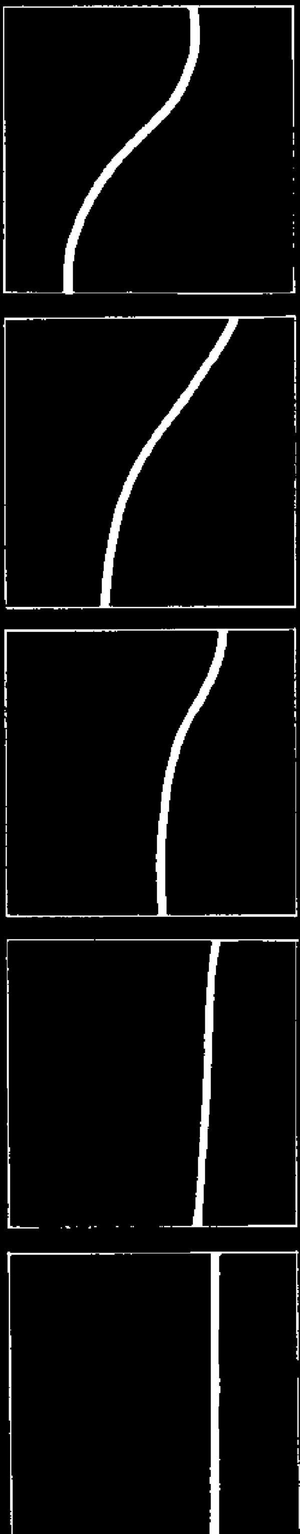

Applying a Water Quality Model to Pollution Management

M. L. Spaulding
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Ocean Engineering
NOAA Sea Grant
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Marine Technical Report 26

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D.O.-B.O.D. in Narragansett Bay

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INTRODUCTION

For centuries man has been using the most convenient and economical means of sewage disposal -- direct discharge into rivers, estuaries and coastal waters. However, with today's population and industrial growth, waste loads are increasing at a rate greatly exceeding the normal self-cleaning capacities of these bodies of water. This situation has brought about the formation of governmental and citizen bodies to address this problem in water pollution management. With this overall problem as a starting point, researchers have progressed rapidly in developing and applying mathematical models for various water quality reaction schemes. These can present technical alternatives for solution of specific pollution problems to political, legal and administrative decision-makers.

To help provide such technical alternatives, we developed a water quality model for the dissolved oxygen-biochemical oxygen demand (D.O.-B.O.D.) scheme for Narragansett Bay. This model is essentially a finite-difference solution to the mass transport equation which assumes lateral integration and a dimensionless vertical axis. The model is described in detail in reference 1.

This report will use the model to verify the D.O.-B.O.D. profiles for typical summertime conditions in Narragansett Bay. We will then use the model as a predictive tool for Bay pollution management by taking into account (1) variations in D.O. profiles caused by surface water temperature changes, (2) the storm-sewage overflow problem and (3) projections of D.O.-B.O.D. levels for the Bay in 1990.

WATER QUALITY MODEL: VERIFICATION OF THE D.O.-B.O.D. PARAMETERS

This study uses the model to compute D.O.-B.O.D. values for Narragansett Bay under typical summertime conditions to verify these things: the computer-modeled D.O.-B.O.D. reaction scheme, which assumes a dimensionless vertical axis; the processes of reareation and B.O.D. decay, and pollutant point loading.

This study uses a current list of pollution sources compiled by the Environmental Protection Agency (Northeastern Area) and the Rhode Island Department of Public Health, published by the Providence Journal Bulletin Company (2). Figure 1 shows sewage loads deposited directly into the estuary. Table 1 lists these loads under both normal (to water) conditions characteristic of dry weather as well as overflow (raw) loading conditions characteristic of rainy weather. In this report, these pollutant load levels represent the simple carbonaceous B.O.D. loads deposited directly into the Bay.

Figure 2 shows how the Bay has been divided into finite grids for modeling both tides and water quality (see reference 1). Reference 1 also outlines in detail how tidal movements were simulated for the model; essentially a net outward flow was added to laterally-averaged components of longitudinal velocity taken from a two-dimensional vertically-averaged tidal hydraulic model.

The authors used samples from the Providence River to determine a preliminary characteristic value of the B.O.D. decay coefficient. Employing a log-type daily-difference approach using the 1, 3, 5 and 7-day B.O.D. values, the decay coefficient was found to be in a range between .065 day^{-1} and .25 day^{-1}. Therefore, as a preliminary estimate, the B.O.D. decay coefficient was approximated at .08 day^{-1} over the entire Bay area. Further work will be necessary to determine more accurate values for this coefficient.

The reareation coefficient formulation for model use was taken from the work of Krenkel and Thackston (3) and modified; the average value obtained was about .25 day^{-1}. This classical reareation formulation was difficult to apply since, like all other presently available empirical formulation techniques of reareation, it incorporates the actual molecular surface transport of oxygen as well as a dispersion coefficient for the entire water column which characterizes the movement of oxygen to the lower depths. To overcome this problem, instead of using the difference between the surface saturation value of D.O. and the value at the surface as the driving potential for reareation, this study uses the difference between the saturation level

TABLE 1. Sources of sewage pollution for Narragansett Bay, Oct. 1971.

STATION	POLLUTER	LOCATION	RAW LB/DAY	TO WATER LB/DAY	SECTION NUMBER (FIG. 2)
1	Providence S.T.P.*	Providence	54,000	14,000	7
2	Narragansett	Warwick	80	15	11
3	East Greenwich S.T.P.	E. Greenwich	420	40	22
4	Quonset-Davisville Naval Base	N. Kingstown	2,700	1,100	31
5	Navy Housing Development	Wickford	280	30	34
6	University of Rhode Island	Narragansett	40	2	44
7	Blackstone Valley Sewer District	E. Providence	52,200	42,300	-
8	East Providence S.T.P.	E. Providence	5,000	1,000	8
9	Rhode Island Lace Works Inc.	Barrington	2.160	2,160	12
10	Warren S.T.P.	Warren	1,900	1,300	15
11	Bristol S.T.P.	Bristol	3,900	2,000	21
12	Pearson Yacht Division of Grumman Allied Industries Inc.	Portsmouth	40	4	25
13	Melville Naval Fuel Depot	Portsmouth	181	161	29
14	Raytheon Company	Portsmouth	164	15	29
15	Newport S.T.P.	Newport	6,700	6,200	39
16	Jamestown Sewer	Jamestown	260	260	42
17	Jamestown Sewer	Jamestown	30	30	42
18	Fort Adams Navy Housing Complex	Newport	170	130	43

*S.T.P. = sewage treatment plant

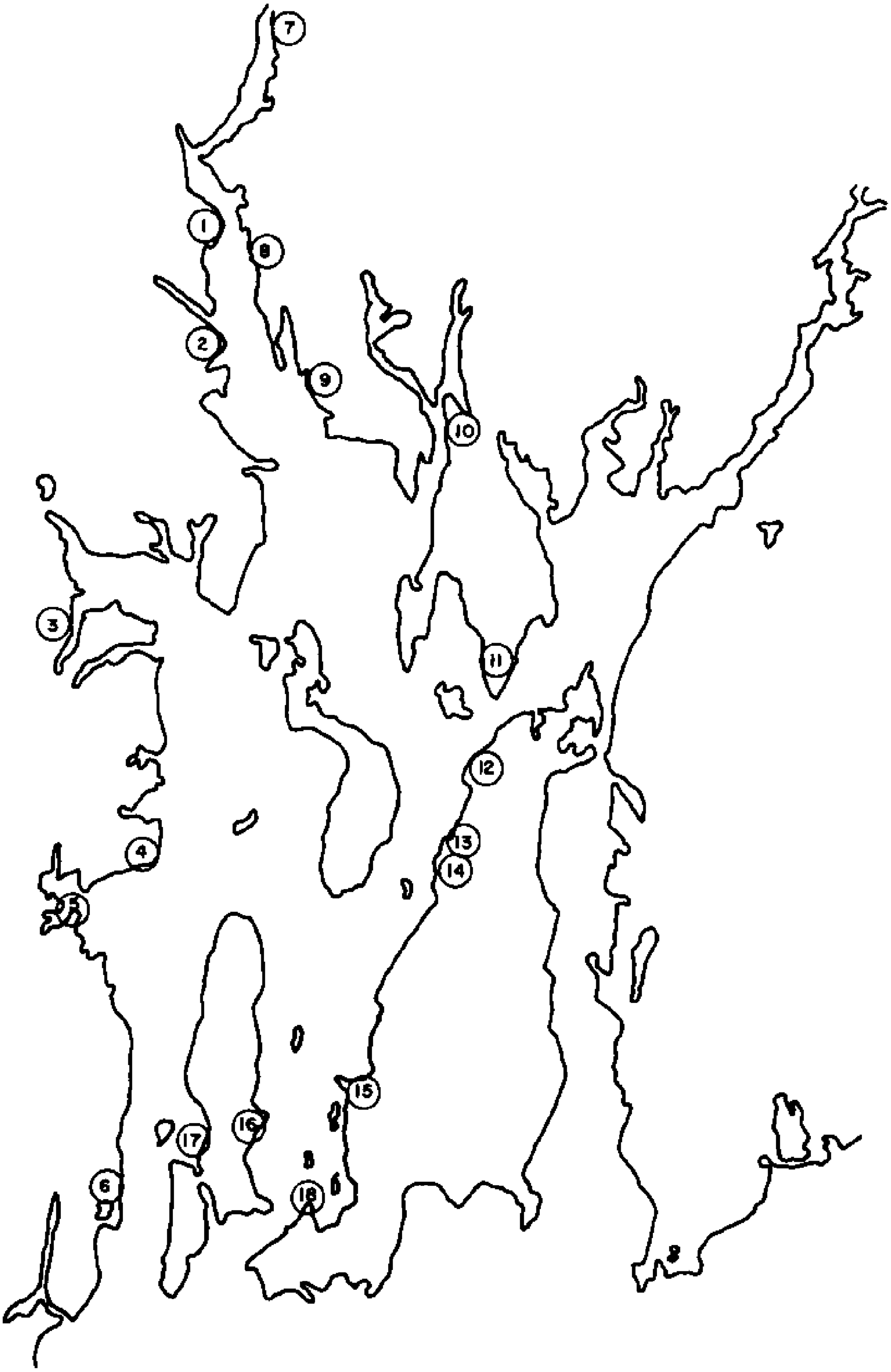

FIGURE 1. Location of sewage pollution sources as listed in table 1.

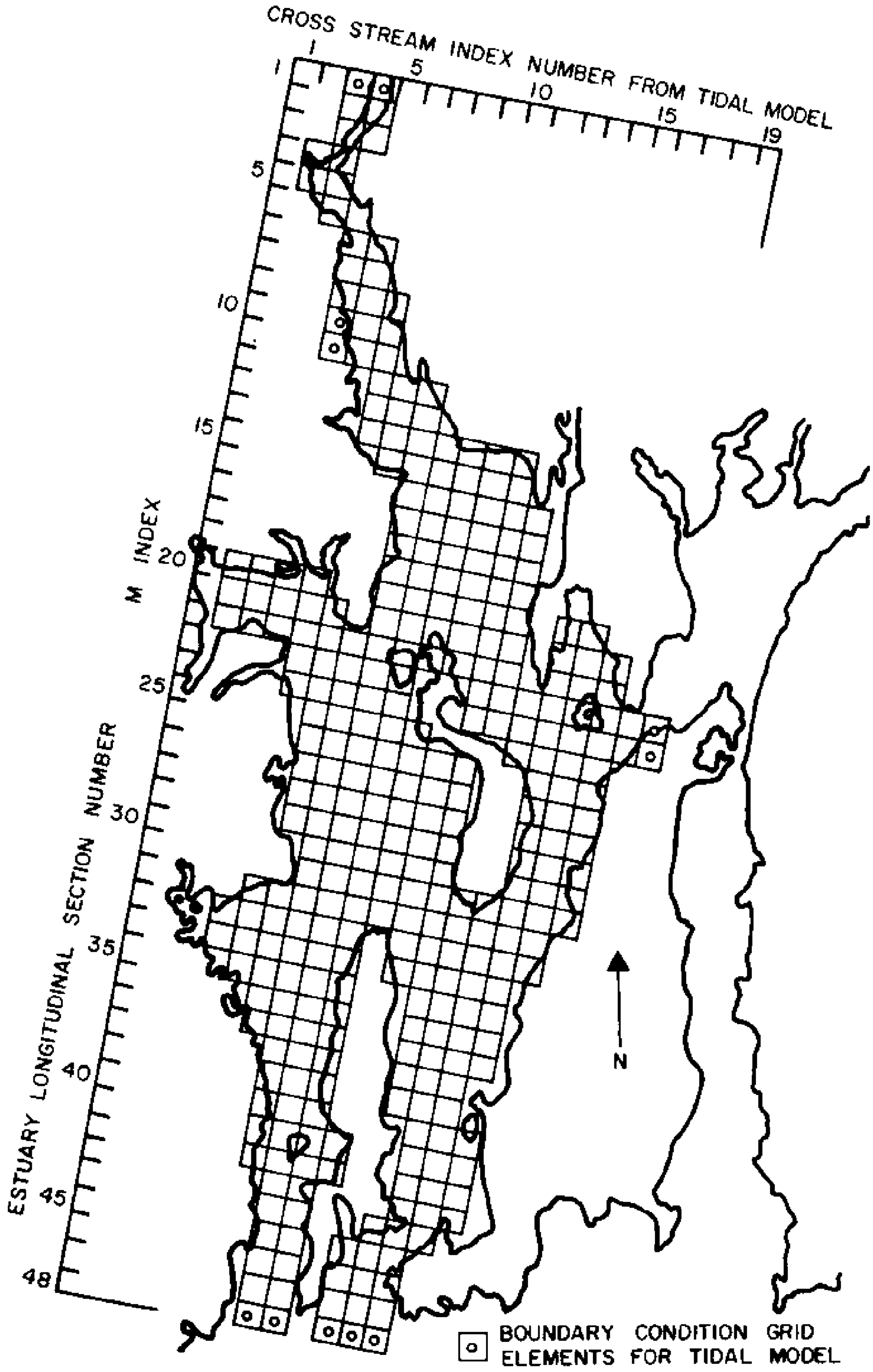

FIGURE 2. Longitudinal estuary section number locations for Narragansett Bay.

and the average value of D.O. for the whole column of water. This technique appears to have substantially solved the problem and provided reasonable reareation rates for the Bay.

A modified version of Elder's formulation (4) was chosen as the longitudinal dispersion coefficient with values of approximately 45 ft^2/sec. Pritchard's density-corrected vertical dispersion coefficient (5), with values ranging between .0001 ft^2/sec and .02 ft^2/sec depending on the gradients in the salinity field, was employed to define the density structure of the Bay.

To help summarize the input for the D.O.-B.O.D. simulation of Narragansett Bay, table 2 presents the values employed in the computer modeling effort. This table also indicates location of the data or the formulation scheme.

To compare the results from the computer model to actual Bay conditions, data for both B.O.D. and D.O. were collected from the Rhode Island Department of Public Health (6), the Army Corps of Engineers Hurricane Barrier Study (7), and the University of Rhode Island's Bay Watch water sampling program (8). The values were then averaged over the summer season for each sampling program and station, then averaged again across each longitudinal estuary section grid in figure 2. The sampling results for D.O. and B.O.D. for both top (5 feet below water surface) and bottom (5 feet above estuary bottom) samples were then plotted against the longitudinal estuary section number. Starting with a set of initial conditions for both D.O. and B.O.D. taken from these data, the computer model was run. Computer input conditions are presented in table 2. The model runs were continued until a quasi-steady condition was reached, determined by no significant change in the depth-averaged D.O. and B.O.D. profiles other than that caused by tidal fluctuations. This process required approximately 30 days simulation time. Figures 3 and 4 show computed profiles for both depth-averaged and top and bottom stations compared to data for the D.O. and B.O.D. values, respectively. Error bars used on both figures show maximum or minimum levels found in the computer model results.

Figure 3 shows that for both the depth-averaged and the top sampling stations, the comparison between estuary D.O. data and modeled results is good to excellent while the agreement for bottom sampling station results is only fair to good. B.O.D. profiles, as shown in figure 4, appear to be in good agreement in the upper Bay, but display considerable variation between model results and actual data in the lower Bay.

Major contributors to the lack of agreement between model results and actual data are chiefly the following: lack of inclusion of any B.O.D. loading due to nitrogenous or benthic demands; less than adequate representation of the actual structure for the vertical dispersion coefficient, need for a biological model to predict D.O. or B.O.D. caused by interaction between phytoplankton and zooplankton

TABLE 2. Summary of input conditions for computer modeling of D.O.-B.O.D. Profile for Narragansett Bay.

MODEL DATA INPUT	RANGE OR VALUE	COMMENTS
Tidal Velocities and Heights	-	Determined by forcing one-dimensional continuity on tidal model (4) output with net outward flow
Longitudinal Dispersion Coefficient	45 ft^2 per sec	Modified Elder (4) formulation with 25 ft^2/sec added for wind effect
Vertical Dispersion Coefficient	.0001-.10ft^2 per sec	Pritchard formulation (5) with vertical structure determined by salinity profiles and wind effect included with WH = 3 ft; WT = 6 sec; WL = 200 ft
Temperature	65° F	Approximate summer average value
B.O.D. Decay K_D	.08 day^{-1}	Experimentally determined
Reareation K_A	.25 day^{-1}	Modified Thackston-Krenkel formulation (3) to obtain ~ .25 day^{-1}
Water Quality Boundary Conditions for D.O. and B.O.D.	Seekonk <u>River Boundary</u> B.O.D. = .2077 (VSN) + 1.392 D.O. = .1538 (VSN) + 1.392 <u>Ocean Boundary</u> B.O.D. = 0.0 D.O. = Saturation Value	Determined from existing data (6, 7, 8, 9) where VSN (vertical section number) 2 → 15, bottom to top, respectively and units for B.O.D. and D.O. are mg/l
B.O.D. Loading from Point Sources	-	Given in table 1 with distribution over vertical
Salinity	27.2-34.‰	Determined from existing data (7, 8)

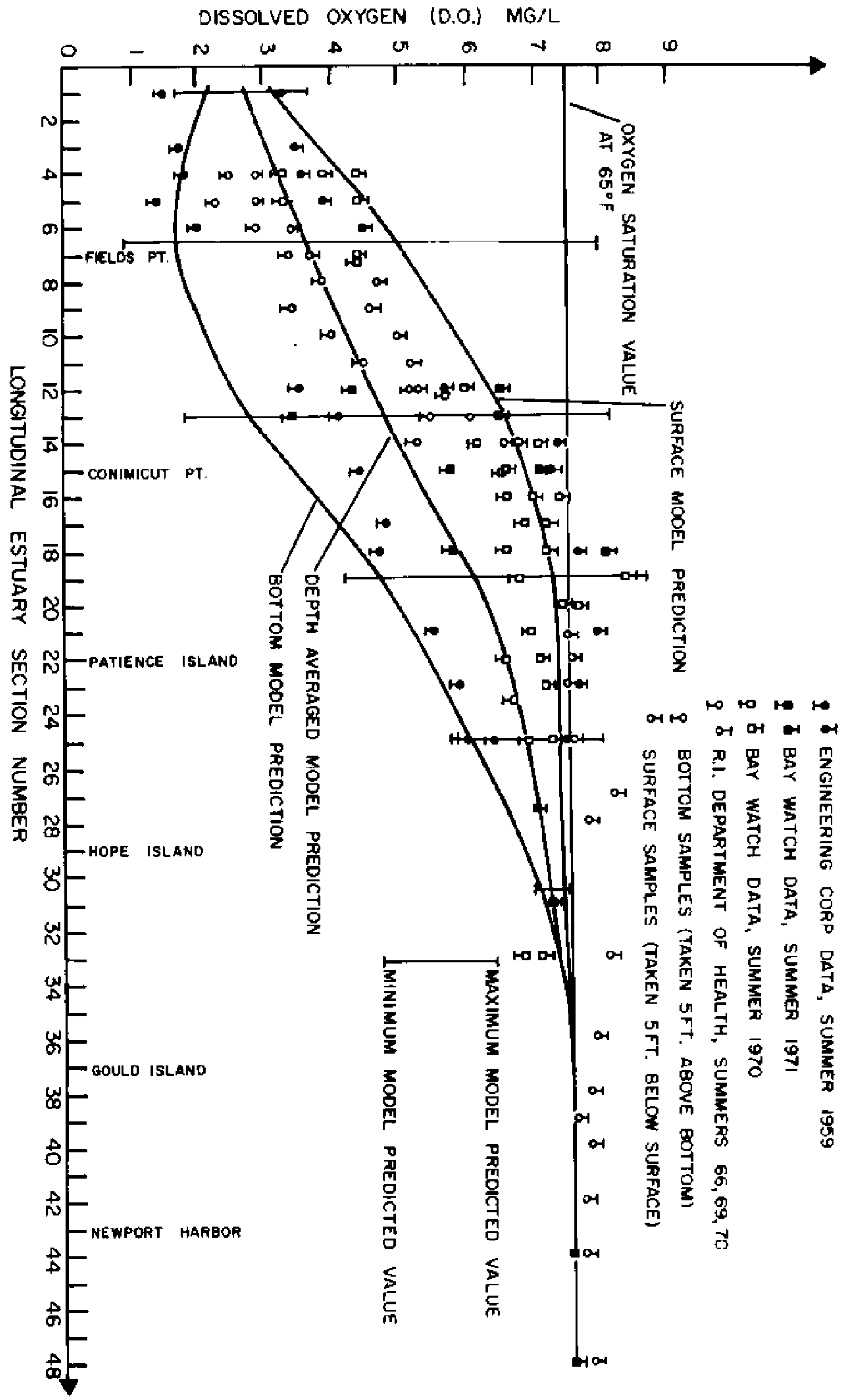

FIGURE 3. Comparison of model predicted D.O. profiles to data for Narragansett Bay.

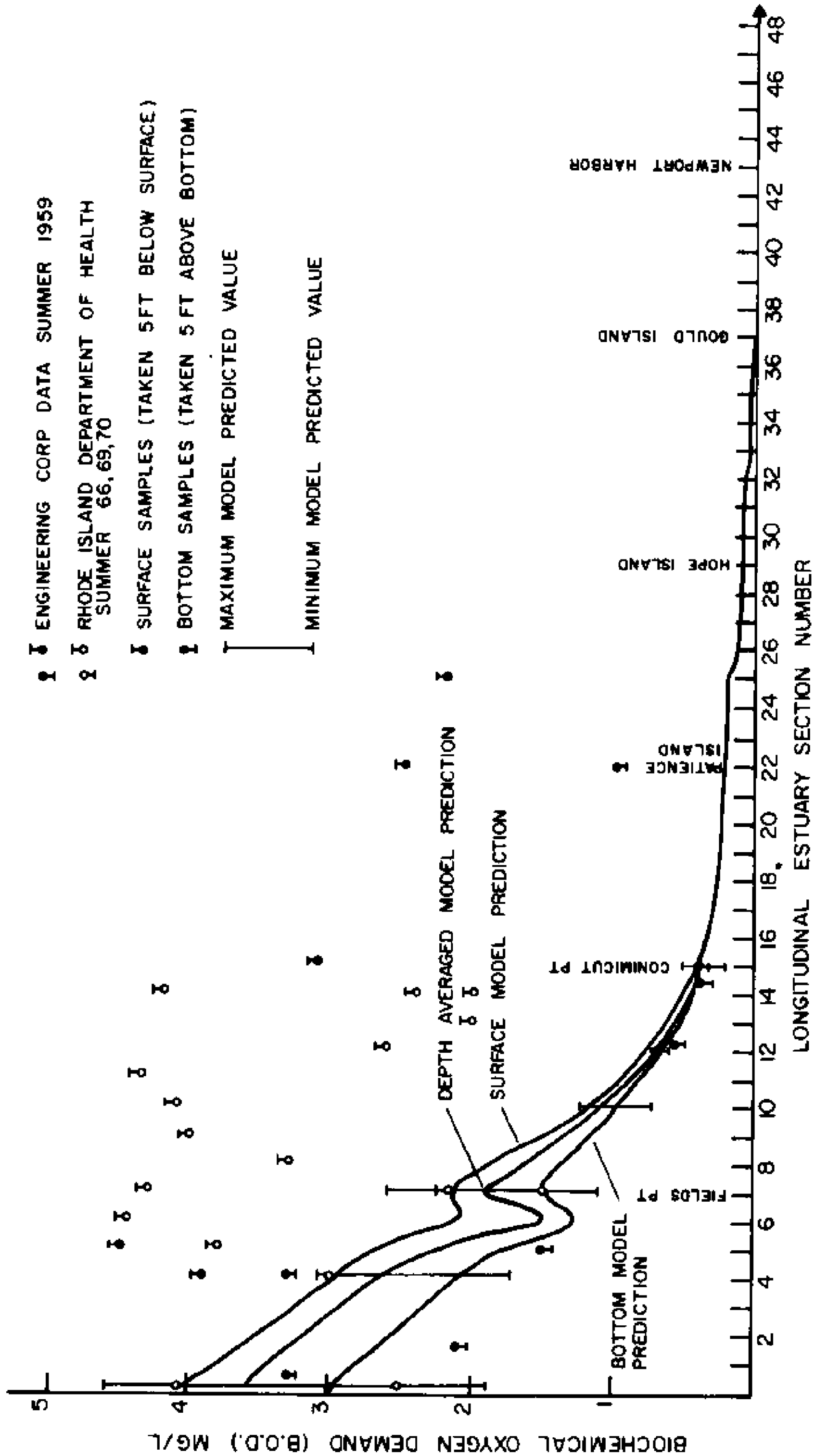

FIGURE 4. Comparison of model predicted B.O.D. profiles to data for Narragansett Bay.

populations; lack of knowledge about the loading distribution over the vertical sections, and only fair estimates of the coefficients for both reareation and B.O.D. decay. However, in light of all these difficulties, the computer model results appear to be in good agreement with the Narragansett Bay data.

Another important model output is a time-varying plot of the D.O., B.O.D. and tidal height for any particular location in the estuary. Typical outputs from the model appear similar to figure 5. Of particular significance is the fact that the variations of D.O. and tidal height are approximately in phase, while the B.O.D. profile is consistently out of phase. This effect can be quite simply explained. As water progresses up the Bay (flood, rising tide), cleaner water (higher D.O. levels) characteristic of each higher longitudinal section number of the Bay is carried up toward Providence. The opposite process occurs during ebb tidal flow. Thus, we can see why the D.O. and tidal height are in phase. Using a similar argument to explain why B.O.D. levels become higher as one proceeds from the Bay mouth to Providence, the B.O.D. levels should increase as the tidal flow ebbs. But, there are cases where D.O. and B.O.D. are in phase, but 180 degrees out of phase with the tidal height. This situation can occur when there is a dip in the D.O. profile, such as in figure 3 in the bottom values predicted by the model. Also of concern is the variation in D.O. and B.O.D. levels over a tidal cycle. Typical changes between mean low water and mean high water, and overall depths range between 10 percent and 20 percent of the averaged value of the mean tidal cycle. These variations appear to be considerably smaller than those noted during the Army Corps of Engineers Survey (7) of 1959, but the differences are more than likely attributable to inadequacies in incorporating short-term and transit phenomena in present model development.

Probably the single most important feature of the model is its ability to predict vertical structure for both D.O. and B.O.D. The variations over depth in each of these cases are determined by loading distributions from B.O.D. and D.O. sources as well as the vertical dispersive structure. The variations caused by vertical velocity components have been considered small and, thus, have been neglected in the present modeling effort. To determine the loading distribution for sources of B.O.D., it was assumed that sewage discharge was buoyant when entering the estuary. Therefore, the loading for all cases was evenly distributed over the top five non-dimensional grids except when the loading in shallow water areas was large (more than 10,000 lbs B.O.D. per day). In these cases the load was evenly distributed over the entire water column. Regarding reareation, oxygen was assumed to enter only at the estuarine surface. Defining accurate values for variable coefficients for the vertical dispersion formulation was impossible due to lack of any data of this kind for Narragansett Bay. Hence, the standard Pritchard constants were used and the results viewed accordingly.

A partial view of the vertical structure has already been noted in figures 3 and 4 which show that the trends of higher B.O.D. and D.O. that occur near the surface have been qualitatively predicted by the model. Figures 6 through 11 show comparisons of actual D.O. field data to model prediction plotted against depth for several sections of the Bay. The figure order shows a logical progression from upper to lower Bay vertical D.O. structure. The depths listed on the figures often do not correspond to actual estuary depths at those stations, but are actually cross-sectional averages and should be interpreted in that manner. Careful observation of figure 7 through 11 shows a progressive case of increased vertical mixing as one proceeds from the Providence Hurricane Barrier to Beavertail at the mouth of Narragansett Bay. This fact has been well confirmed by observation of salinity profiles in the area over many years. The Seekonk-Red Bridge area (see figure 6) does not display the severely inhibited vertical mixing structure due to its upper boundary condition approximations and its large land and river inflows. Comparison of the data obtained from references (6, 7, 8, 9) and from a current URI Bay Watch sampling program show that the model results are remarkably good, considering that the vertical structure of the dispersion coefficient has been taken from a standard Pritchard formulation and that the B.O.D.-D.O. loading distributions have been rather crudely approximated. The model results shown in the figures represent approximate mean tidal averages and, therefore, are subject to a 10 percent - 20 percent deviation in either direction due to the influence of tidal variation.

Profiles of the vertical structure of B.O.D. have not been presented since all data sets available have taken only top and bottom samples of B.O.D. and these results have already been adequately presented in figure 4. They, however, would more than likely display a somewhat similar vertical structure, varying only in sections where large B.O.D. loadings were made.

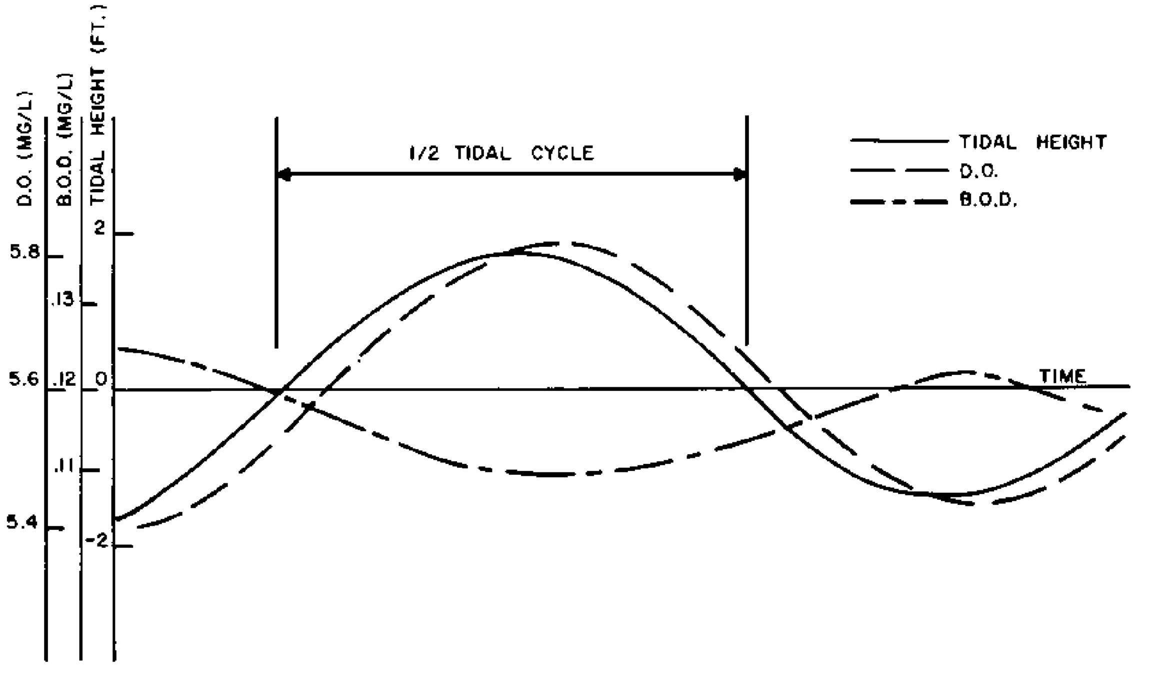

FIGURE 5. Typical variations of D.O., B.O.D. and tidal height for a given location in Narragansett Bay.

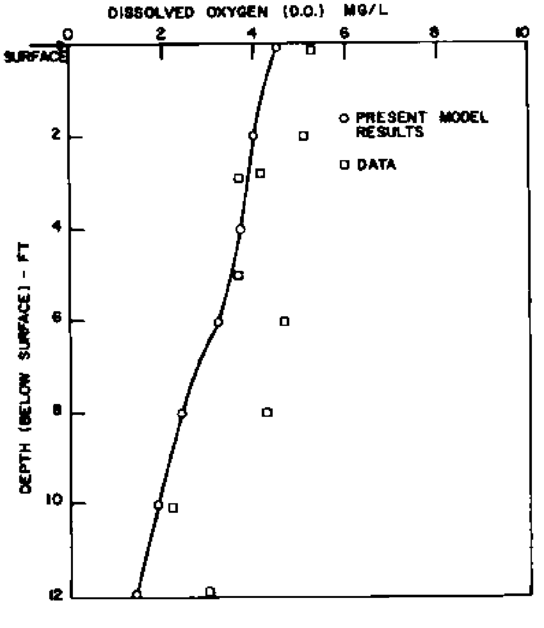

FIGURE 6. Comparison of D.O. vs. depth for data and model results at longitudinal grids 5.

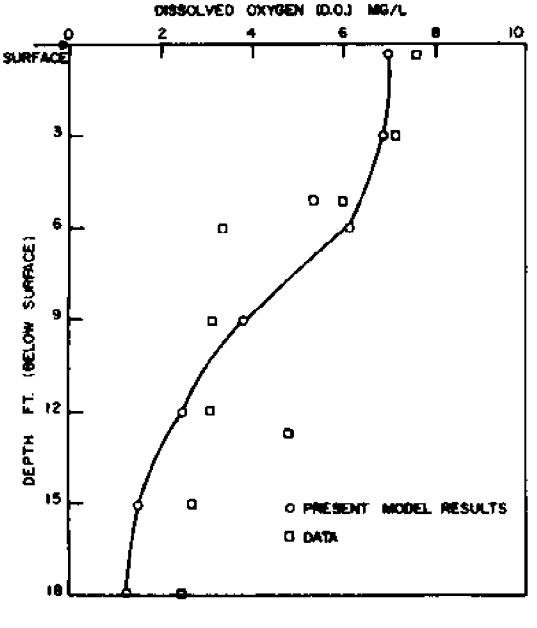

FIGURE 7. Comparison of D.O. vs. depth for data and model results at longitudinal grids 2.

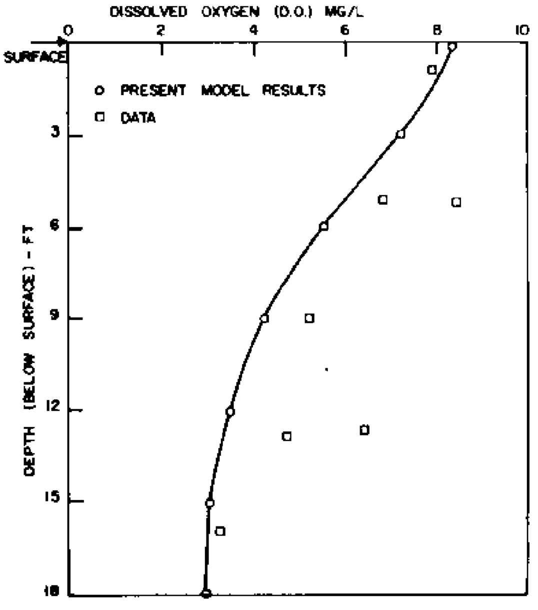

FIGURE 8. Comparison of D.O. vs. depth for data and model results at longitudinal grids 15.

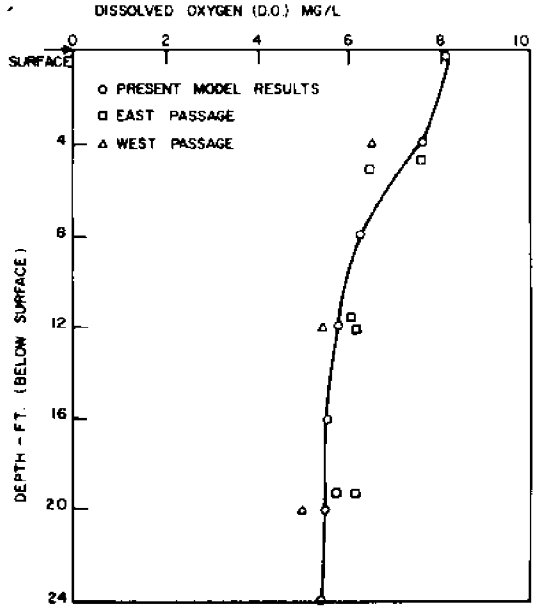

FIGURE 9. Comparison of D.O. vs. depth for data and model results at longitudinal grids 24.

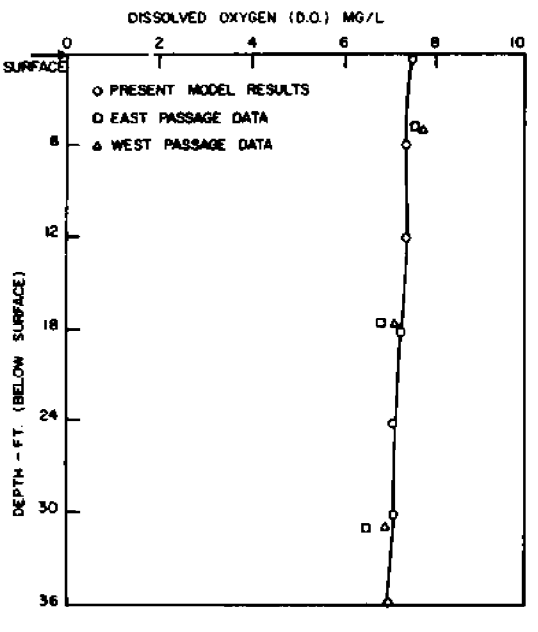

FIGURE 10. Comparison of D.O. vs. depth for data and model results at longitudinal grids 33.

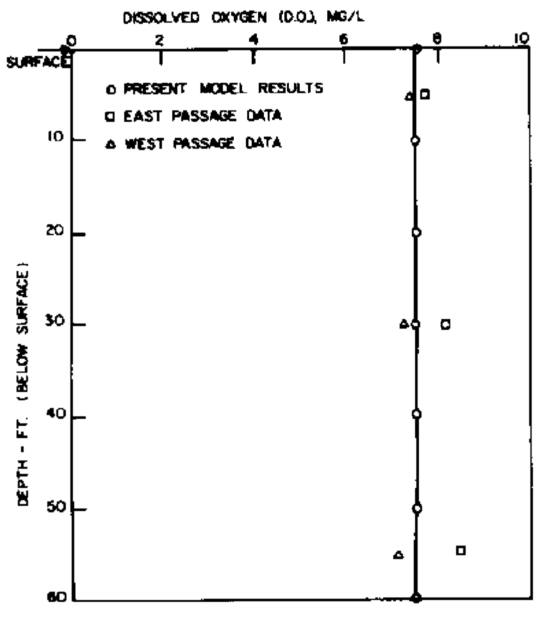

FIGURE 11. Comparison of D.O. vs. depth for data and model results at longitudinal grids 47.

WATER QUALITY MODEL: APPLICATION OF THE D.O.-B.O.D. REACTION SCHEME

Once a model has been developed and verified to predict actual estuary D.O. and B.O.D. levels with reasonable accuracy, the next step is to apply that model to some specific problems and, thus, begin to use it as a predictive tool in coastal water pollution management.

In the following sections the model will be applied four ways to show: (1) effects of surface-water temperature on the D.O. profiles; (2) a typical storm-sewage overflow case; (3) an accelerated estuary cleanup run (removal of B.O.D. loadings), and (4) a projection of the D.O.-B.O.D. profiles for 1990.

Temperature Effects

To simulate the effect of variation in water temperature on the D.O.-B.O.D. profiles, the computer model was run for two different water surface temperature levels, 65° F and 55° F, which were kept constant over the entire Bay until a quasi-steady-state was achieved. Figure 12 presents the comparison of the D.O. and B.O.D. profiles for each case. Since the effect of temperature is included only in the saturation and reareation values of D.O. at the estuary surface, one would expect changes only to occur in the level of D.O. in the water column. This indeed is the case as shown in the figure for these vertically-averaged profiles.

Vertical profiles of D.O. show that the increase in oxygen saturation levels increases the D.O. levels at all depths with little change in the overall vertical structure. It is evident from viewing this simple comparison that slight changes in water temperature have a major effect on the oxygen saturation and reareation processes.

Storm-Sewage Overflow

Typical sewage overflow characteristics for a one-day period were applied to the model for Narragansett Bay; the Bay was then "allowed to" reach its quasi-steady-state value once again. The levels of these overflows were taken as the raw loadings given in table 1, while normal loadings corresponded to river values in that table.

Figures 13 and 14 display the values of the D.O. and B.O.D. depth-averaged profiles, respectively. From the inserted graph, we can determine the approximate time of overflow conditions and the subsequent return to normal loading situations. As expected, the levels of D.O. drop due to the excess loads while the B.O.D. values rise rather substantially (especially in high load areas); and both appear to reach their maximum or minimum levels, respectively, at the end of 40 hours. This trend is to be expected since when the excess loading ceases, the process of B.O.D. decay continues in its customary concentration-dependent manner. The decrease in D.O. between initial levels and minimum value ranges approximately from 2 percent to 5 percent while B.O.D. levels display deviations as large as 175 percent from the initial value.

Note that in the area of longitudinal estuary section 6 and 7 large differences appear in the B.O.D. levels. The relatively high value for section 7 can be explained by an excessively large load in that grid, while the relatively low value in grid 6 is attributable to the adjustment in the finite-difference approximation for the large point loading in 7 and insufficient local dispersion.

The next major point of interest is to determine the approximate period of time required for the estuary to recover from this excess load and return to its normal quasi-steady-state values for both D.O. and B.O.D. With this goal the average section-depth profiles for D.O. and B.O.D. were compared to the initial values until agreement between the two was achieved; that is, both reached the same depth-averaged value for a given longitudinal section. Preliminary results show that the time from which the excess load was stopped to the time of approximate steady-state levels occurred in about 2-1/2 days. This number appears reasonable when compared to the 5-7 day estimate used by the Rhode Island Department of Public Health to determine closing times for the shellfish areas in the upper Bay after periods of significant rainfall.

Plots of the vertical structure for the Bay were not made since they show similar trends to the normal sewage loading verification run. Variations of D.O. and B.O.D. levels show the expected increases in B.O.D. and decrease in D.O. where loading is high and vice versa where loading is low.

The results of this application run with the computer model are surprisingly good in giving an estimate of the order of magnitude of the "excessive load cleanup time," considering the number of gross approximations made in setting up the model parameters. Further work in this area, however, is undoubtedly needed to provide more accurate predictions.

Removal of B.O.D. Loadings (Cleanup)

In order to verify the reaction scheme for estuarine cleanup, the D.O.-B.O.D. system was run under a zero B.O.D. loading condition. This exercise does not imply any final results of estuary cleanup time, but merely demonstrates the response of the model and the subsequent changes in D.O. and B.O.D. concentrations.

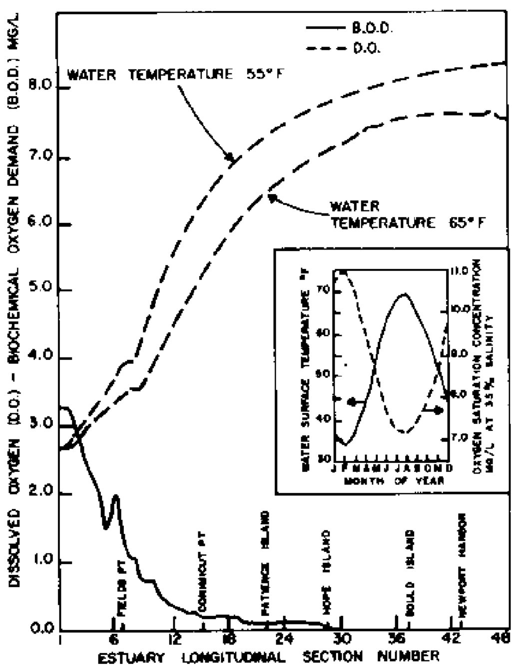

FIGURE 12. Comparison of depth averaged D.O.-B.O.D. profiles for variation in surface water temperature.

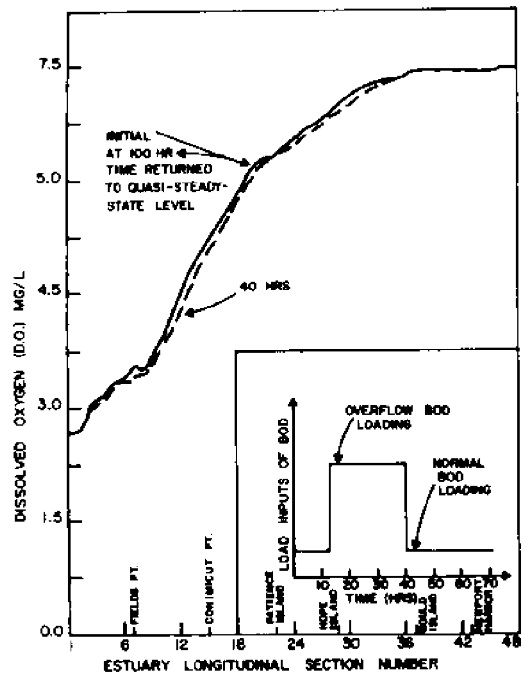

FIGURE 13. Depth averaged D.O. variation caused by overflow B.O.D. loading.

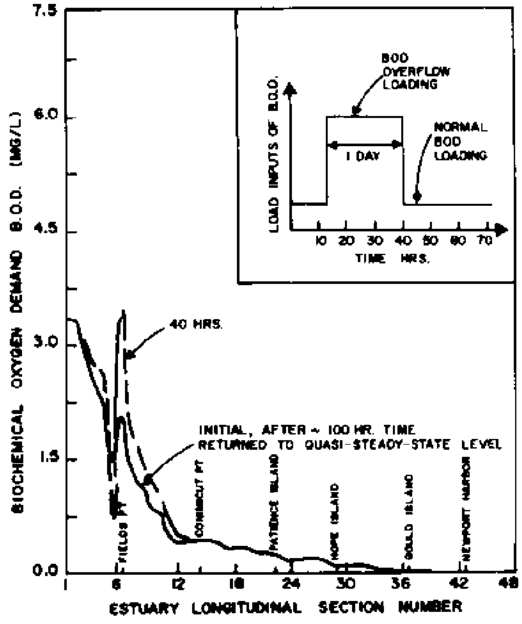

FIGURE 14. Depth averaged B.O.D. variation caused by overflow B.O.D. loading.

Using initial profiles of D.O. and B.O.D. obtained from existing data for the Bay (6, 7, 8, 9), the model was run for a period of about 24 days. All boundary conditions were linearly extrapolated to their cleanup values over a two-day period (i.e., B.O.D. concentration to 0.0 and D.O. concentration to saturation value) and remained constant at that level throughout the following days. Since the reareation process is particularly slow for large, deep bodies of water a value of 30 times the Dobbins-O'Connor reareation coefficient was chosen to accelerate the surface reoxygenation phenomena. The decay coefficient of .25 day^{-1} for B.O.D. was also chosen on the basis of similar reasoning.

Figures 15 and 16 display the vertically-averaged profiles of B.O.D. and D.O., respectively, in four-day intervals beginning with the initial conditions, where the longitudinal estuary section numbers are equivalent to the M values shown in figure 2. The decrease of B.O.D. due to flushing and natural decay processes is readily demonstrated in figure 15. Also note that the decay model for B.O.D. is a first order process, this is clearly demonstrated by the decreasing difference between the B.O.D. profiles as time progresses. Simultaneous with the decrease of these B.O.D. concentrations, the D.O. (figure 6) exhibits the expected increase due to dispersion and reareation. In the early stages from the initial profile to the levels at 12 days, however, the vertically-averaged D.O. concentrations are below the initial level. This phenomenon can be attributed to the large loadings of B.O.D. during the first few days, again, due to the first-order decay process. Another point of interest is the peak which occurs in the area of estuary grids 11, 12 and 13. Careful observation of the grid sectioning in figure 2 shows that there is a factor of about 2 in the change in the cross-sectional area which leads to large velocity changes and subsequent increases in the reareation coefficient.

Projection for 1990

The greatest benefit of the model could be its ability to predict water quality profiles under some new quantitative, temporal, or spatial distribution of pollutant loading. With this flexibility, estimates can be made of the general water quality after projections of pollutant loads and locations have been made, thus, allowing the model to aid in pollution management of coastal waters.

Using data gathered from the State of Rhode Island Water Resources Board (10) and personal interviews with planners from the Rhode Island State Wide Planning Office (11) projections for B.O.D. loading in 1990 were made for all the large municipal sewage treatment plants that deposit wastes directly into the Bay. Tables 3 through 9 present the summation of this data. The projected loadings of B.O.D. were computed by finding a simple ratio -- the relation between estimated daily flows for the present and 1990 and the relation between present and future B.O.D. loadings. Where projections were not available for the daily flows in 1990, estimates were made, under the assumption that the same portion of the projected population will be served by sewers as are being served at the present. These values have been noted by triple asterisks in the tables.

Future sewage loadings caused by sources other than municipal treatment facilities, such as private citizens and small industries, have not been included in the present study. It also is assumed that the present permit granting capabilities of the Army Corps of Engineers and the Environmental Protection Agency will keep the size of these loadings in check.

Employing the projected loadings of B.O.D. for 1990 (table 9) the water quality computer model was run for 12 days until a new quasi-steady-state condition was reached. Boundary conditions for the Seekonk River were estimated on the basis of the change in B.O.D. loadings from the Blackstone Valley Sewer District plant's projected discharge while the ocean boundary condition remained unchanged from the 1972 conditions with zero B.O.D. and saturated D.O. Other parameters, such as decay and reareation coefficients, as well as the vertical loading distribution of B.O.D. remain unchanged from previous runs (table 2).

A comparison of the results for the present levels of D.O. and the 1990 projections are shown in figure 17. The influence of increased capacity and secondary sewage treatment at the Blackstone Valley plant clearly increased the levels of D.O. in the lower regions (Red Bridge Area) of the Seekonk River and upper regions (Sabin Point Reach) of the tidal portion of the Providence River. The levels remained essentially unchanged at Fields Point since the Providence treatment plant's B.O.D. loading remained unchanged. The characteristic sag in the D.O. curve under the assumed new loading conditions has then moved from the Bucklin Point region in the Seekonk River to the Fields Point area in the Providence River. Comparison of the B.O.D. profiles (figure 18) for the same conditions show similar trends with the peak B.O.D. levels occurring in the Fields Point area.

No attempt has been made in the present effort to model either the vertical structure or sewage overflow problem, since we felt that the projections for B.O.D. loadings as well as the upper boundary condition approximation near Bucklin Point are not accurate enough to make these results meaningful.

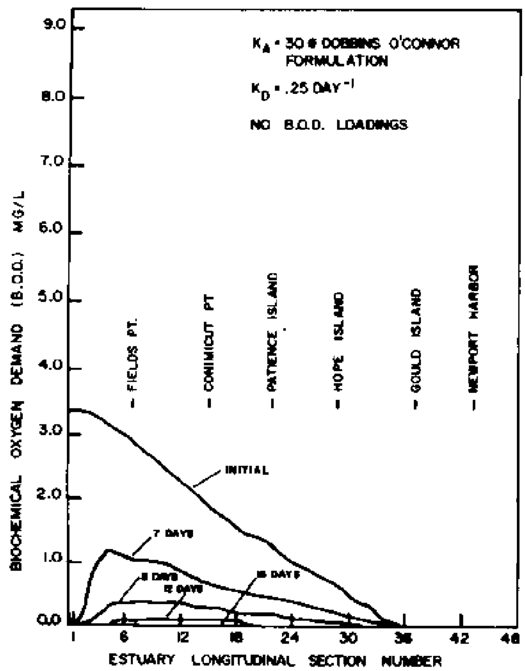

FIGURE 15. Variations in depth averaged B.O.D. for estuary cleanup case.

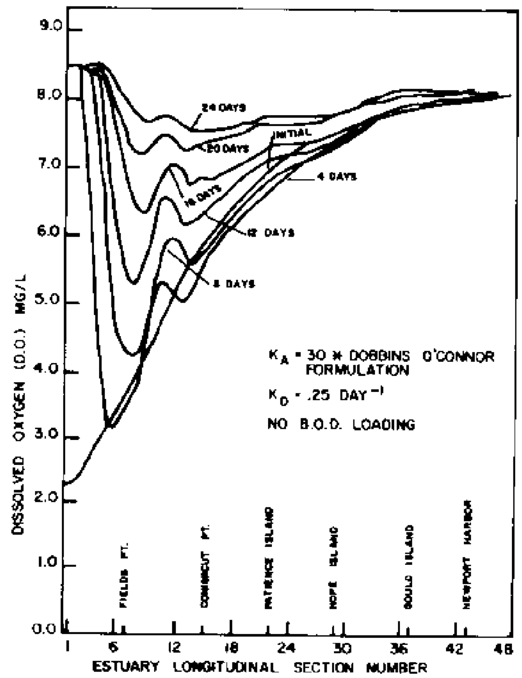

FIGURE 16. Variations in depth averaged D.O. for estuary cleanup case.

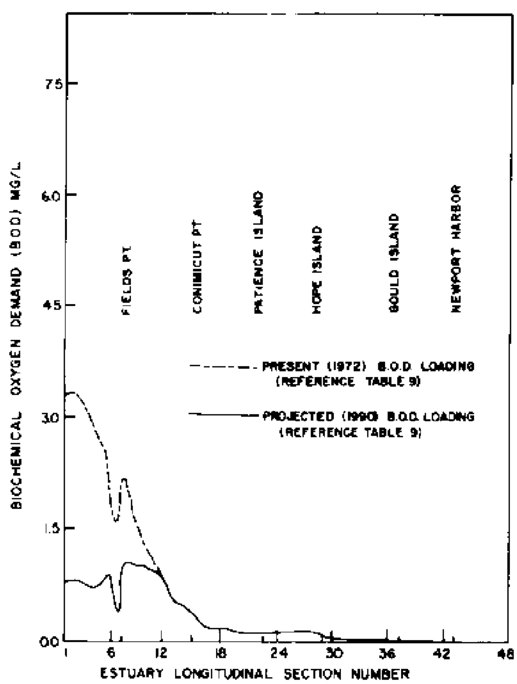

FIGURE 17. Comparison of depth averaged D.O. profiles for present (1972) and projected (1990) B.O.D. loading.

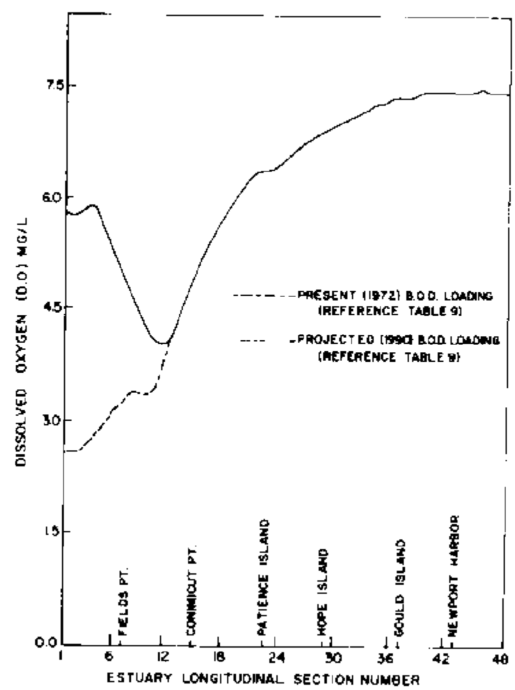

FIGURE 18. Comparison of depth averaged B.O.D. profiles for present (1972) and projected (1990) B.O.D. loading.

TABLE 3. Treatment levels for treatment plants using Narragansett Bay as a disposal municipal sewage area, present (1971) and projected (1990).

	SOURCE OF POLLUTANT (LOCATION)	LEVEL OF TREATMENT (10)*	
		PRESENT (1971)	PROPOSED (1990)
1.	Blackstone Valley Sewer District Commission (East Providence)	Primary + Cl_2	Activated Sludge + Cl_2
2.	Providence S.T.P.**	Activated Sludge + Cl_2	Activated Sludge + Cl_2
3.	East Providence S.T.P.	Trickling Filters + Cl_2	Activated Sludge + Cl_2
4.	Warren S.T.P.	Primary + Cl_2	Primary + Cl_2
5.	Bristol S.T.P.	Primary + Cl_2	Secondary
6.	Newport S.T.P.	Primary + Cl_2	Secondary
7.	Quonset-Davisville Naval Base S.T.P. (North Kingstown)	Primary + Cl_2	Activated sludge +Cl_2
8.	East Greenwich S.T.P.	Trickling Filters, Sand Filters + Cl_2	Trickling Filters, Sand Filters + Cl_2
9.	Jamestown Sewage Treatment	None	Primary + Cl_2

*Numbers in parentheses refer to items in the Reference section of this report.

**S.T.P. = sewage treatment plant.

TABLE 4. Areas served (1971) and projected improvements (1990) in municipal sewage treatment systems.

SOURCE OF POLLUTANT (LOCATION)*	AREA SERVED (10) BY SEWERS 1971	PROJECTED IMPROVEMENTS (10)** IN SEWAGE SYSTEM
1	Central Falls, Cumberland, East Providence, Lincoln, Pawtucket	Extension of system into Cumberland and Lincoln and improved treatment facilities
2	Cranston (industry), Johnston, North Providence, Providence	General improvement of existing facilities
3	East Providence, Barrington	Extension of present facilities to serve Barrington
4	Warren	Extension of present system and disconnection of some storm drains
5	Bristol	Extension of present system to cover all residents
6	Newport, Middletown, U.S. Navy	Expansion and renovation of present system and disconnection of some storm drains
7	North Kingstown	Development of a collection system and expansion of Quonset treatment plant
8	East Greenwich	Collection of industrial waste presently discharged into Hunt River
9	Jamestown	Extension of present collection system and construction of treatment plant

*See table 3, column 1.

**Numbers in parentheses refer to items in the Reference section of this report.

TABLE 5. Population: Total and numbers served by sewers in municipal sewage treatment areas for 1970 (census) and 1990 (projected).

SOURCE OF POLLUTANT (LOCATION)*	POPULATION TOTAL: A. CENSUS [1970] (12) B. ESTIMATES [1990]	POPULATION SERVED BY SEWERS**: A. 1970 (10) B. ESTIMATE [1990] (10)
1	A. 147,077 B. 174,970	A. 99,441 B. -
2	A. 225,587 B. 245,800	A. 225,587 B. -
3	A. 65,751 B. 86,600	A. 34,000 B. 59,000
4	A. 10,583 B. 12,800	A. 7,500*** B. 9,150
5	A. 17,654 B. 20,600	A. 13,200*** B. 15,600
6	A. 63,487 B. 79,100	A. 54,000*** B. 67,500
7	A. 27,673 B. 32,400	A. 10,000 B. 14,200
8	A. 9,514 B. 16,200	A. 3,370 B. 6,400
9	A. 2,911 B. 3,400	A. 1,410*** B. 1,670

*See table 3, column 1.

**Numbers in parentheses refer to items in the Reference section of this report.

***Estimates made by author assuming same percentage of projected population has sewers as at present.

TABLE 6. Waste distribution (%) treated by municipal sewage treatment plants.

SOURCE OF POLLUTANT (LOCATION)*	WASTE DISTRIBUTION % (10)** (1971)		
	DOMESTIC	INDUSTRIAL	DRAINAGE & INFILTRATION
1	50	50	0
2	-	-	-
3	60	30	10
4	60	30	10
5	50	20	30
6	70	2	28
7	-	-	-
8	55	10	35
9	100	0	0

*See table 3, column 1.

**Numbers in parentheses refer to items in the Reference section of this report.

TABLE 7. Daily average flows (MGD) from municipal sewage treatment plants for 1970 and 1990 (estimates).

SOURCE OF POLLUTANT (LOCATION)*	DAILY AVERAGE FLOWS (MGD) OBTAINED FROM REFERENCE (10) EXCEPT WHERE NOTED			
	1970		1990	
	DESIGN	ACTUAL	DESIGN	PROJECTED
1	23	18.3	31	26.6 (11)**
2	84	52.99	84	53.09 (11)
3	4.0	4.4	8	7.8 (11)
4	1.6	1.77	-	2.16***
5	3.0	1.77	-	2.09***
6	7.6	8.41	-	10.5***
7	2.35	1.5	4.4	1.9 (11)
8	.5	.19	.9	.4***
9	-	.275	-	.326***

*See table 3, column 1.

**Numbers in parentheses refer to items in the Reference section of this report.

***Estimates made by author based on population projections.

TABLE 8. Five-Day B.O.D. removal for municipal sewage treatment plants for 1970 and 1990.

SOURCE OF POLLUTANT (LOCATION)*	5-DAY B.O.D. REMOVAL % (10)**	
	ACTUAL (1970)	PROJECTED (1990)
1	15-20	90
2	65-70	65-70
3	93	90***
4	17	25***
5	10	90***
6	33	90***
7	72	90-95
8	80-90	99-100
9	0	25-40

*See table 3, column 1.

**Numbers in parentheses refer to items in the Reference section of this report.

***Estimates made by author.

TABLE 9. B.O.D. loads deposited in Narragansett Bay by municipal treatment plants for 1972 and 1990 (projected).

SOURCE OF POLLUTANT (LOCATION)*	B.O.D. LOADINGS RAW 1972 (2)**	B.O.D. LOADINGS RAW PROJECTED 1990***	B.O.D. LOADINGS TO RIVER 1972 (2)**	B.O.D. LOADINGS TO RIVER PROJECTED 1990***
1	52,200	76,000	42,300	7,600
2	54,000	54,000	14,000	14,000
3	5,000	8,850	1,000	885
4	1,900	2,320	1,300	1,740
5	3,900	4,600	2,000	460
6	6,700	8,400	6,200	840
7	2,700	3,420	1,100	342
8	420	885	40	8.85
9	290	344	290	240

*See table 3, column 1.

**Numbers in parentheses refer to items in the Reference section of this report.

***Author's projection based on average daily flow rates.

SUMMATION

Simulations with the computer model of the reaction scheme for the B.O.D.-D.O. system have displayed the model's ability to predict reasonable vertical structure definition for D.O. and B.O.D. in typical summertime conditions. In addition, variations over a tidal cycle show expected phase relationships between D.O. and B.O.D. Application of the model to a change in water surface temperature shows reasonable changes in the D.O. levels and lower D.O. values typical in summertime conditions.

Predictions using the model for storm-sewage overflow situations have shown a good order-of-magnitude estimate compared to the meager data available for "excessive load cleanup times." In addition, projections of the state of D.O. and B.O.D. for the Bay in 1990 have shown reasonable results and indicate how the model can be used to help in the management of our coastal waters.

REFERENCES

1. Spaulding, M.L., "Two-Dimensional, Laterally-Integrated Estuarine Numerical Water Quality Model," Ph.D. Thesis, Department of Mechanical Engineering and Applied Mechanics, University of Rhode Island, Oct. 1972.

2. The Providence Sunday Journal, The Providence Journal and the Providence Evening Bulletin, "Our Dirty Water," Oct. 1971.

3. Thackston, F.L. and P.A. Krenkel, "Reareation Prediction in Natural Streams," ASCE, Sanitary Engineering Division Journal, Feb. 1969.

4. Leenderste, J.J. and E.C. Gritton, "A Water Quality Simulation Model for Well Mixed Estuaries and Coastal Seas, Vol. II: Computational Procedures," The Rand Corporation, July 1971.

5. Pritchard, D.W., "The Movement and Mixing of Contaminants in Tidal Estuaries," 1960, Proceedings 1st International Conference on Water Disposal in the Marine Environment, E.A. Pearson, ed.

6. Rhode Island Department of Public Health, unpublished reports on Narragansett Bay water quality sampling program.

7. U.S. Army Engineers District, New England Division Corps of Engineers, "Effects of Proposed Hurricane Barriers on Water Quality of Narragansett Bay," 1959.

8. University of Rhode Island, Bay Watch Project, unpublished data, 1970, 1971, 1972.

9. Oviatt, C., unpublished data, Graduate School of Oceanography, University of Rhode Island, 1971.

10. State of Rhode Island Water Resources Board. "Municipal Sewage Treatment Systems - Inventory of the Structure and Functions of Rhode Island's Public Sewage Treatment Systems," Water and Related Land Resources Planning Task No. 4, Preliminary Report.

11. Southworth, B.E. and V.J. Parmentier, Supervising and Principal Planner, respectively, for Rhode Island State Planning Office, Personal Interview.

12. U.S. Department of Commerce, Bureau of Census, "Population Characteristics," Washington, D.C.

13. Rhode Island State Wide Planning Program, "Population Projections for the State of Rhode Island and its Municipalities 1970-2000, Report No. 7, Dec. 1966, revised 1972.