDENT VARIABLE - K_2
DEPENDENT VARIABLE - DO

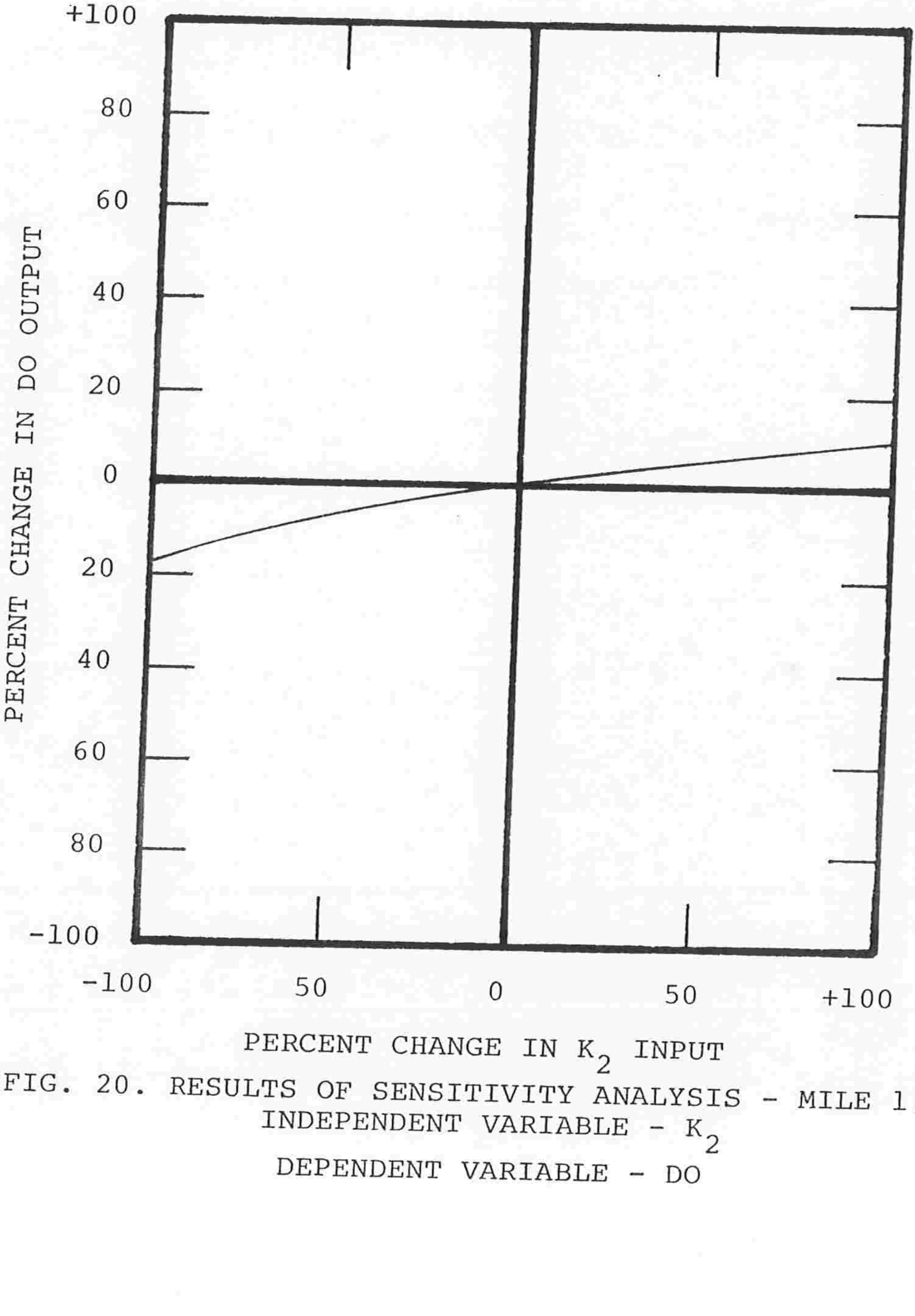


FIG. 20. RESULTS OF SENSITIVITY ANALYSIS - MILE 1.75:
INDEPENDENT VARIABLE - K_2
DEPENDENT VARIABLE - DO

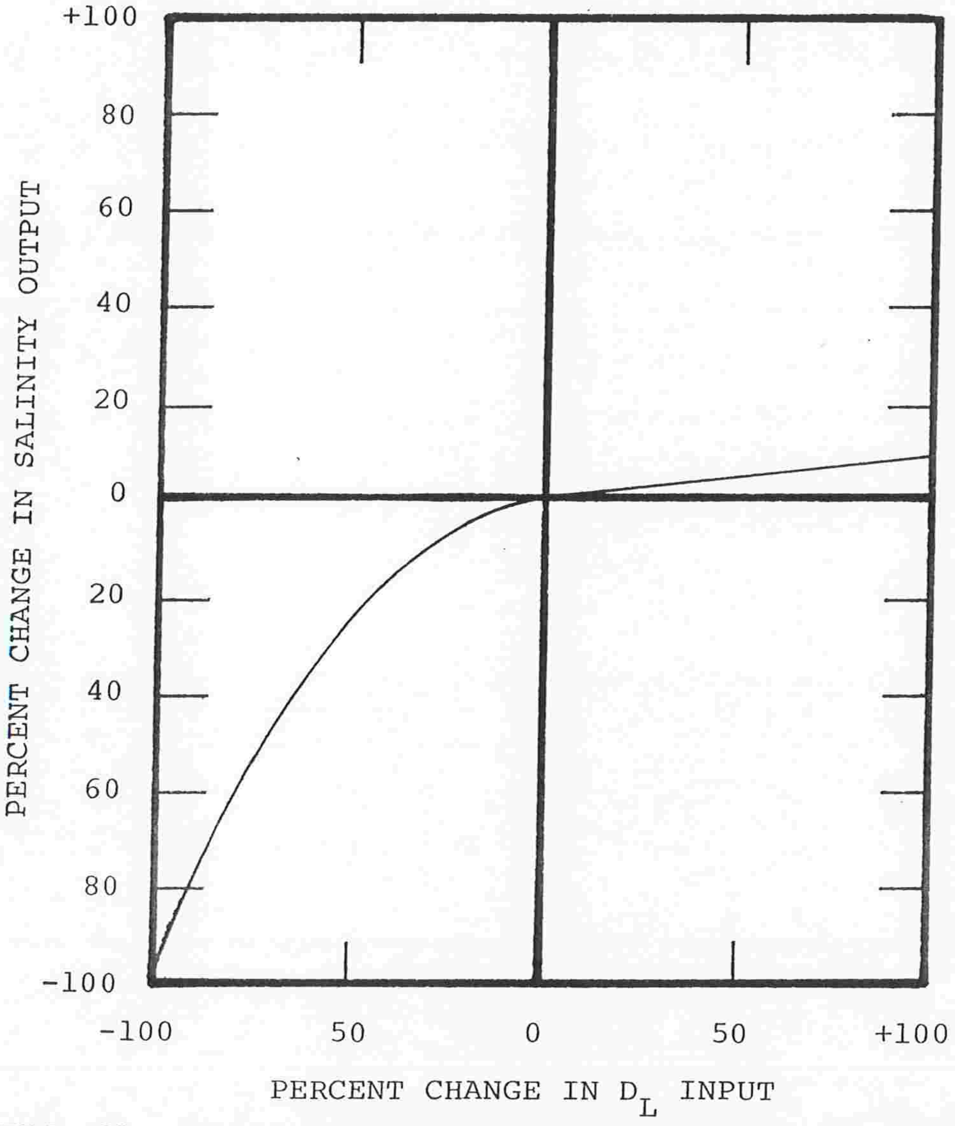


FIG. 21. RESULTS OF SENSITIVITY ANALYSIS - MILE 10.25: INDEPENDENT VARIABLE - D_L
DEPENDENT VARIABLE - SALINITY

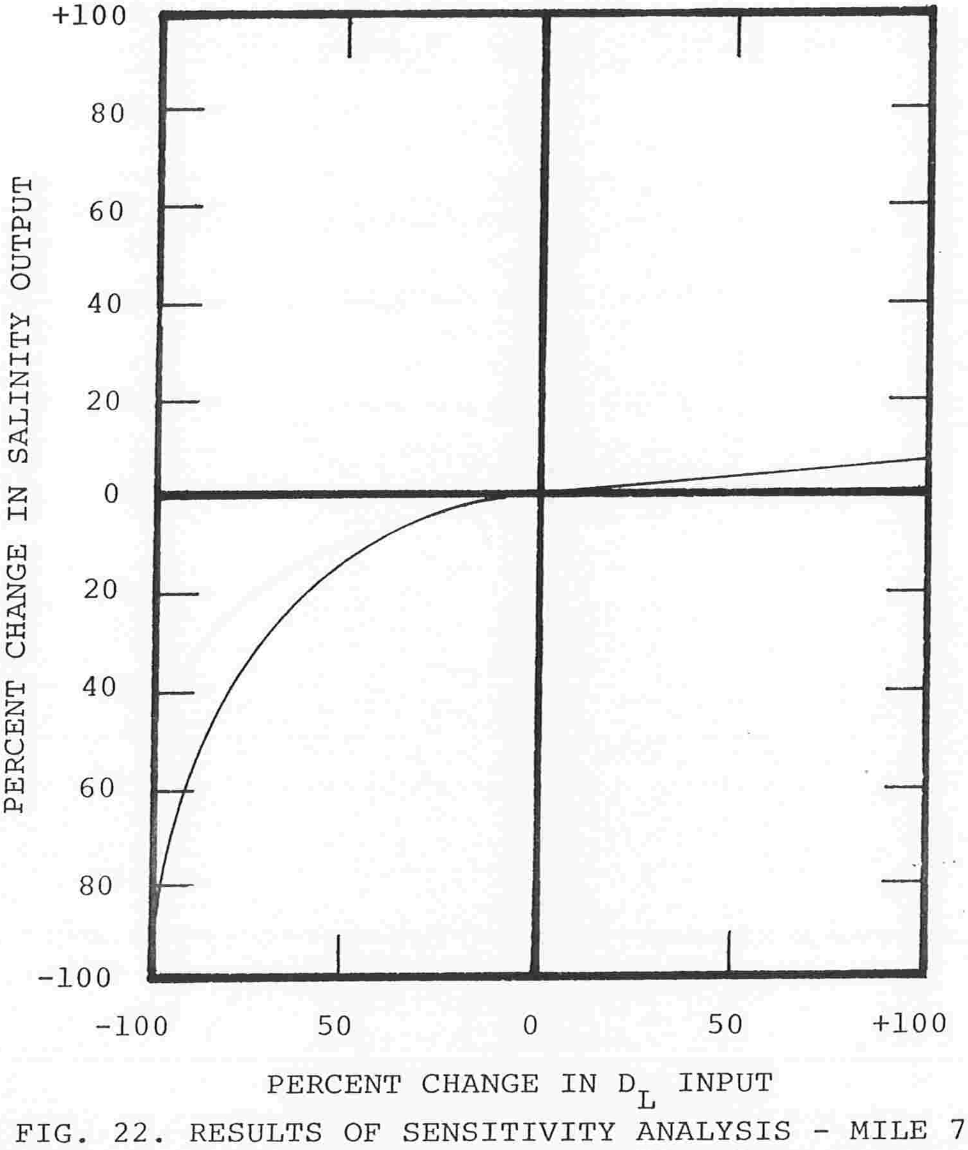
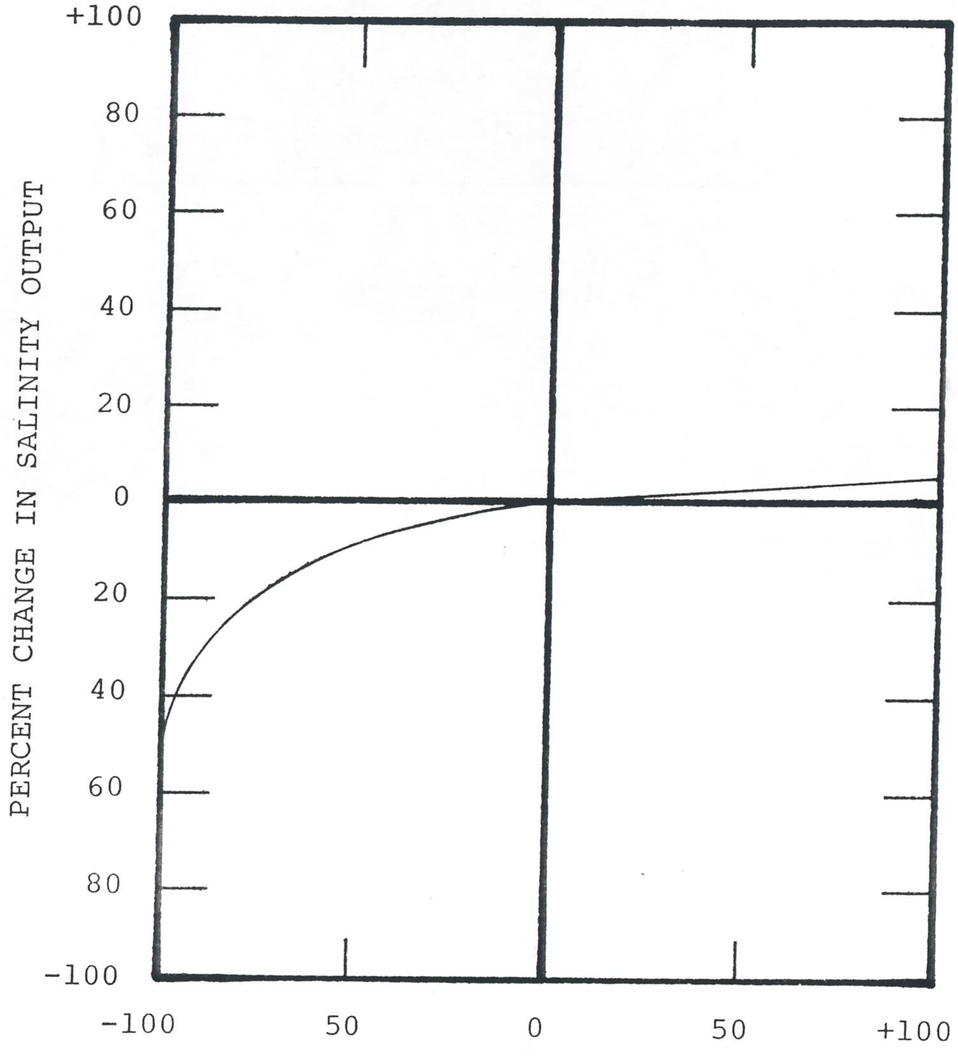


FIG. 22. RESULTS OF SENSITIVITY ANALYSIS - MILE 7.00:
INDEPENDENT VARIABLE - D_L
DEPENDENT VARIABLE - SALINITY



PERCENT CHANGE IN D_L INPUT

FIG. 23. RESULTS OF SENSITIVITY ANALYSIS - MILE 1.75:
INDEPENDENT VARIABLE - D_L
DEPENDENT VARIABLE - SALINITY

each percent change of total BOD in the Cubatao River, an average change of 0.398 percent resulted in the instream concentrations of DO. Only minor changes resulted from variation in other BOD and DO loadings.

The reaeration rate also had a noticeable effect on the system, although this effect was not as significant as the dependency on the BOD loadings of the Cubatao River. A 100 percent increase in the value of K_2 resulted in an average increase of 18.6 percent in the instream concentrations of DO, and a 100 percent decrease in the K_2 value yielded an average decrease of 12.7 percent in the DO concentrations.

Analysis of the dispersion coefficient plots show that the system is highly affected by a decrease in dispersion, and this effect is much greater in the upstream sections of the estuary than in those near the mouth.

PREDICTION

The results of the predictions of CBOD, NBOD, and DO for the years 1985 and 2000 are shown in Figure 24. These plots also include the present conditions as simulated by the model for comparison with the water quality improvement in each level of treatment.

For the year 1985 in which primary treatment is assumed to exist for all discharges, the following improvements in water quality were calculated: (1) an average decrease of instream CBOD concentrations of 10.6 percent; (2) an average decrease of instream NBOD concentrations of 31.3 percent; and (3) an average increase of instream DO concentrations of 27.2 percent.

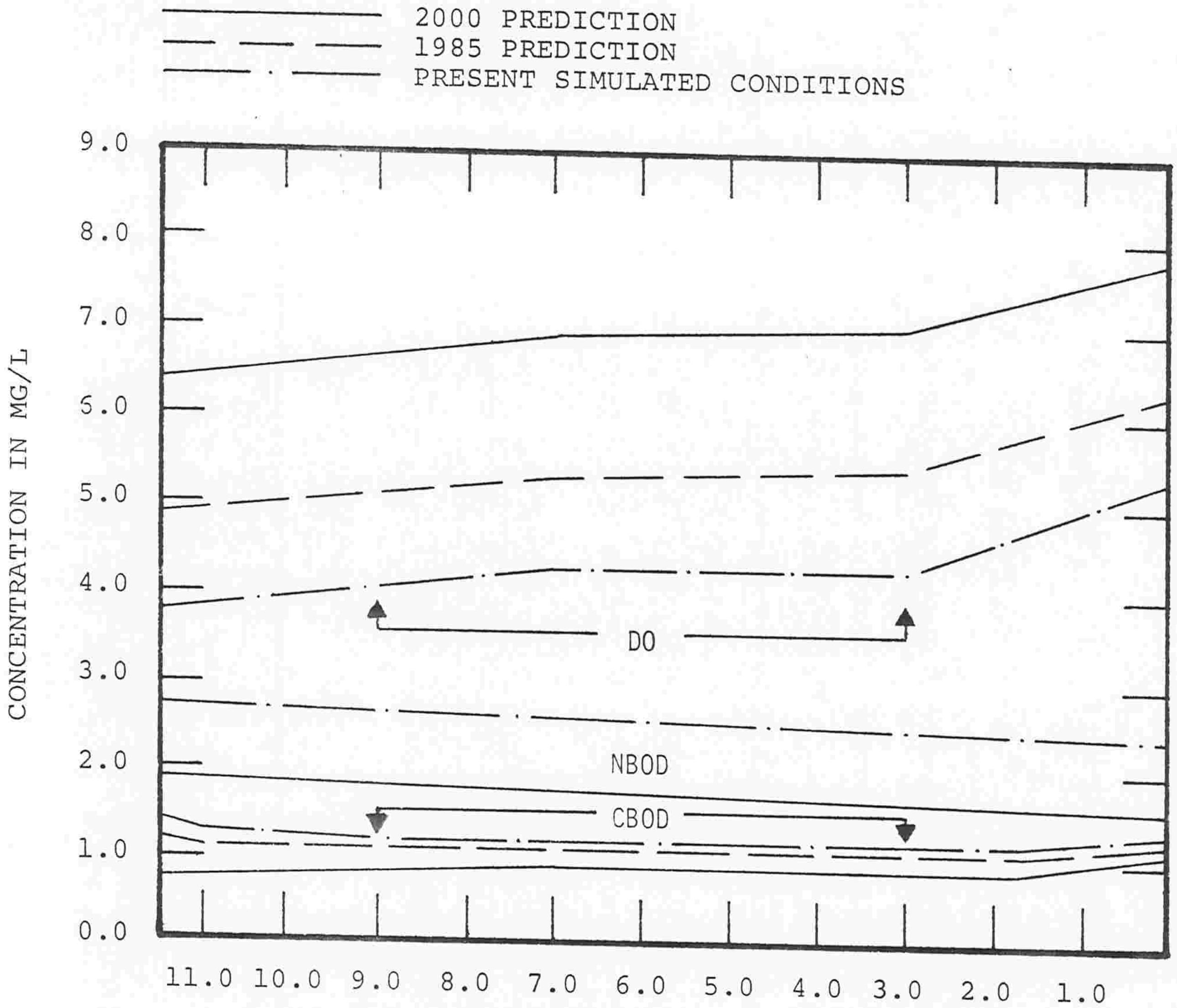


FIG. 24. RESULTS OF WATER QUALITY PREDICTIONS FOR THE YEARS 1985 AND 2000

For the year 2000 in which secondary treatment is assumed to exist, the following improvements over present levels of water quality resulted: (1) an average decrease in CBOD concentrations of 32.4 percent; and (2) an average increase in DO levels of 65.5 percent. Since there was no further reduction of NBOD assumed for secondary treatment, no improvement of in-stream NBOD concentrations resulted in the prediction for the year 2000.

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CHAPTER V

DISCUSSION

INTRODUCTION

The application of QUAL-1 to the Santos estuary presented a unique problem. The usual methods of simulating the water quality of a stream or estuary did not always apply to this situation.

Due to the absence of data concerning waste discharges, locations and amounts of wastes entering the estuary had to be estimated from the calibration of the model. In the case of system parameters and dissolved oxygen, this information was known prior to the application of the model, and it was used as input for the calibration.

WATER QUALITY DATA

The seasonal averages used in the calibration of QUAL-1 were based on four samples at each sampling station. The summer data showed greater variation and larger 80 percent confidence limits than the winter data, and therefore the winter seasonal model was calibrated first.

Two reasons are offered for the greater variation of summer water quality data. The summer data were collected on six separate days, and the winter data were collected on four days. The variations in the power plant flow and waste discharges could have caused greater deviation in the concentrations of the water quality parameters that were sampled. Also, the summer field study was conducted before the winter study. This was the first attempt to collect water quality data in the estuary. Due to the period of time needed to develop the skills associated with the collection and analysis of samples, the first study may have been the less accurate of the two.

MODEL APPLICATION

The application of a one-dimensional model to the stratified system is considered by the author as a preliminary effort to simulate the water quality of the estuary. The results of the model should be considered as time-averaged water quality, and the problems incurred during this study should be considered in further applications of other mathematical models to the estuary.

One aspect that was not considered in this study because of limitations in the model used was the relationship between DO and salinity. The addition of chlorides to water lowers the saturation concentrations of dissolved oxygen. This reduction of DO saturation levels implies that the DO concentrations predicted by the model exceed levels that are expected with salinity taken into account. The difference in the saturation values is approximately 1.2 mg/l for the range of summer seasonal temperatures and approximately 1.4 mg/l for the winter seasonal temperature range (Metcalf and Eddy, 1972). This suggests that the removal rates used in this study may be greater than the rates under actual conditions, because a lower rate of deoxygenation would be needed to achieve the observed DO levels for the calibration of the model.

REALISM OF ESTIMATED WASTE LOADS

The flows and loadings of the waste discharges that had to be estimated for simulation purposes are considered by the author as realistic. A loading of 162,000 pounds per day of untreated biochemical oxygen demanding material (50 percent CBOD and 50 percent NBOD) was estimated for all wastes entering the freshwater portion of the Cubatao River. The total waste flow was calculated to have a DO level of 0.5 mg/l. Other loadings such as the canals and estimated discharges to the estuary are reasonable, but verification of these sources is impossible due to absence of data at this time.

CONFIDENCE IN PREDICTIONS

The predictions made in this study are considered by the author as reasonable, but the degredation of the water quality of the Santos estuary has reached an advanced stage. Construction of treatment facilities probably will not begin in the near future, and further deterioration of water quality may result. Improvement of the quality of the Santos estuary will require a substantial amount of time, and predictions made in this study are only estimations of a very complex situation.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Model Structure

1. QUAL-1 gave approximate results for the stratified system with the physical and hydraulic data used.
2. Problems (e.g., a high dispersion coefficient) occurred in the application of the model because of the strong density stratification, and these problems must be considered in further analysis of the estuary.
3. A two-layered or three-dimensional model may be more appropriate to the estuary than QUAL-1, the model used in this study.

Model Application

1. A present total BOD loading of 162,000 pounds per day at a DO level of 0.5 mg/l was estimated for the waste loadings that discharge to the freshwater portion of the Cubatao River.
2. The water quality parameters of BOD and DO in the estuary are most influenced by the water quality of the Cubatao River, which is controlled by the industrial waste loadings discharged to the River. Results of the analysis are as follows:
    a. For each percent change in the CBOD loading of the Cubatao River, an average change of 0.846 percent resulted in the instream concentration of CBOD.
    b. For each percent change of total BOD in the Cubatao

River, an average change of 0.398 percent resulted in the instream concentration of DO.

3. Results of the sensitivity analysis show that the water quality of the estuary also is influenced to a lesser extent by other parameters as described below:
    a. For each percent change of BOD in the estimated discharges to the estuary, a 0.0619 percent change in average instream DO levels resulted.
    b. For each percent change of CBOD in the estimated discharges to the estuary, a 0.134 percent change in the average CBOD concentrations of the estuary resulted.
    c. A 100 percent decrease in the reaeration rate gave an average decrease of 18.6 percent in the DO concentration over the estuary, and a 100 percent increase in the reaeration rate gave an average increase of 12.7 percent for DO values.
    d. A 75 percent decrease in the dispersion coefficient gave an average decrease of 27.3 percent in salinity over the estuary, and a 100 percent increase in the dispersion coefficient yielded an average increase of 6.00 percent.
4. A level of secondary treatment for all discharges in the Santos area may be necessary to maintain a level of 5.0 mg/l of dissolved oxygen over the entire length of the estuary based on the information used herein.

RECOMMENDATIONS

1. A water quality sampling program should be begun in the

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Cubatao River Basin which includes the following:

a. Monthly sampling with depth at existing stations (or at more convenient stations) in the Santos estuary for temperature, CBOD, NBOD, and DO;

b. Measurement of velocity profile with depth in locations in the estuary with reasonable cross-sectional areas;

c. A schedule of sampling and reporting (including flow information) for dischargers of pollutants to the Cubatao River Basin, including the Santos estuary, to determine if the loadings for the wastes as computed in this report are correct; and

d. A sampling program to determine the flows and water quality of the freshwater tributaries and canals which flow into the Santos estuary.

2. Daily records of meteorological data for the Santos area should be kept in case these data are needed for a simulation of temperature in the next application of a mathematical model to the Santos estuary.

3. If QUAL-1 is used in a second application to the Santos estuary, the equation for the calculation of dissolved oxygen saturation should be modified to include the effects of salinity.

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VITA

Fritz Wagener, III was born in Gainesville, Georgia on May 21, 1952, the son of Myrtle Weaver Wagener and the late Fritz Wagener, Junior. After completing his work at Toccoa High School, Toccoa, Georgia in 1970 he entered the Georgia Institute of Technology, Atlanta, Georgia. He received the degree of Bachelor of Chemical Engineering under the Co-operative Plan in August, 1975 from the Georgia Institute of Technology. In September, 1975 he entered the Graduate School of the University of Texas at Austin to study Environmental Health Engineering.

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