CHAPTER 185

STATE ESTIMATION OF ESTUARINE CIRCULATION AND WATER QUALITY BY NUMERICAL SIMULATION AND OBSERVATION

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SUMMARY

This paper describes a hindcast of post-rainstorm coliform bacteria distributions in Jamaica Bay made by use of a water-quality simulation model of that bay and models of the surrounding drainage basins on the basis of tide, wind, and rainfall data. That hindcast is then compared with coliform estimates obtained by field sampling.

Although the investigators did not have access to the results of the field sampling until the hindcast was completed, the estimates obtained by simulation agree well with the estimates from field data. It is concluded that the models used here are capable of making predictions for engineering assessments.

INTRODUCTION

The City of New York is presently working to terminate the discharge of untreated combined sewer overflows after rainstorms by constructing Auxiliary Water Pollution Control Facilities (AWPCFs) around the periphery of Jamaica Bay (Fig. 1). The completion of this plan, together with ongoing upgrading of existing Water Pollution Control Facilities (WPCFs), would open the possibility of extensive use of the area for recreational purposes. Being within the City limits, it is ideally suited for that purpose.

Control of water pollution is generally a difficult task; extensive engineering analysis is required prior to committing large amounts of capital for the construction of facilities. The problems of analysis are compounded in this case, where water pollution control must be applied to the large intermittent discharges of relatively short duration caused by rainstorms.

For the optimal design of a control system as a whole and the auxiliary plants which are part of that system, the quality and quantity of the overflows, as well as the impact of each of the overflows upon the water quality in the bay, must be determined for rainstorms of different intensity and duration.

To optimize the design of AWPCFs with respect to required storage and treatment characteristics, it is particularly important to know the drainage basins' responses to rainstorms in quantity and quality of overflow, since overdesign would make the installations much more expensive to build and underdesign would impair the system's effectiveness. The tools for such assessments have been developed in a previous study [1]. Models of the different drainage basins around the bay are now available, and water-quality distributions can be computed by means of a two-dimensional model of the bay [2-7].

Figure 2 presents an overview of the Jamaica Bay urban estuarine water-quality simulation system. This figure shows the boundaries of several major drainage systems, together with the results of the water-quality simulation model for the bay itself.

The area around the bay is generally residential, with a large population. In certain areas there are more than 100 housing units per acre. However, along the northwestern shore of the bay much open undeveloped space still exists. These areas can be noted easily in the aerial photograph of the bay (Fig. 1), which is on the same scale as Fig. 2. It will also be noted that the islands in the bay are not developed except the Broad Channel community along the north-south connection through the bay.

Two airports are situated near the bay. A runway of John F. Kennedy International Airport extends onto a marshy island in the bay. The boundaries of the drainage basins near Kennedy Airport are not known exactly, but their storm-water discharges into the bay are accounted for and the discharge points are shown. Similarly, we accounted for a major storm-water discharge from a large, densely populated area west of the bay, namely, the Mill Basin separate system.

The effectiveness of the drainage basin models and the water-quality simulation model was evaluated by the observation, simulation, and state estimation of coliform distributions in Jamaica Bay resulting from a rainstorm during the period from May

Fig. 1--Aerial photograph of Jamaica Bay, Kennedy International Airport and vicinity, New York City, U.S.A. (Courtesy of U.S. Army Corps of Engineers)

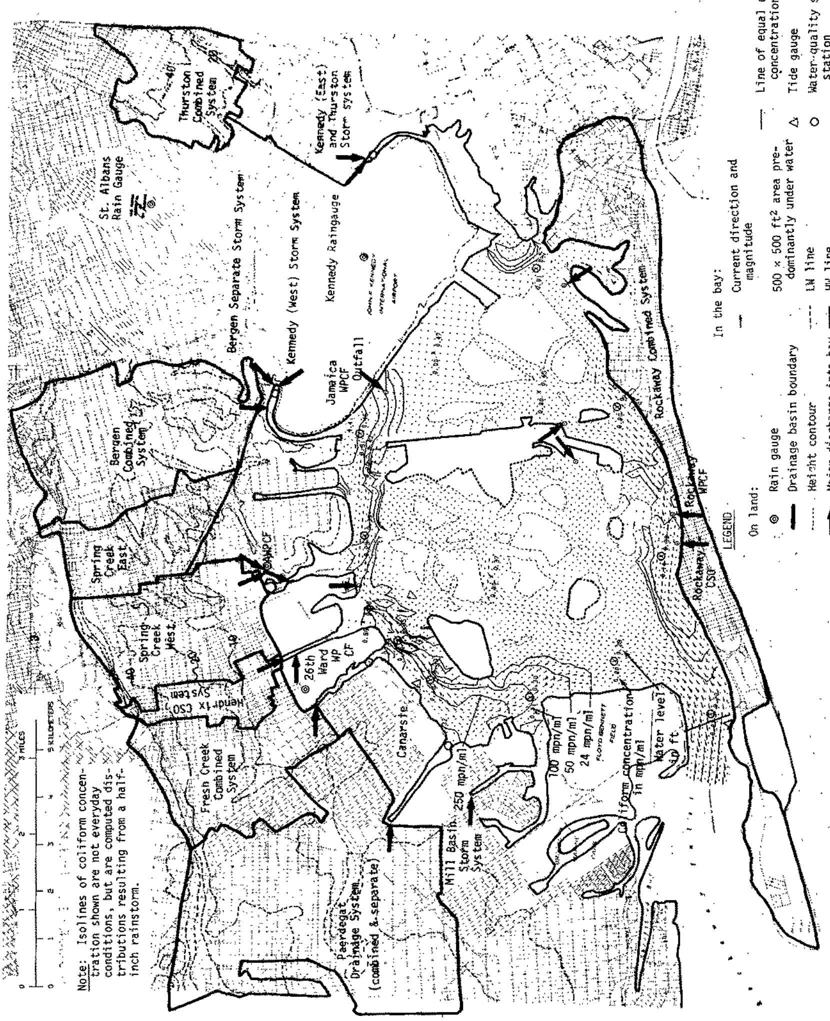


Fig. 2--Jamaica Bay urban-estuarine water-quality simulation system

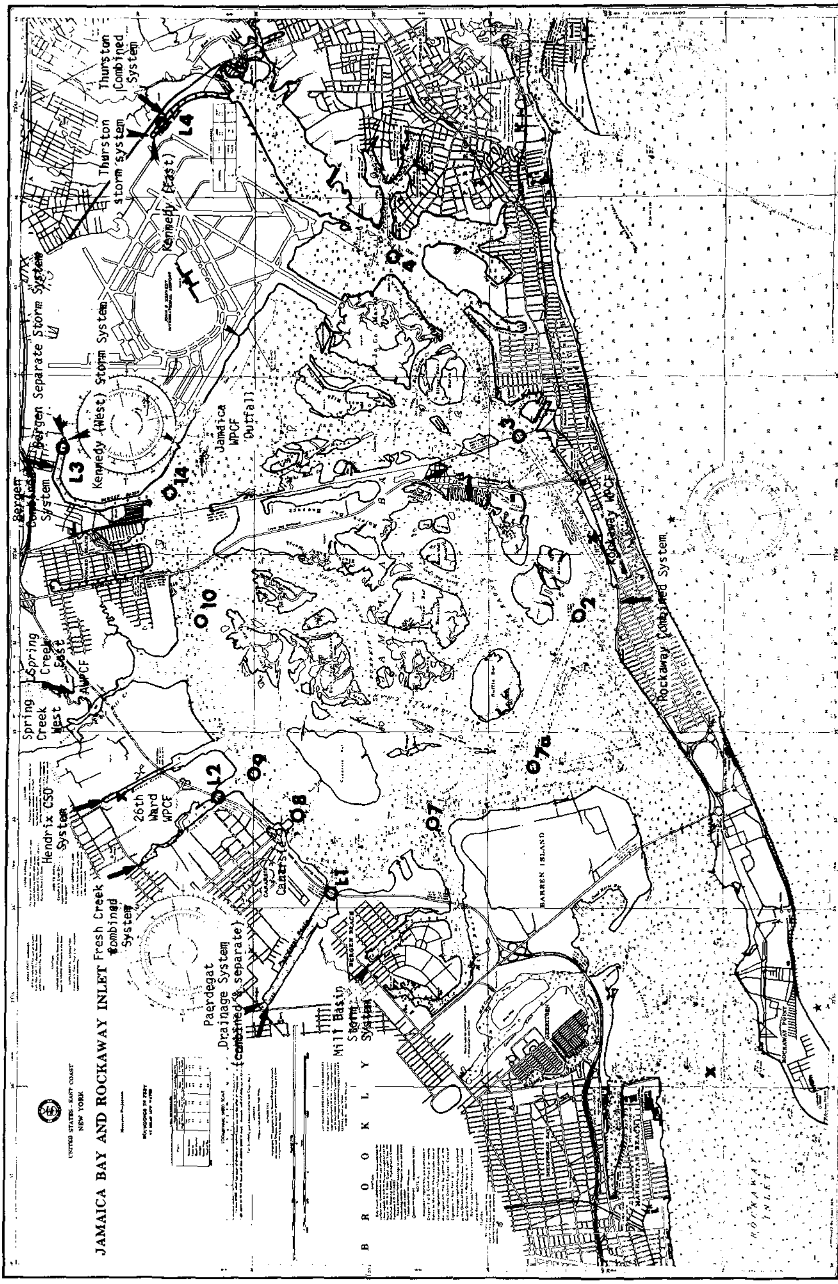


Fig. 3--Location of field sampling stations and the major discharges into Jamaica Bay

31 to June 3, 1972. This evaluation is presented in Ref. 7. In that experiment the results obtained by estimation agree well with those obtained by field measurement.

Because these predictive tools are important to the optimal design of the control system and its components, another evaluation was made based upon very extensive field measurements made by City personnel in the period of June 13 to June 17, 1973. To obtain from these models predictions completely unbiased by knowledge of observed water-quality data in the bay, the data from the observations were retained by the City until the predictions were completed. The present paper describes the results of this second evaluation experiment, in which state estimates obtained from field measurements were compared with estimates obtained from simulations.

DRAINAGE BASIN SIMULATIONS

The peripheral drainage areas of Jamaica Bay are served by nine major sanitary storm combined systems with a total drainage area of approximately 17,700 acres. An additional 19,000 acres of peripheral drainage areas have storm water systems which are separate from the sanitary system. These drainage systems, together with their points of discharge, are shown in Figs. 2 and 3. To simulate the water quality of the bay, the quantity and quality of discharge from these drainage areas during and after the storm must be determined.

These data were obtained by models for each of the drainage basins. Models were used because it is not physically possible to measure the quantity and quality of the time-varying overflows from each of the drainage systems simultaneously. Also, the City intends to use these drainage basin models for the real-time control of AWPCF operation after rainfall, as described in Ref. 1.

Consequently, the applicability of these models was proved in the experiment described here by predicting the time histories of the discharges and coliform concentrations from rainfall data. Thus, if the predictions made with the drainage basin model provided adequate input for the water-quality simulation and if the state estimates of coliform in the bay obtained by simulation agreed well with those obtained by observation, both types of models would be verified* and the models would be then considered suitable for use in prediction and control.

The drainage basin models use response functions which relate the overflow to the rainfall after taking into account depression storage of the rain and infiltration into the ground. For five of these basin models, the response functions were derived from extensive data sets of rainfall and the resulting overflow. These data, measured in 1970 and 1971 during a field study of water quality in the bay and inputs into the bay, were made available to us by the City. In determining the response functions from these data sets, we made extensive use of cross-spectral analysis, as described in Ref. 1. For those basins where these data were not available, response functions of a basin with similar hydrological and waste loading characteristics were used with modifications for the size of the basin.

* In a strict sense, compensating features do exist for these two types of models; they originate mainly from the time variability in the runoff quality estimates and the estimation of diffusive transport in the bay model. These characteristic compensating components would have equal probability of realization in future prediction when both models are used together. The expected variability of prediction should be similar to that determined from the present experiment.

To prepare the drainage system inputs of the water-quality simulation, the digitized rainfall data were first converted into effective net rainfall by estimating the system's imperviousness parameter and the depression storage. Then, for the free-flow system (i.e., no tidal influence downstream), the computed overflow hydrographs were obtained by means of numerical convolution of effective net rainfall and response functions.

For the downstream-controlled system, the time-varying overflow discharges were determined from the effective rainfall by a procedure which takes into account the water levels on each side of the tide gates in the overflow structure and the storage and flow characteristics of the sewer system. Determining these downstream-controlled discharges is much more complicated than for the free-flow discharges, since the former may have a delay of several hours for part or all of the discharged quantity when the tide gates close during high water.

The time histories of the bacterial concentration in each of the CSOs were computed from a formula that incorporates the basic mechanisms of surface washing, conduit dilution, and bottom scouring from within the system[1]. For the separate storm water systems, the quality of the discharge was based upon field data monitoring during a summer season, and a mean value of 70,000 MPN/ml was estimated.

A typical result of a drainage basin simulation is presented in Fig. 4. The hyetograph and the overflow, the response kernel, the overflow hydrograph, and the pollutograph are shown for the Thurston combined system.

The hyetograph is expressed in terms of inches per hour per unit area. The resulting system overflow is presented in the same graph in the same units for easy comparison. It will be noted that the total rainfall quantity is much larger than the overflow, since there is considerable loss from infiltration into the ground, especially within a large cemetery situated in the middle of this drainage area. Furthermore, part of this precipitation was handled by the WPCF as intercepted flow.

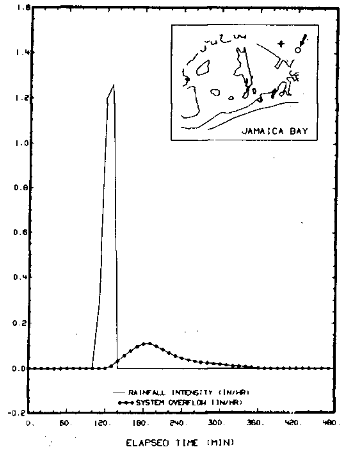
The location (+) of the rain gauge and the overflow (0) are indicated in the insert map on the hyetograph. The location of overflow as indicated refers to the location of the discharge in the two-dimensional model, not necessarily the actual geographical location due to the schematization. The zero reference for the elapsed time in this figure is at noon, June 13, 1973.

The rainfall intensity for this drainage basin was obtained from the rain gauge at John F. Kennedy International Airport.

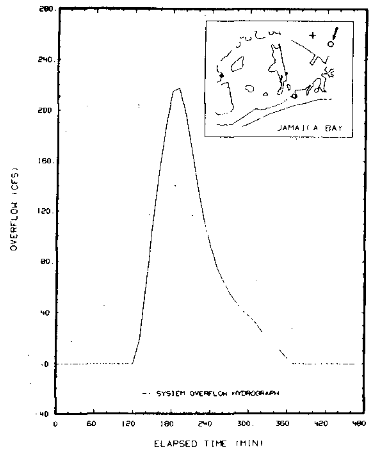
The coordinates of the response kernel are expressed in terms of cubic feet per second per inch. This unit was selected so that digitized rainfall data sensed from the tilting-bucket rain gauge (volume increments per 10 min) network installed in the drainage systems can be used directly to produce overflow discharges in cubic feet per second (cfs) through a simple machine computation.

The peak of the response kernel occurs at a time of one hour. As the rainfall intensity is strongly peaked, the overflow hydrograph also shows a peak, but at an elapsed time which is one hour later than the occurrence of the peak of the rainfall intensity.

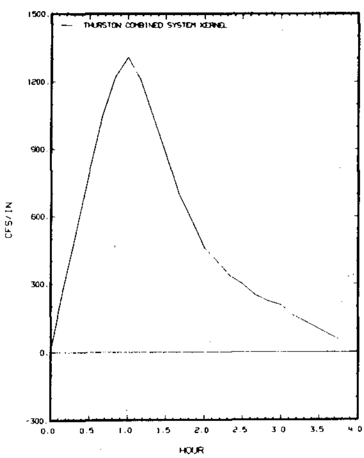
The overflow hydrograph is also presented in cfs. The pollutograph shows the time history of coliform concentration on the overflow in MPN/ml.



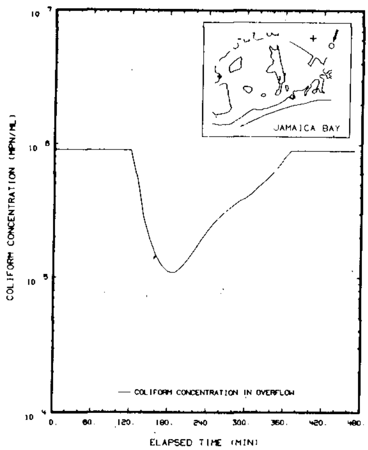
RAINFALL INTENSITY AND OVERFLOW (IN/HR)
THURSTON COMBINED SYSTEM



SYSTEM OVERFLOW HYDROGRAPH
THURSTON COMBINED SYSTEM



THURSTON COMBINED SYSTEM KERNEL



COLIFORM CONCENTRATION IN OVERFLOW
THURSTON COMBINED SYSTEM

Fig. 4--The rainfall intensity and overflow, the system overflow hydrograph, the system kernel, and the coliform concentration graphs of the Thurston Combined System

THE SIMULATIONS

The water-quality simulation was carried out for four calendar days from 0000 hr of June 13, 1973 through 2400 hr of June 16, 1973, with T = 0 at 0000 hr of June 13, which is approximately 14 hr before the beginning of the rainstorm. The time step of the simulation was 1 min ($\Delta t = 60$ sec). A coliform disappearance rate of 2.65×10^{-5}/sec, which corresponds to a 90-percent decay in concentration per day, was used throughout the simulation; this is the same as previously used. All the other parameters required for the simulation were kept the same as for the simulations of the previous rainstorm which was used for verification, as reported in Ref. 7.

The first simulation run which was made without the geostrophic boundary correction as described earlier caused some perturbations in the velocity field near the entrance. However, these local perturbations did not appear to influence the interior of the model.

In preparing the graphical outputs of the spatial distributions of coliform after the briefing, we noted that part of the records were lost because of a bad computer graphics tape. Also, from reviewing the drainage basin inflow time histories, we noted that several small values of inflow from the Rockaway CSO were inserted by mistake at the first hour of the second simulation day when the values should have been zero. For these reasons and because of our intention to try the geostrophic boundary correction, we made another simulation run without using any additional field information.

As mentioned earlier, this correction was made in anticipation of using this boundary information not only for this experiment, but also for a future investigation of the influence of a planned hurricane barrier in Rockaway Inlet. The major portion of the graphical results presented herein is from the second simulation. Charts with spatial distributions of velocities, mass transports, and coliform were obtained at time intervals of 124 min (2 lunar hr); a typical example of the velocity distribution is shown in Fig. 5 The following basic information is given in this chart, which represents the situation at 2235 min from the beginning of the simulation:

1. Clock time and date.
2. Wind speed (kn) and direction.
3. Locations and names of eighteen peripheral inputs, indicated by (0).
4. Tidal and wind-induced current velocity vector (2 ft/sec corresponding to a grid) on every point of the computation in each direction.
5. Current velocity and tide stage at eighteen stations throughout the bay. The value to the left of these current stations marked by (x) is the local velocity, the value to the right is the local water level.
6. Contours of equal velocity, with the values of the isolines indicated in the lower right corner of the chart. The lowest contour is at 0.2 ft/sec.

To relate the flow field to the tide stage, we also show in the figure a graph of the computed tide at Rockaway near the boundary of the model. The tide stage is indicated by a small arrow on the tide curve.

The velocities in Grassy Bay in the northeastern part of Jamaica Bay are very low: only in part do the vertically-averaged velocities exceed 0.2 ft/sec. If the velocit-

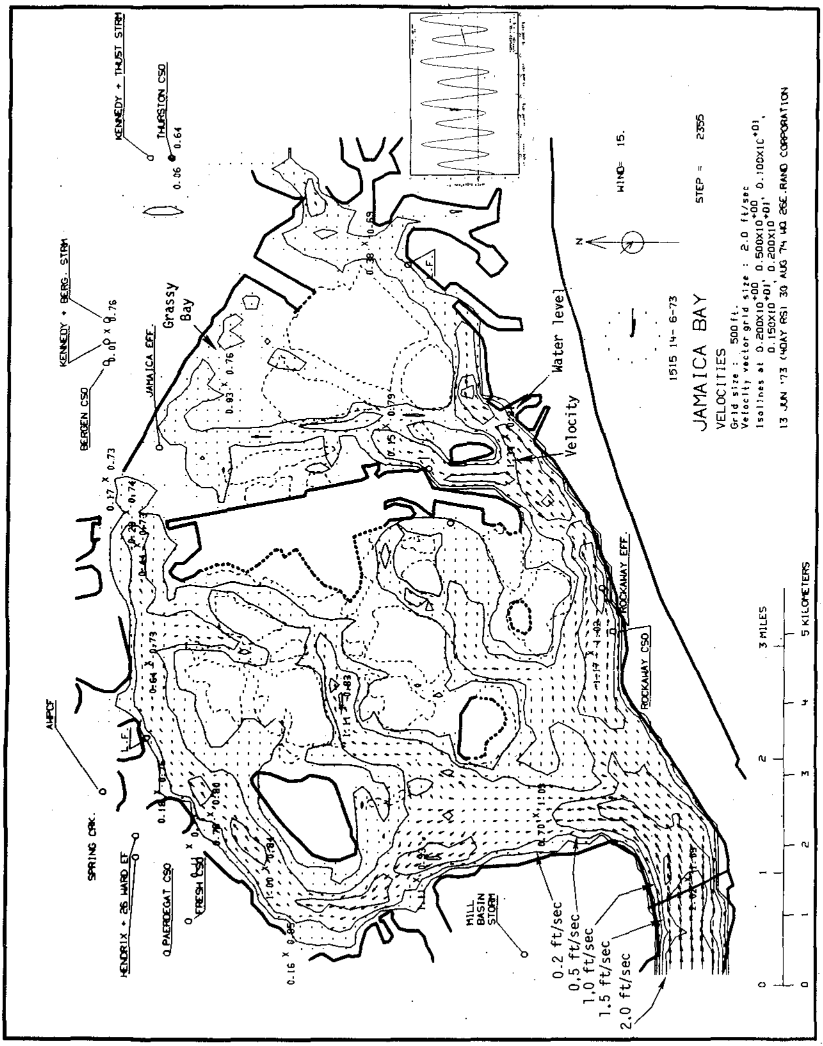


Fig. 5--Hindcasted velocity distributions in Jamaica Bay on June 14, 1973 at 15 hr 15 min

ies are a little smaller than 0.2 ft/sec, the vectors are not plotted, since their direction cannot be determined from the graphical output. The velocities in the inlet are the highest, exceeding 2 ft/sec.

Figure 6 shows, for the same time, the transports in cfs per ft width. The basic information on the chart is very similar to that of the velocities in Fig. 5 In this graph the isocontours of the transports are shown, as well as the transport vectors. Since the transports also reflect the depth, the figure shows more clearly the flow in the bay during the incoming flood tide. As water flows out of the channels onto the tidal flats, the transport intensities decrease towards the northeast. It will be noted that at this time the wildlife refuge in the center of the bay is filled to a large extent by flow in a northeasterly direction, through the so-called Pumpkin Patch Channel.

Grassy Bay is filled by the flood flow from the south as well as from the west. In order to study the flow pattern in this bay in more detail, the transport vectors in the bay were enlarged five times in comparison with the vector intensities in the remainder of the figure. The flow, through the deep channel which enters from the south, generates eddies in Grassy Bay, apparently by a kind of jet effect.

Figure 7 shows another typical result of the simulation. This graph shows the isocontours of the coliform concentrations as well as the velocity vectors and the area flooded at that time. This is shown by a dot (·) at the water-level point which participates in the computation at the time of plotting.

The condition represented by this figure shows that the marshes in the bay are only partially flooded. In contrast to figures shown in previous publications, the velocity vectors in all the graphs are now located at the point where the water depth is inserted. The vector is suppressed, however, if the velocity is smaller than 0.2 ft/sec. This method presents the submerged areas more clearly.

In this figure, the state estimates of coliform and water level are shown at the locations at which bay samples were obtained. The location at which this numerical data is presented is indicated by (x). The numerical value on the left of the mark in this case is the coliform concentration in 1000 MPN/ml, whereas the values on the right are water levels. The coliform estimate shown can assist in finding the values of the coliform contours.

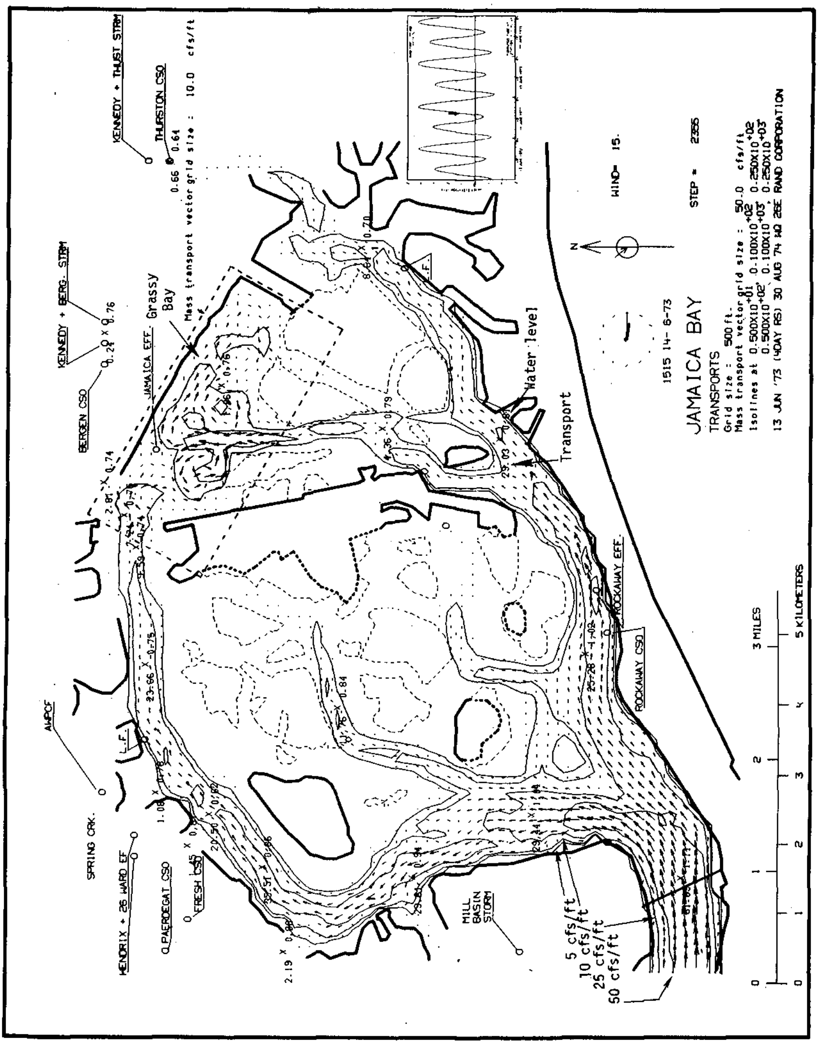


Fig. 6--Hindcasted transport distributions in Jamaica Bay on June 14, 1973 at 15 hr 15 min

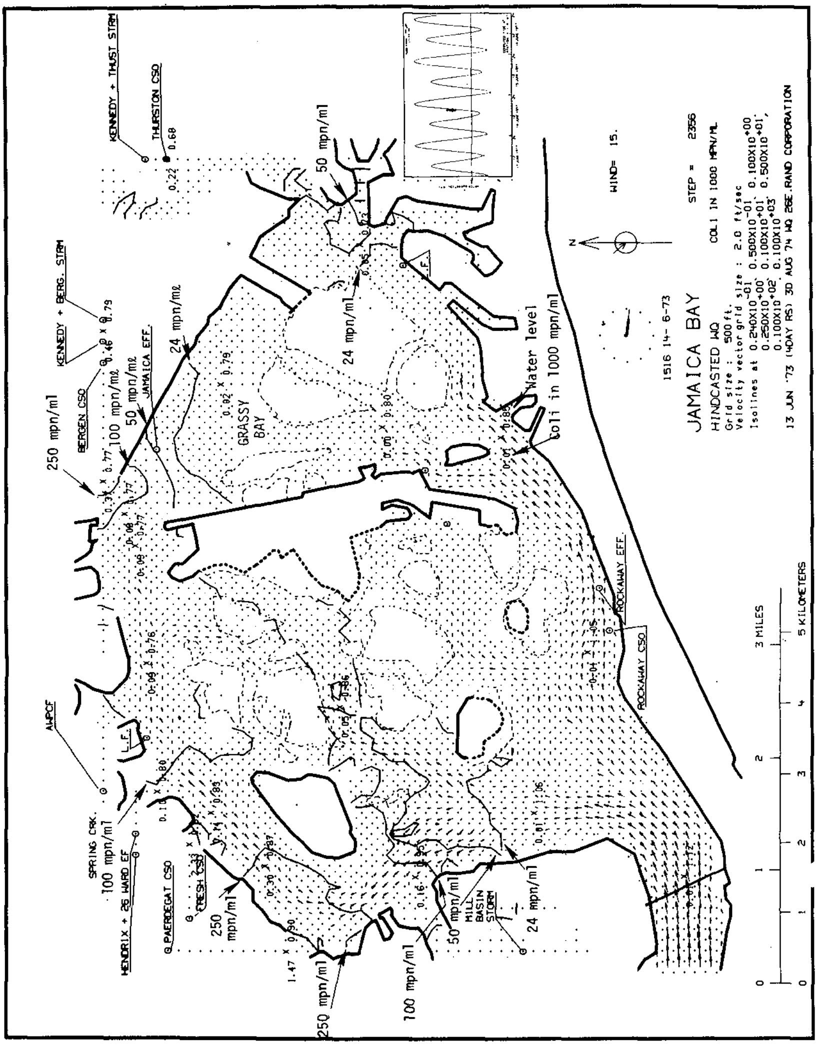


Fig. 7--Hindcasted coliform distributions in Jamaica Bay on June 14, 1973 at 15 hr 16 min

STATE ESTIMATES OF COLIFORM FROM SIMULATION AND OBSERVATION

At thirteen stations in the bay, samples were taken which can be compared with the state estimates from the simulation. These comparisons are shown in Figs. 8 through 10

In these figures the 90-percent confidence interval is shown for the observations as well as for the computed estimates. The upper limit shown is the upper 95-percent confidence limit, and the lower is the lower 95-percent confidence limit. Thus, in a statistical sense, we have 90-percent confidence that the computed and observed estimates are within the interval of the limits shown. The interval of the observed coliform concentrations is determined by the nature of biological tests made. The interval of the computed estimates is the same as the number of tests used to determine the characteristics of the drainage basin model, and the confidence interval can be carried over from the drainage basin model results into the water-quality simulation.

Since animal life is present nearly everywhere in the bay, small randomly distributed coliform loads are being applied to the system continuously. Because the results of extensive coliform surveys made a few years ago indicated that these sources give a background level of about 10 MPN/ml, this value was added to the results of the simulation presented herein.

In Fig. 8 the observed coliform estimates agree well with the estimate by simulation; only two observed estimates are outside the confidence band of the simulation. These values are somewhat suspect, since these high values occur at about the same time at each station and thus have likely been processed in the same manner.

In Fig. 9 also only a very few observations are outside the confidence band. Generally we underestimated some high values in the second day of the simulation. An underestimate is quite well possible near discharges, since we are computing with averages in a 500 $\times$ 500 ft^2 area, which averages can be lower than observed if steep gradients are present.

In Fig. 10 as well only a few observations are outside the confidence limit.

A time-independent plot of the observed and the computed coliform concentration is presented in Fig. 11 In this diagram the ordinate represents the observed values, whereas the abscissa represents the computed values. The solid line across the diagram represents the location of all values in the hypothetical case that we were able to exactly predict computed values for and make error-free field observations. The six values denoted by cross hatches (+) indicate the discrepancies in the Paerdegat Basin as described earlier.

The model and the field sampling are far from being free of error, but we are able to indicate confidence bands. The confidence band representing the testing variability of the observed samples is delineated by dashed lines. Thus, according to the nature of the laboratory test, there is approximately a 10-percent probability that the actual number of bacteria in a given sample lies outside of these limits. Approximately the same confidence band also exists for the computed estimates, which are represented by a horizontal range of limits. This probabilistic behavior of the computed values is inherited from the water-quality inputs derived from the

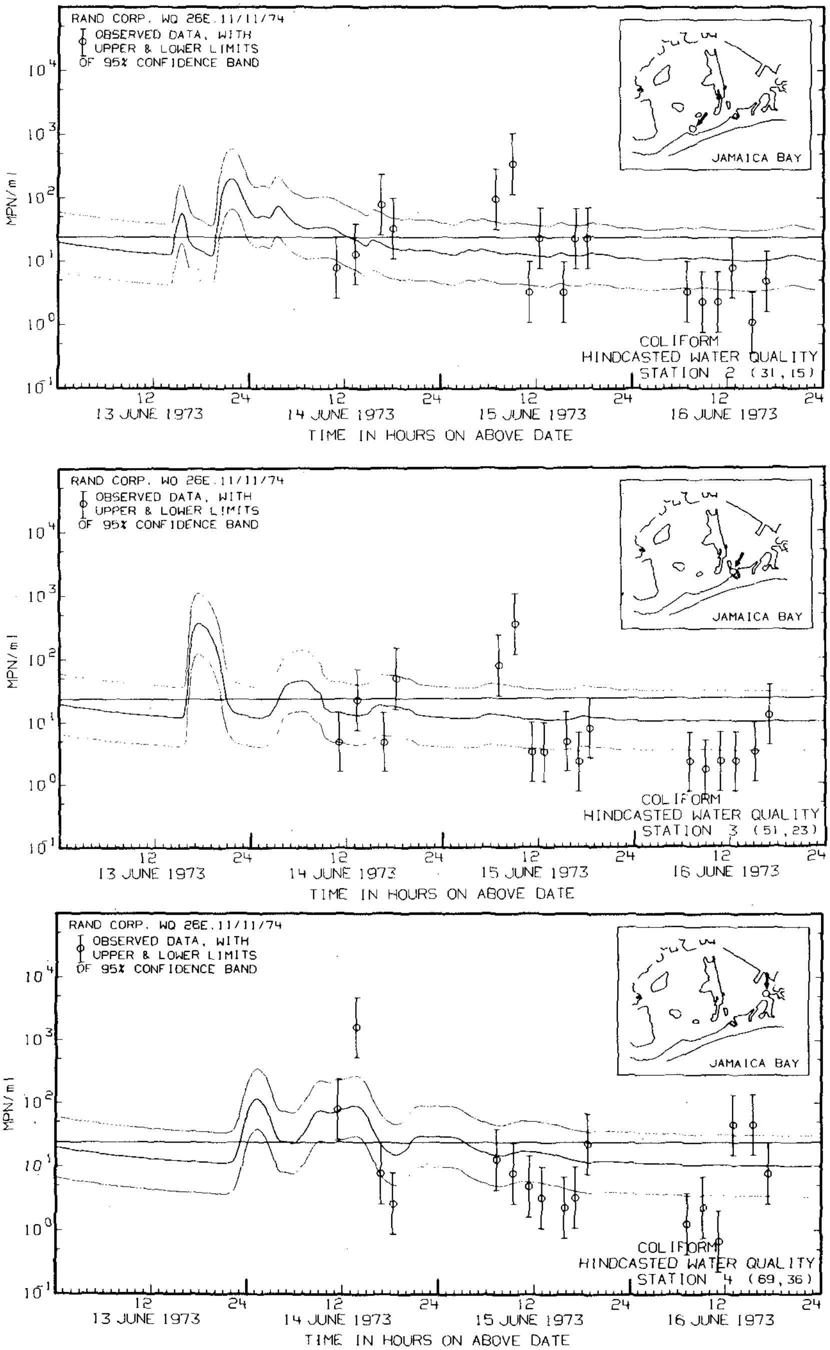


Fig. 8--Hindcasted coliform concentration histories and observed values at three stations in the southern part of Jamaica Bay

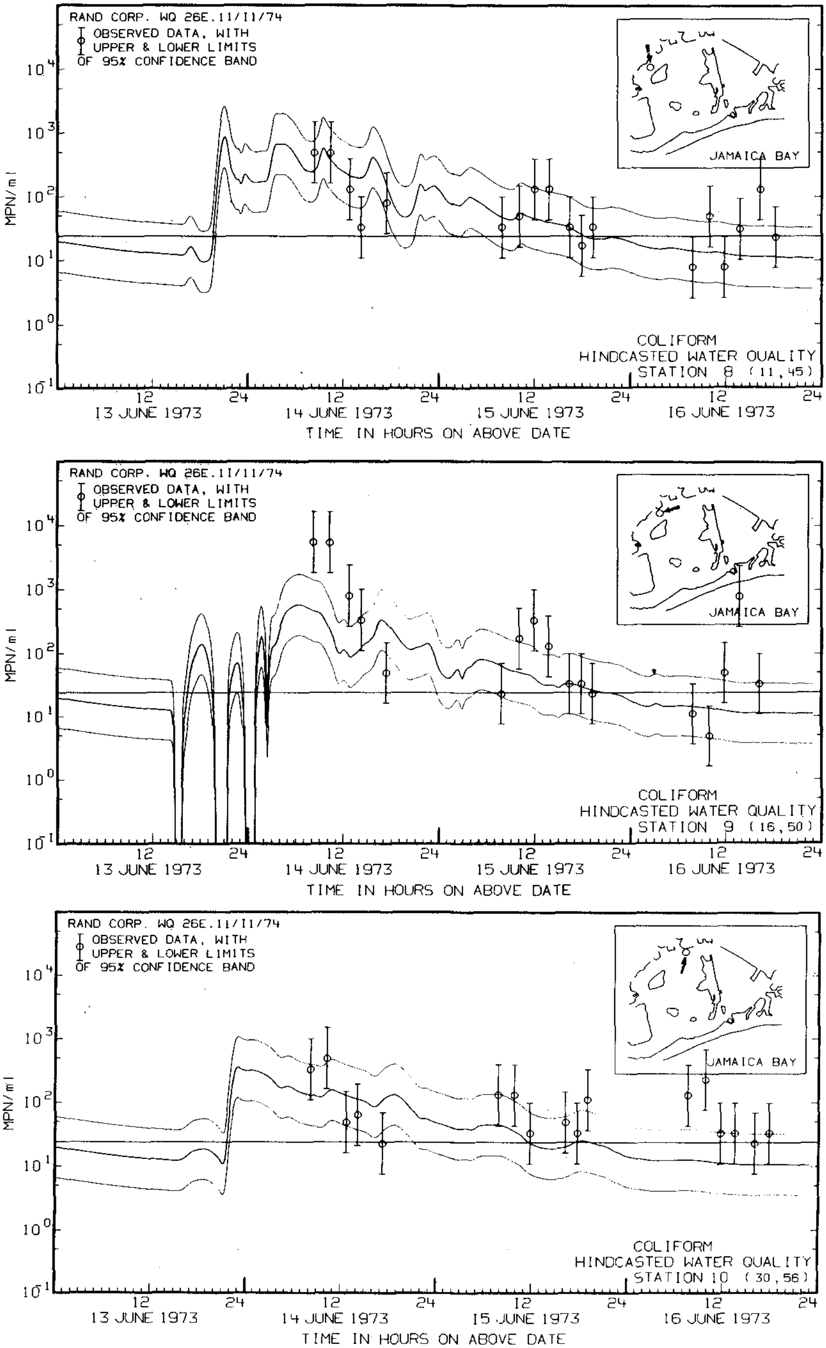


Fig. 9--Hindcasted coliform concentration histories and observed values at three stations in the northern part of Jamaica Bay, New York

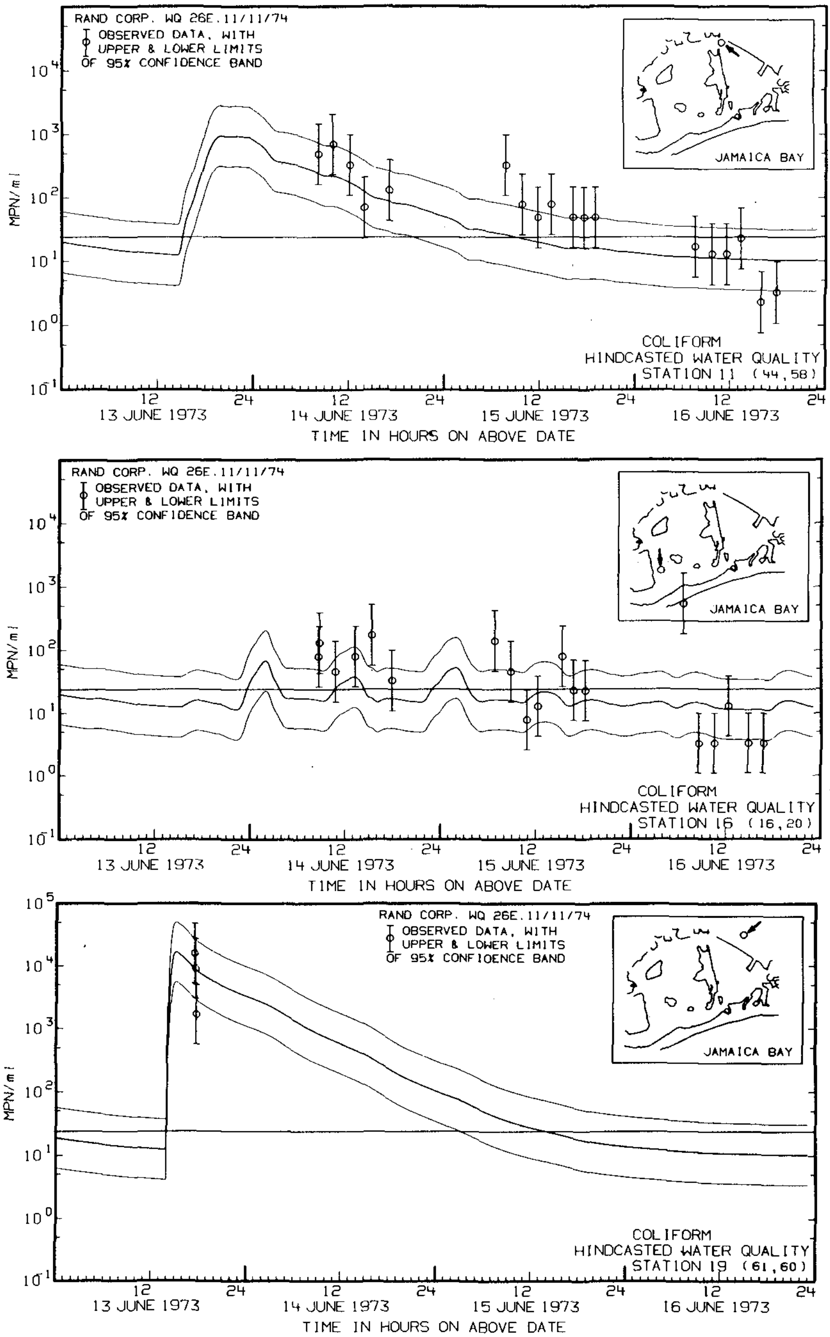


Fig. 10--Hindcasted coliform concentration histories and observed values at three stations in the western and northeastern part of Jamaica Bay, New York

peripheral drainage models and applied to this two-dimensional hydrodynamic computation of the bay water quality. Because the former derived its coliform prediction functions using observed coliform estimates, it is subject to a testing variability similar to that mentioned for the observed samples in the bay. The other error sources which contribute to the total deviation between the computed and the observed values are as follows:

- The resolvability of the rain gauge network.
- The prediction of overflow quantity.
- The time of discharge of the estimated overflow within the drainage system.
- The intercepted flow to the WPCF for the particular day and time.
- The computation of the flow in the water-quality model.
- The estimated parameters governing the diffusion and advection in the water-quality model.
- The sampling location in the field, especially in the vicinity of a discharge point where a sharp gradient exists.
- The resolvability of the grid system for representing computed estimates in the model.

In Fig. 11, no computed values lower than 10 MPN/ml are shown because of the assumption that a uniformly distributed background level of 10 MPN/ml exists in the bay. This value appears to overestimate the stations in the southernmost channel along the Rockaway peninsula, as indicated by the number of coliform observations lower than 10 MPN/ml.

It is apparent from the comparisons presented here and in the previous report that the models are able to make predictions quite well within the confidence bands. In the time-independent comparison (Fig. 11) it appears that only a small percentage (approximately 10 percent) is outside the expectation range. Thus, if other simulations are made, one would expect the results to be similar.

CONCLUSIONS

From the comparison of coliform estimates from observations in Jamaica Bay and the estimates obtained by simulation, it can be concluded that coliform density distributions in the bay, as well as discharges in the bay, can be predicted with confidence. Consequently, the models used in this investigation are capable of making predictions for engineering assessments.

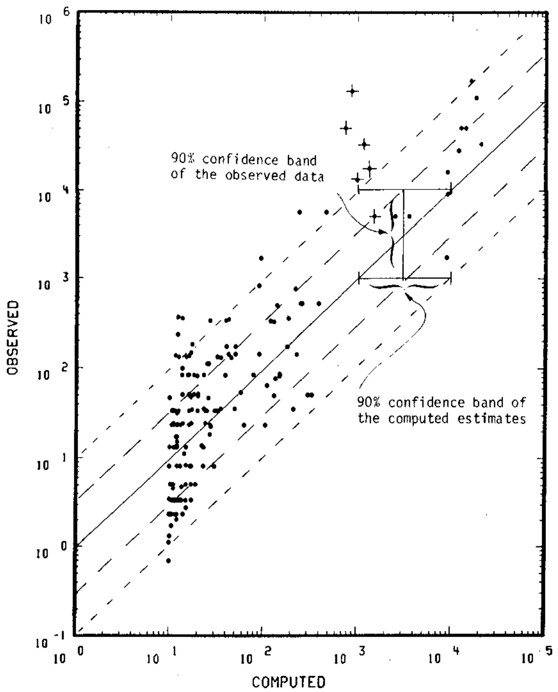


Fig. 11--Observed versus computed coliform state estimates with their confidence bands

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The many graphs in this report were prepared by Ms. M. Lakatos and Ms. G. Burkholtz. Our colleague Mr. A. Nelson made the simulations.

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