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JULY 1972

A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol. IV, Jamaica Bay Tidal Flows

J. J. Leendertse

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PREFACE

This report describes progress in the application of a simulation model of the tidal flow in Jamaica Bay. It is the fourth volume in a series of reports prepared under contract with the City of New York on the effects of combined sewage overflows and other discharges on the water quality of Jamaica Bay. In the first volume,[1] the basic formulation and the principles of computation of the model are reported. The second volume[2] discusses the detailed numerical procedures and design philosophy used in the development of the model and includes a description of the biochemical and biological reaction model.

The third volume[3] presents results obtained with the model concerning coliform, salinity, Biochemical Oxygen Demand and Dissolved Oxygen distributions, and their movements in Jamaica Bay. The available tidal data at that time were not sensitive enough to obtain a meaningful adjustment of tidal flow. This volume describes the adjustment and verification of the tidal flow in the model based on tide stage and velocity measurements made in October 1970. With the tidal flow conditions being firmly established by the work reported here, simulations of time-varying water-quality distributions in the bay can be made.

A summary of the results presented in this report was briefed to the Commissioner of Water Resources of the Environmental Protection Administration of the City of New York and his advisors on October 30, 1971. Also at that time, a series of simulations was presented that assessed the impact of the Spring Creek Auxiliary Water Pollution Control Facility, currently under construction, on the water quality in the bay. These simulations are described in a companion report.[4]

[1] Leendertse, J. J., *A Water-Quality Simulation Model for Well-Mixed Estuaries and Coastal Seas: Vol. I, Principles of Computation,* The Rand Corporation, RM-6230-RC, February 1970.

[2] Leendertse, J. J., and E. C. Gritton, *A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol. II, Computation Procedures,* The Rand Corporation, R-708-NYC, July 1971.

[3] Leendertse, J. J., and E. C. Gritton, *A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol. III, Jamaica Bay Simulations,* The Rand Corporation, R-709-NYC, July 1971.

[4] Gritton, E. C., *A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol. V, Jamaica Bay Rainstorms,* The Rand Corporation, R-1010-NYC, June 1972.

SUMMARY

The report describes the adjustment and verification of the hydraulic model for tidal flow in Jamaica Bay, based on tide measurements during a 4-day period (October 27-30, 1970). The Manning's coefficients in the different regions of the bay model were adjusted using tide-stage data for a 2-day period.

Since no tide-stage data were available at the boundary, the input tide was derived from amplitude and phase relations between the boundary and the gauge recorder closest to the boundary, with a correction for the resonance mode derived from all five stage recorders. After adjustment, an excellent agreement was found between observed and computed water levels with standard deviations ranging from 0.03 to 0.06 ft. Subsequent simulation for verification of the second 2 days, using the Manning's coefficients derived previously, resulted in standard deviations ranging from 0.03 to 0.09 ft, with an average of 0.06 ft. This increase in standard deviation was caused mainly by a few-minute advance or retardation of the timing mechanism of the stage recorders. Velocities did agree well; the standard deviation between observed and computed data was 0.26 ft/sec.

The model indicates a weak general circulation in the bay, which is influenced to a considerable extent by wind.

ACKNOWLEDGMENTS

The author wishes to thank Martin Lang, Commissioner of Water Resources for the City of New York, and his staff for the encouragement and support of the study described in this report. The cooperation of the U.S. Army Corps of Engineers, New York District, and the Waterways Experiment Station in Vicksburg, Mississippi, in obtaining the field data is appreciated. In particular, the cooperation and assistance of M. Laderman, H. B. Simmons, and T. C. Hill are acknowledged. Computing assistance was obtained from the Health Sciences Computing Facility, UCLA, sponsored by NIH special research resources grant RR-3.

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I. INTRODUCTION

This report describes the adjustment and verification of the hydraulic model for the tidal flow in Jamaica Bay. Adjustment of hydraulic models is an iterative procedure designed to establish, by adjustment of certain parameters, agreement between the values of tides and currents obtained with the model and the values obtained from field measurements.

Verification is the process by which the accuracy of the model is tested after adjustment by comparing computed and observed data, using the parameters established in the adjustment phase. After this procedure it is assumed that the model will accurately simulate conditions similar to those for which the adjustments and verifications were made. The procedures used for adjustment and verification will vary according to the physical features of the area to be modeled and to the insight of the engineer making the verification into the existing physical processes. The magnitude and the scope of the field measurements also determine the procedures used.

A good understanding of the varying flow field was obtained from earlier simulations [1]. Consequently, the adjustment of the model could be made with only a limited number of separate computations.

In the analysis, computer graphics was used extensively for the simultaneous comparison of computed results with field measurements. The relative ease with which graphs of certain phenomena can be made resulted in hundreds of figures for a few days' simulation. These figures were analyzed and compared with results of previous computations and with computations that used different data inputs. However, this report presents only the more important results. To enhance the relationships between certain phenomena, many graphs have been considerably reduced so that several can be presented on one page for ease of comparison, even though this impairs the readability of the graphs. In the actual analysis, large (11 $\times$ 14 in.) hardcopy outputs were used; these were compared and analyzed by means of a light table.

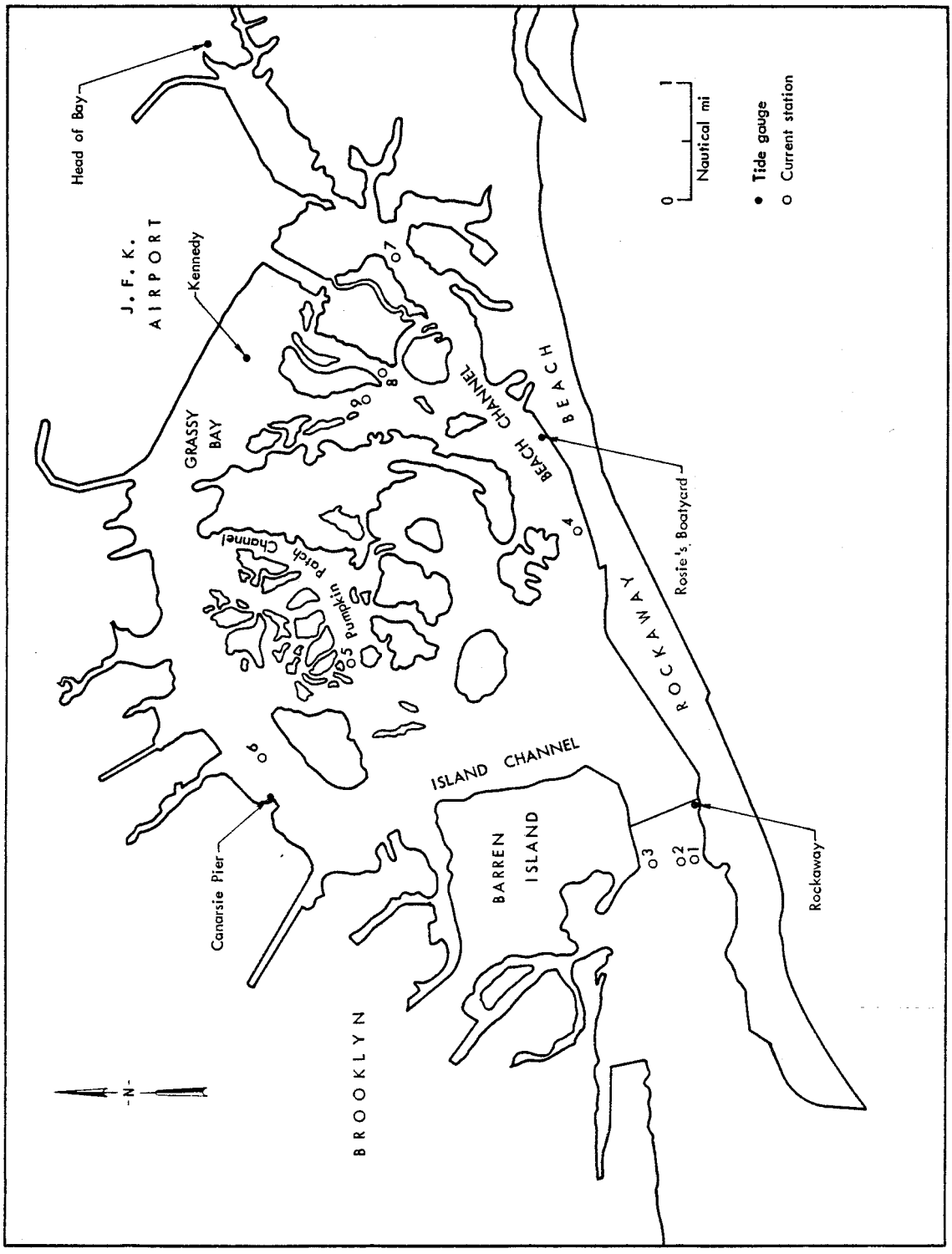
II. FIELD MEASUREMENTS

The data used for adjustment and verification of the model were obtained from a rather extensive program of observations made in October and November 1970. This program was set up in about the same manner as a program of field measurements made in 1967 [1]. The aim of the present study is to simulate actual conditions of the tidal flow. Consequently, it was advisable to select a period in which some extreme values occurred in the flow, since we are interested in these values as well as in the average ones. If we can simulate the extreme values adequately, we should be able to simulate the more normal conditions quite well.

The data obtained in the 1970 survey not only served for the hydraulic model described in this study, but also for studies independent of this model. These studies required tidal data roughly representing average conditions. As a result, a period of data collection was selected in which the tides had about a mean range.

For the adjustment and verification of the model, it was preferable to obtain data simultaneously at many of the observation stations in the prototype area. However, the available means of data collection were limited, particularly the velocity measurements, since these were made by current meters of a type normally used for stream gauging. For the water-level observations, continuous digital recording stations were installed so that observations could be made without field personnel being in direct attendance. However, this could not be done for velocity measurements because they require visual observations of instruments. Hence, the velocity-measurement program entailed a lot of manpower and long working hours for those making the observations.

The selection of the observation periods was also influenced by availability of personnel. Nevertheless, at each tidal station in the field, periodic observations of currents were made twice during a complete tidal cycle, but not at all stations simultaneously. The measurements were made over a 4-day period (October 27-30, 1970). The first 2 days were used for adjustment and the second 2 days for verification of the model. Tide stages were recorded by Fischer Porter digital punch-tape recorders, which punched at 6-min intervals. The locations of the tidal stations are shown in Fig. 1, the comparable stations in the model in Fig. 2. The accuracy with which the tide stage was recorded by the instruments is 1/100 of a foot. The timing


Head of Bay
J.F.K. AIRPORT
Kennedy
GRASSY BAY
Channel
Pumpkin Patch
BEACH CHANNEL
BEACH
ROCKAWAY
Rosie's Boatyard
ISLAND CHANNEL
Canarsie Pier
BARREN ISLAND
Rockaway
BROOKLYN
N
0
1
Nautical mi
Tide gauge
Current station
01
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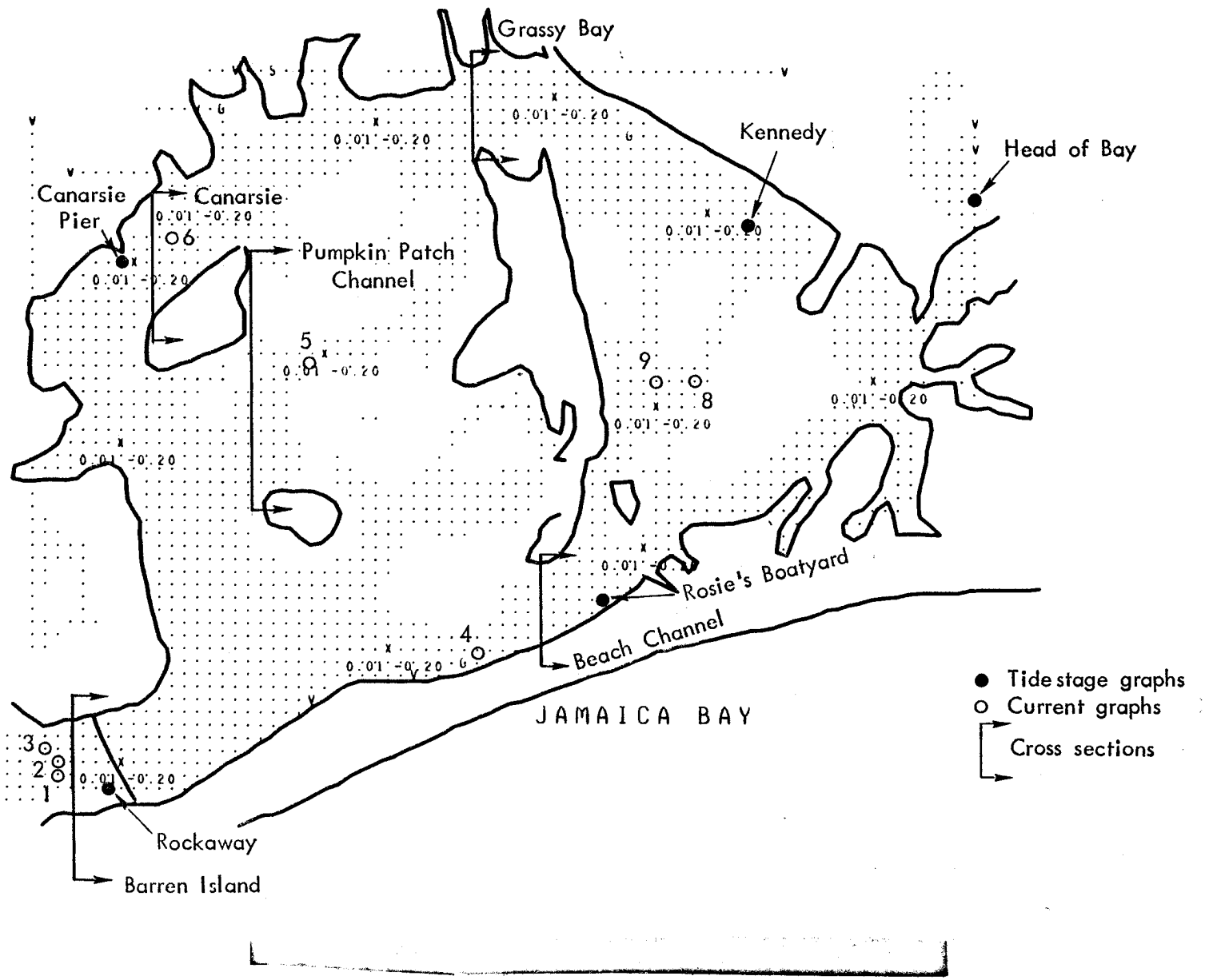

Grassy Bay
Kennedy
Head of Bay
Canarsie Pier
Canarsie
Pumpkin Patch Channel
Rosie's Boatyard
Beach Channel
JAMAICA BAY
Rockaway
Barren Island
1
2
3
4
5
6
8
9
0.01 -0.20
Tide stage graphs
Current graphs
Cross sections

mechanism was a conventional clock, which was periodically checked during the main period of observation. From the inspection logs of the five recorders, it was concluded that the time error was generally not more than 1 min. However, in a few instances the clocks ran slow or fast and thus influenced simulations and the analyses. This will be discussed later in the report. In general, the observations made of the tide stages were well fixed in time and in space.

Observations of currents were of a much lesser quality, as they were recorded by observers. The instruments used were Ott and Price current meters. The observations at each current-measuring station were made by two observers in a small, flat-bottomed boat anchored at different locations in the bay, as shown in Fig. 1. The observations were recorded manually in a log.

No assessment can be made of the accuracy of these observations, but some impression could be obtained from the mode of data collection. Since the measurements were made from boats, which were naturally subjected to wave action, the instruments were also subjected to vertical motions. As shown in Figs. 3 and 4, vertical motion has considerable influence on the measured stream velocity. This is particularly true for the Price current meter. Current observations were probably severely affected for those stations that were exposed to waves during times of

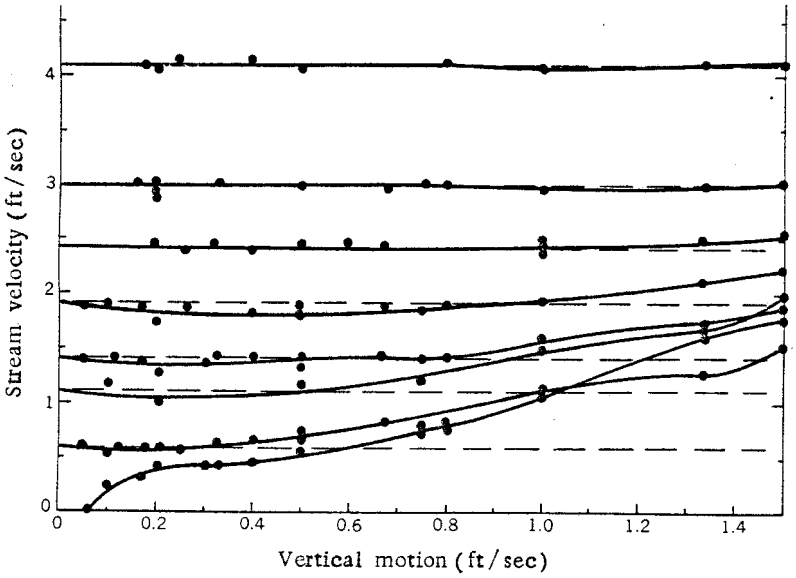


Fig. 3—Effect of vertical motion on the Price current meter suspended by a cable. The vertical intercept is the true stream velocity, and the departure from the dashed line through the intercept is the error in registration caused by the rate of vertical motion (abscissa). The true stream velocity for the lowest curve is zero (Ref. 2)

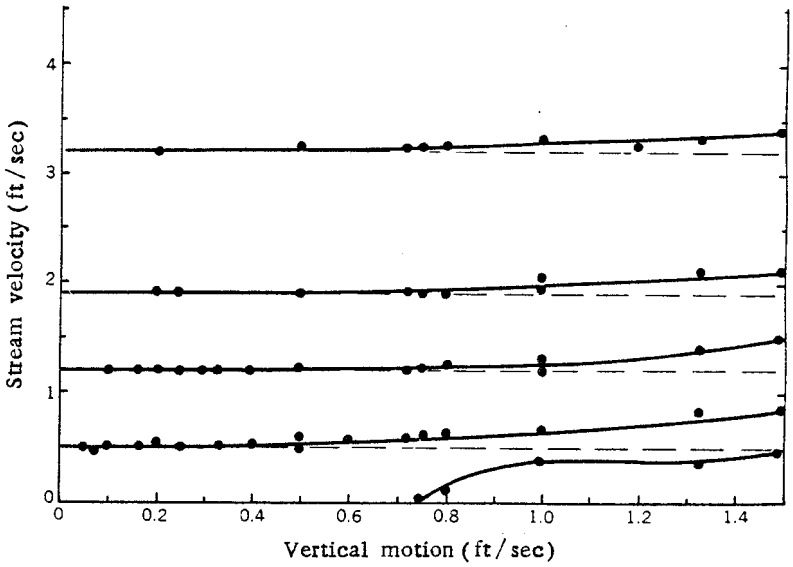


Fig. 4—Effect of vertical motion on the Ott current meter suspended by a cable and equipped with rotor 8646-A and a standard tailpiece without stabilizer. The true stream velocity for the lowest curve is zero (Ref. 2)

considerable wind. The higher winds occurred during the afternoons, and in all measurements of the more exposed locations, better agreement was obtained during the nighttime observations, when there were low wind velocities, than during the daytime. Observations of currents with low velocities were particularly affected, and the measured velocities were overestimated.

Observations of velocities generally had a high variability, since measurements were made of a turbulent fluid flow at particular locations. To smooth the data, the velocity measurements were made as averages over a period of 1 min. The current measurements were generally made at three locations over a vertical—namely, 2 ft below the surface, at mid-depths, and about 2 ft above the bottom.

One of the first steps in analyzing the field data was to make graphs of the digital data of the tide records. These graphs are presented on a reduced scale in Fig. 5. It is evident that there was considerable noise at the Rockaway station. Apparently the opening in the floatwell of the recorder was too large or the well of the recorder was leaking somewhat. Some of the other gauges also indicated perturbations.

To obtain an impression of the noise levels present in the records, the differences between records of adjacent gauges were plotted on an enlarged vertical scale. These plots are shown in Fig. 6. Since we are presenting differences between two stations, we also obtain an impression of the time history of the water-level gradient

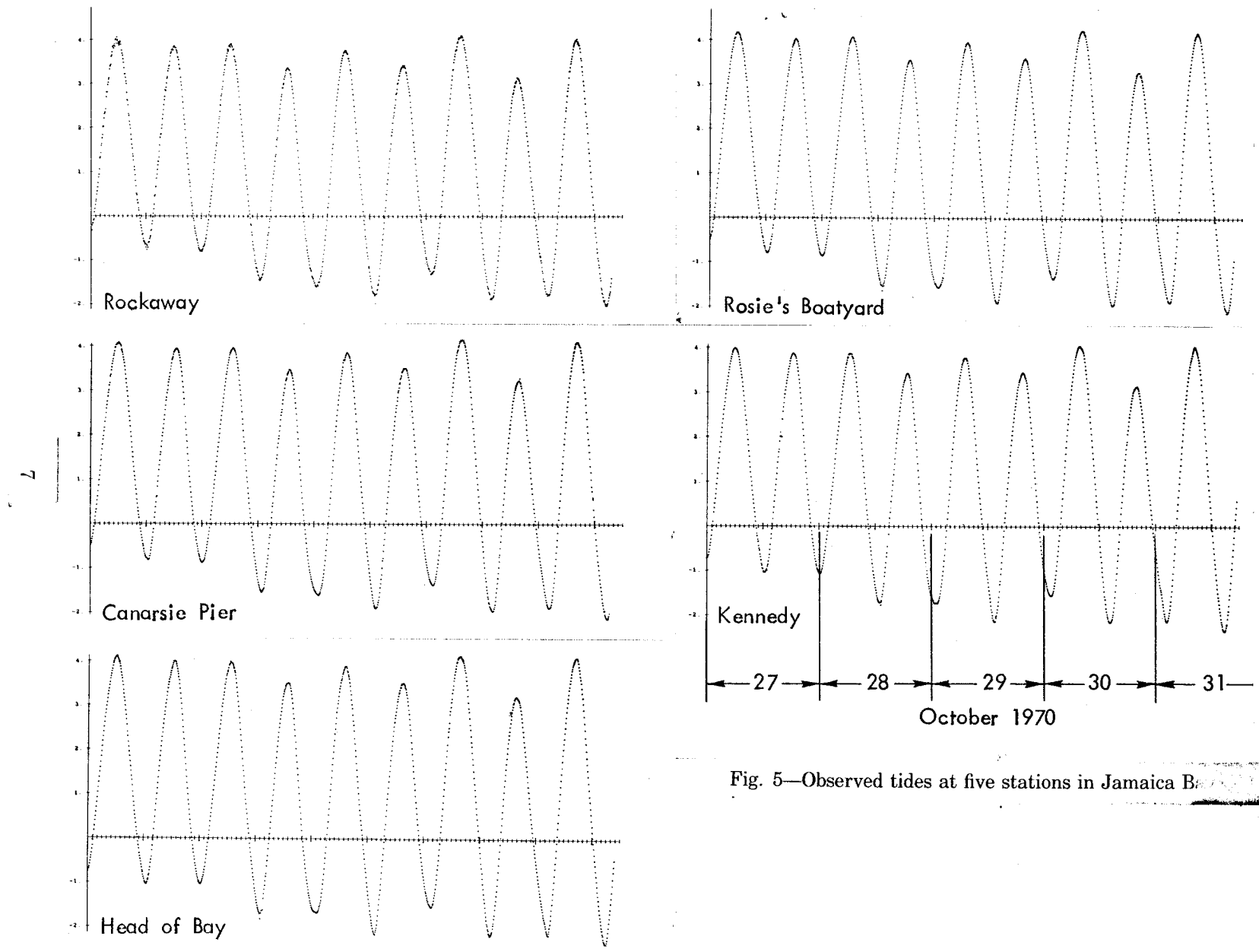
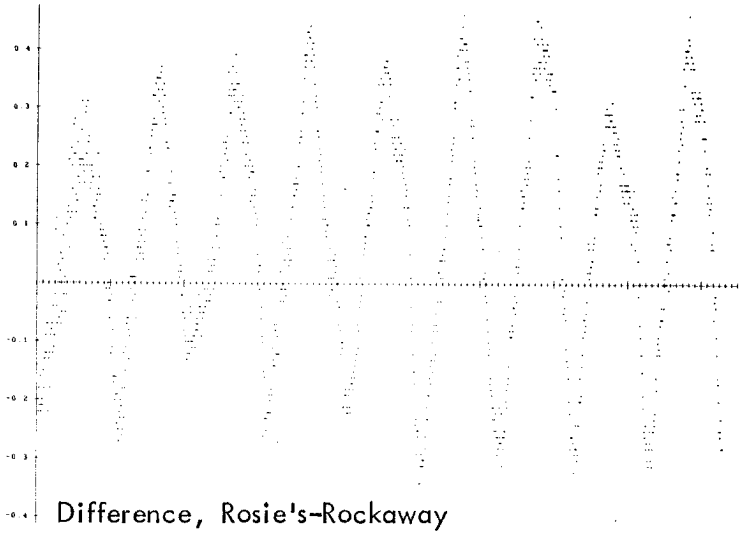
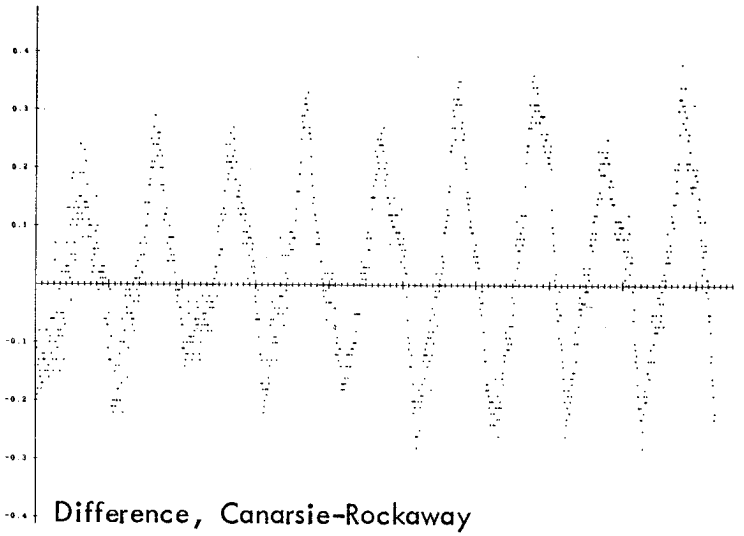


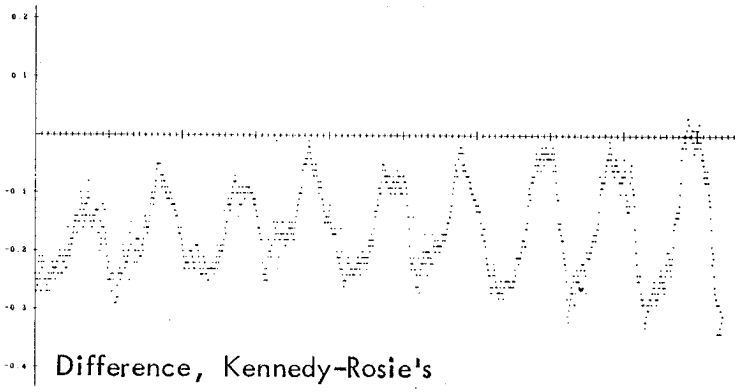
Fig. 5—Observed tides at five stations in Jamaica B[illegible]



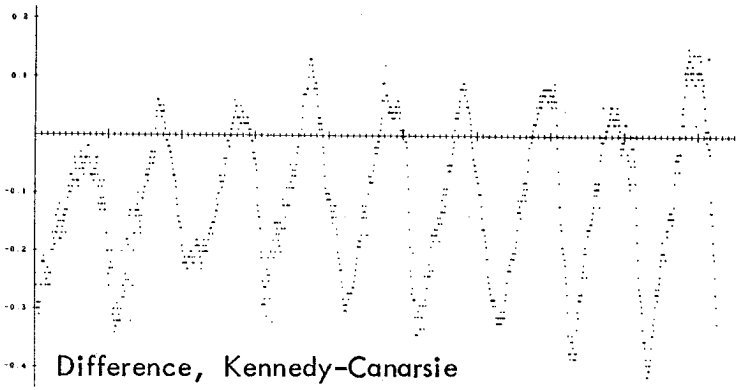
Difference, Rosie's-Rockaway



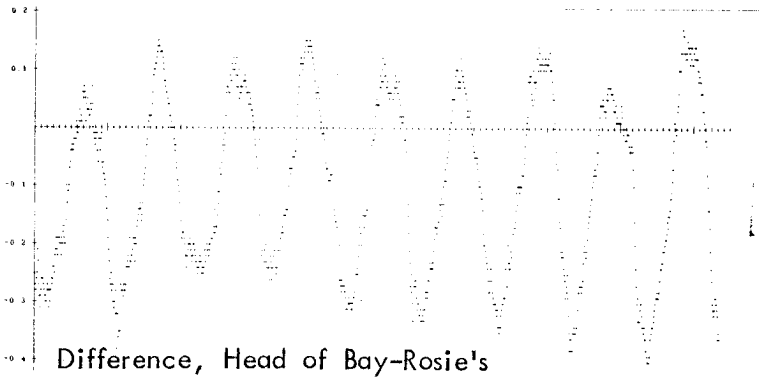
Difference, Canarsie-Rockaway



Difference, Kennedy-Rosie's



Difference, Kennedy-Canarsie



Difference, Head of Bay-Rosie's

Fig. 6—Observed differences between adjacent statio

between these stations. It is apparent that the tidal phenomenon is highly nonlinear, as we would expect by the large difference between the water surface area of the bay at high water (HW) and low water (LW). If we had a linear, or nearly linear, system, the differences between the stations would be directly in proportion to the tidal amplitude. It can be clearly seen in Fig. 6 that this is not the case. For example, the difference between the tide stages of Kennedy and Rosie's Boatyard nearly doubles in amplitude when the tide increases by only about 20 percent. A close observation of these difference graphs also shows that there are oscillations of a higher frequency than the tide present.

The zero level of each of the gauges was established from U.S. Coast and Geodetic Survey bench marks, and the representations of the tides and the differences between the stations (Figs. 5 and 6) reflect the observations and the differences of the base level at each of the stations. Figure 6 shows that the mean water level at Kennedy is about 0.15 ft lower than at Rosie's Boatyard and that the mean levels of Rosie's Boatyard and Rockaway are about the same. We would have expected that the mean water levels at Kennedy would be slightly higher compared with those at Rockaway because of energy dissipation occurring in the bay; also the salinity concentrations at Kennedy were expected to be somewhat lower than those at Rockaway. Using the reference level for each of the gauges, however, the inverse was found to be true.

In all of our observations we will start from a level at the boundary of the model just west of Rockaway, and all adjustments will be made according to this level.

It had been found previously that the wind influenced both the tide levels and the circulations. Thus, simultaneously with the simulations, the effect of wind had to be introduced in the computation. Wind measurements were available from observations at Kennedy Airport just northeast of the model. These observations were logged as wind speed and direction every 3 hr. In the initial simulations, these values were interpolated every 18 min for speed and direction.

III. ADJUSTMENTS

In the previous section, it was stated that the water levels were recorded with high accuracy over a long period of time, but that velocity data are sparse, being available for only two tidal cycles, and are subject to considerable error. In the adjustment, the tidal data were used as the primary data upon which all the adjustments were made, while the velocity data were used as supporting data for adjustment and verification.

Since the purpose of the model is to simulate actual conditions, we attempted to make a direct matching of all observed and computed data. Such a procedure follows the practice used in adjusting physical models. However, not all the data are used in their most advantageous form; i.e., digital recorded data and computed data could be analyzed with time series, and important additional gross parameters could become available to assist in the adjustment procedures. At the time phase of adjusting the model, however, no programs for time-series analysis were available with the appropriate graphical output representations. The development effort therefore was not warranted in view of the resultant delay in adjustment.

Particular emphasis in the analysis was placed on the simulation of the differences between the recording stations. The time histories of the differences in tide stage are extremely sensitive for comparison of amplitude and phase between observed and computed data. These differences represent, more or less, one of the domineering terms of the equation of motion, and this term is of the same order of magnitude as the bottom stress term which contains the unknown Chezy value used for adjustment of the flow. If computations are made with a slightly different Chezy coefficient, the effect is immediately noticeable in the difference graphs.

The adjustment procedure has another facet, namely, that of finding the appropriate water-level histories for the model, since no field measurements were made at the boundary of the model. Consequently, the boundary data had to be derived from data collected at the different tide-stage recording stations. In a previous attempt to adjust the model [1], the tidal data of the closest available station were used, and the adjustment procedure was applied. At that time the gauge was closer to the boundary. After computations were made using the observed tide for Rockaway as the input, it was determined that a phase lag of about 6 min existed between

the boundary tide and the tide computed at the Rockaway station. Also, the amplitude at the boundary was slightly smaller than the amplitude at Rockaway. Finally, after a few experiments, the amplitude of the basic tide at the boundary was assumed to be 98.3 percent of the amplitude at Rockaway.

The record of the Rockaway gauge contained considerable noise, generated by wind waves and possibly by small surges in the basin within which the tidal gauge was installed. Naturally, we did not want to drive the model with a boundary that contained much noise. Thus, a numerical filter was applied to the Rockaway record before using it in the procedure described above. The expression used for filtering was

$$H_t = \frac{1}{12}\left(h_{t-2\Delta t} + 3h_{t-\Delta t} + 4h_t + 3h_{t+\Delta t} + h_{t+2\Delta t}\right),$$

where h is the recorded value, H is the tide level used in the computation, and Δt is the recording interval.

The smoothing operator filtered short-period variation quite well and retained oscillations of 30 min and larger. The boundary data thus derived were sufficient for the initial series of simulations for the adjustment of Manning's value. This value was then used to compute the new Chezy value periodically every 20 min of real time for each gridpoint in the computational array [3].

In order to explore the model's sensitivity to changes in the values of Manning's coefficient, several short simulations were made, each being typically 1½ tidal cycles in duration, to explore the response of the system. The Manning's value finally used was n = 0.030, except at Broad Beach Channel, which connects Beach Channel with Grassy Bay, and in several other areas of limited size, where cross-sectional approximations resulted in a very shallow channel. At these locations the value used was n = 0.026. For a limited section of Beach Channel, the value of 0.034 was used. It appeared that the computations were not too sensitive to the latter changes.

From the computations, a large number of graphs were made that show computed and measured data simultaneously. Some typical graphs are shown in Figs. 7 and 8, which are half-size reproductions of the original hardcopies made with the Integrated Graphic System for the DatagraphiX 4060. Figure 7 represents computed and observed data at Rockaway on October 28, 1970. A close inspection indicates very good agreement. However, if the differences between the observed and the calculated data are plotted on a vertical scale ten times larger (Fig. 8), the deviations become more apparent. Disregarding the high-frequency perturbations (noise), certain periodicities can be observed in the differences between calculated and observed data. The period of this oscillation is about 3 to 4 hr.

Since differences between computed and observed data are available every 6 min, the standard deviation of the difference can be computed. The standard deviation at Rockaway was 0.035 ft for a computation of about 2 days' simulation. This standard deviation includes the error introduced by the tide-gauge observation, the error introduced by the actual simulation, the influence of the wind, the error introduced by the unknown or assumed boundary, and the bathymetry. Figure 9

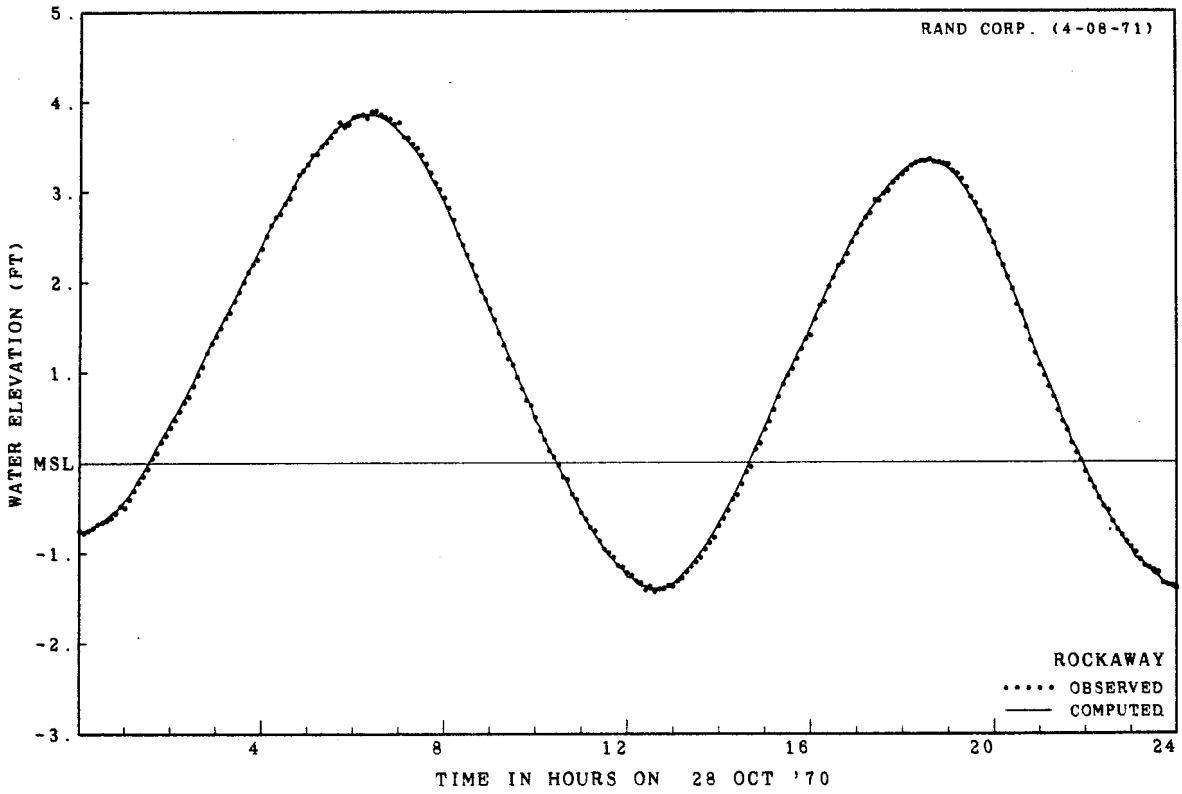


Fig. 7—Computed and observed data at Rockaway

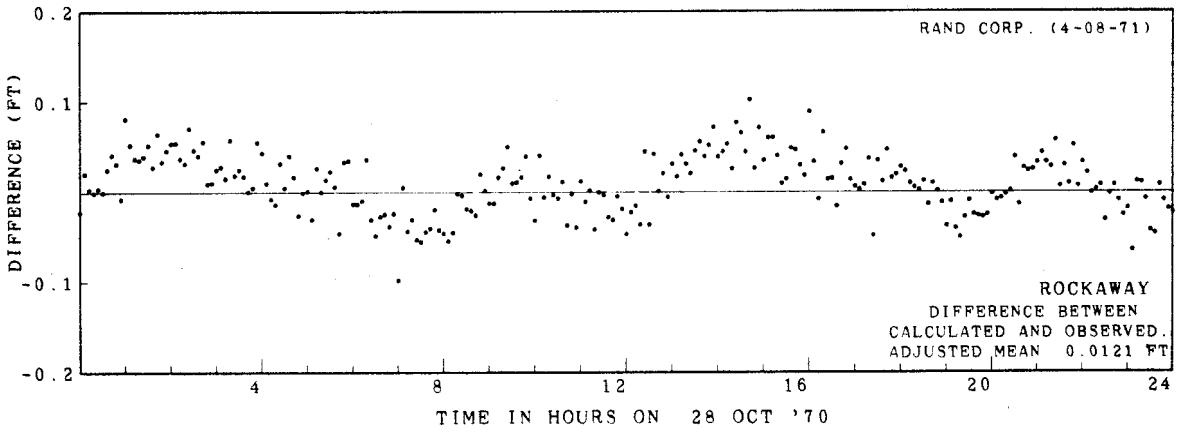


Fig. 8—Comparison between observed and computed data for Rockaway

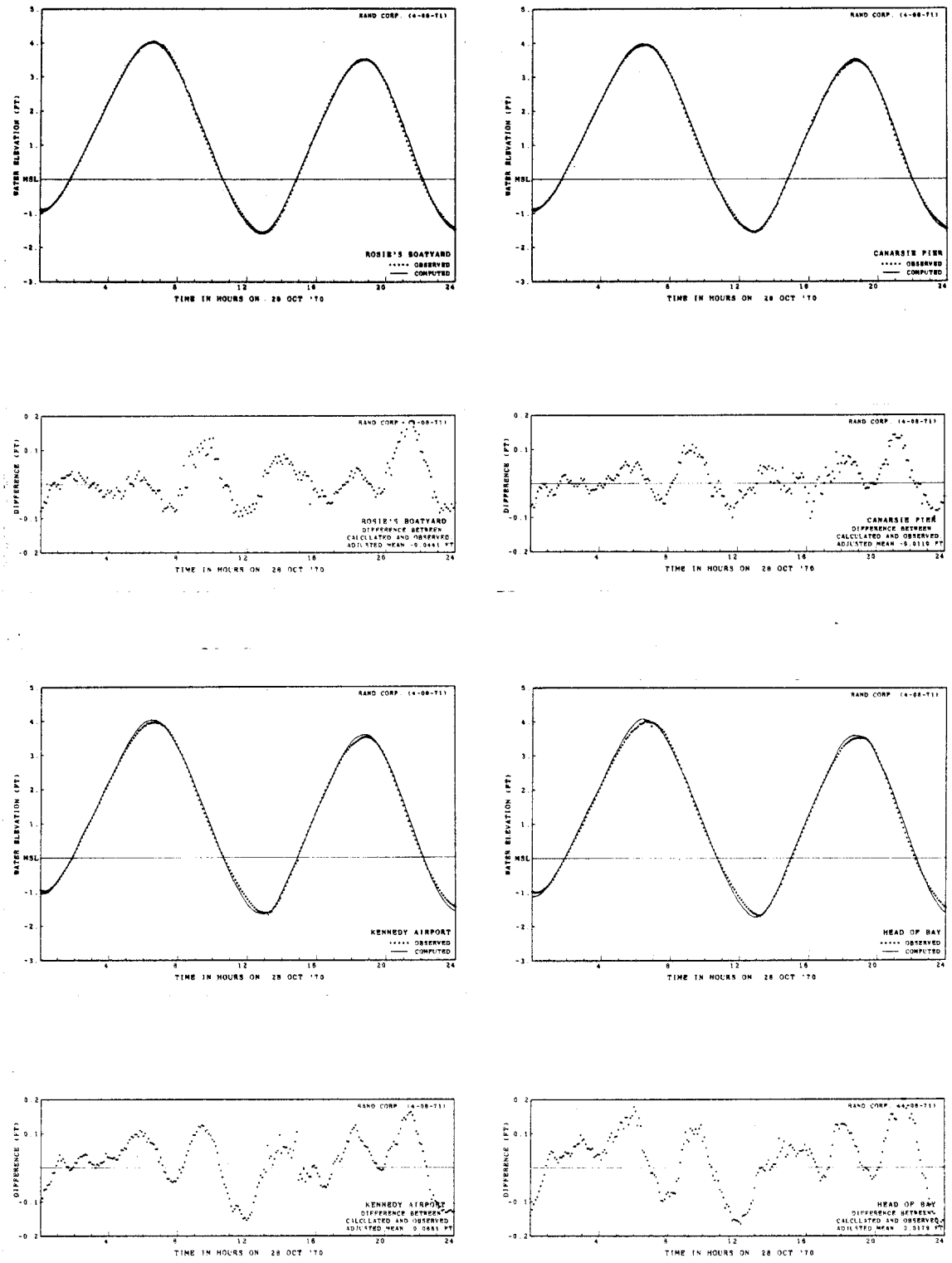


Fig. 9—Comparison between observed and computed data for four stations in Jamaica Bay

presents observed and computed data for the other four stations, together with the graphs of the difference between observed and calculated data for October 28, 1970. The standard deviations for the 2-day time period used for adjustment are: Rosie's Boatyard, 0.065 ft; Canarsie, 0.053 ft; Kennedy, 0.078 ft; and Head of Bay, 0.089 ft.

These graphs do not present the final results of the simulation after all of our adjustment procedures, but are a representation of results obtained after the final adjustment of the bottom stress. It should be noted that the differences between observed and computed data are coherent. To show this more clearly, differences between observed and computed data on October 27 and 28 are presented on one page (Fig. 10). It would appear from these records that, in addition to the tide, an oscillation of the whole bay is introduced with a period of about 3½ hr. In Ref. 1 some tests indicated that a sudden wind generated surges with a period of about 3½ hr, and it was concluded that this would be the basic mode of the oscillation of the bay. Such a mode can generally be easily excited at the boundary of the model. The boundary tide for the computation was based on the Rockaway-gauge tide observation, with corrections in phase and amplitude. These corrections were based on the lunar tidal component. For a surge it can be assumed that the amplitude-phase relations for these two locations are different. Thus we can see that the input derived by reduction of amplitude and a time shift of 6 min would be in error for the oscillation of this frequency. However, it is also possible that the wind generates this basic mode of oscillation.

Since we had 3-hr wind data available at only one location, and were therefore lacking adequate time-varying wind data at several stations around the bay, the only improvement in agreement between observed and computed water levels that could be made was to further adjust the input boundary tide of the model, assuming that the basic oscillation was caused by a deviating boundary value.

It was realized that the oscillation would have considerable change in damping, depending on the stages of the tide and the intensity of the currents at that time. To investigate this particular effect, the deviations shown in Fig. 10 were averaged and subsequently subtracted from the input tidal curve. The tidal curve thus obtained was used for a new computation, and the difference between both computations was determined.

The time histories of the computed differences between the water levels at four stations are shown in Fig. 11. It is obvious that considerable amplification of the basic mode is present, particularly in the back of the bay. Figure 11 clearly shows that the basic resonance mode of the bay is responsible in part for the deviation obtained between the observed and recorded data, as shown in Fig. 10. From the differences between the two computations, we were able to determine quite well the time lag and the amplifications for the basic mode. By weighting the differences between the observed and computed values for all stations, and taking into account time lags and amplifications, we made corrections on the original input used for the computation represented by Fig. 10. The procedure used reduces the standard deviations between the observed and computed values by about one third.

The more important results of the simulations for October 27 and 28 are presented on a reduced scale in Figs. 12 and 13. In these simulations the input is still

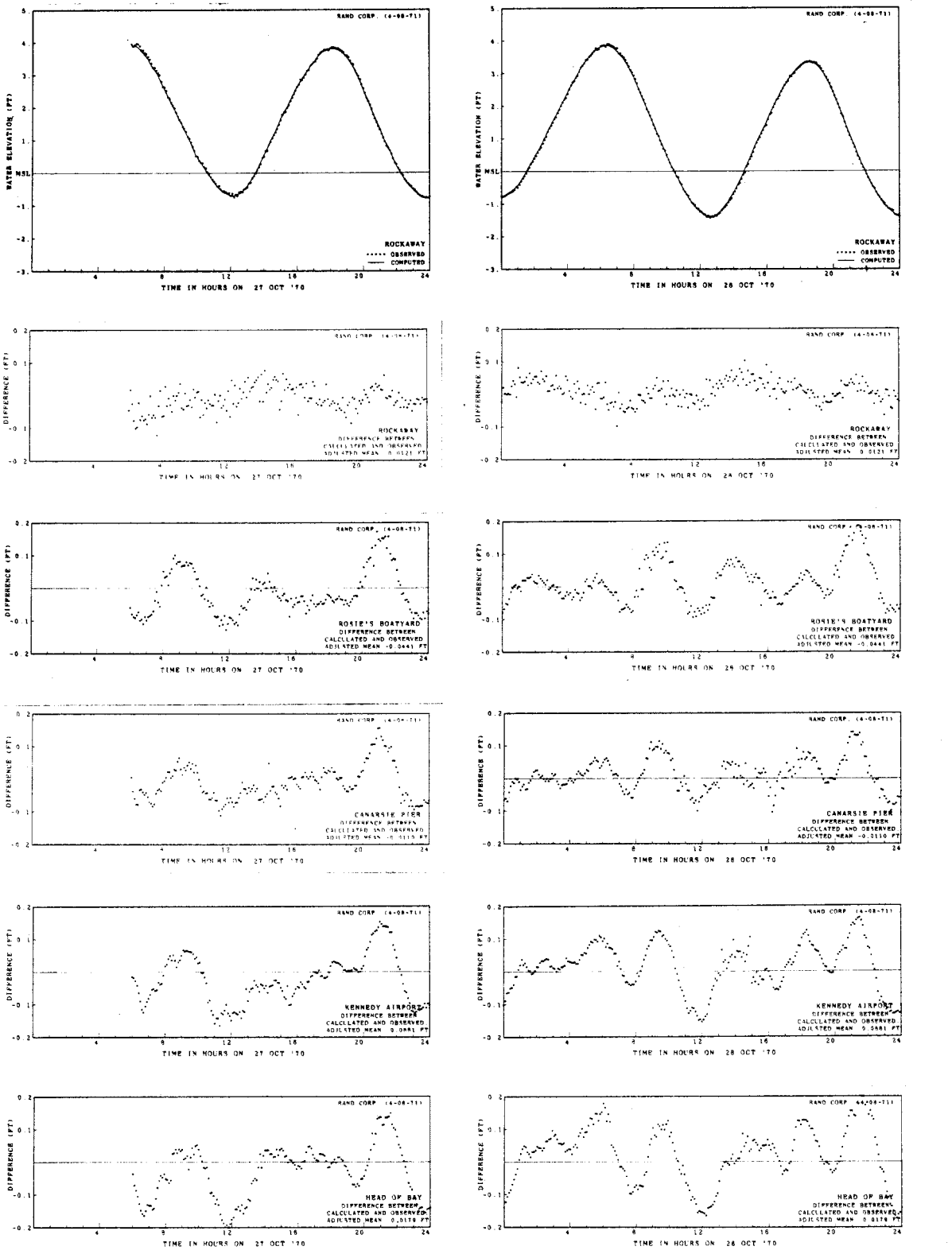


Fig. 10—Deviations between observed and computed data for five stations in Jamai

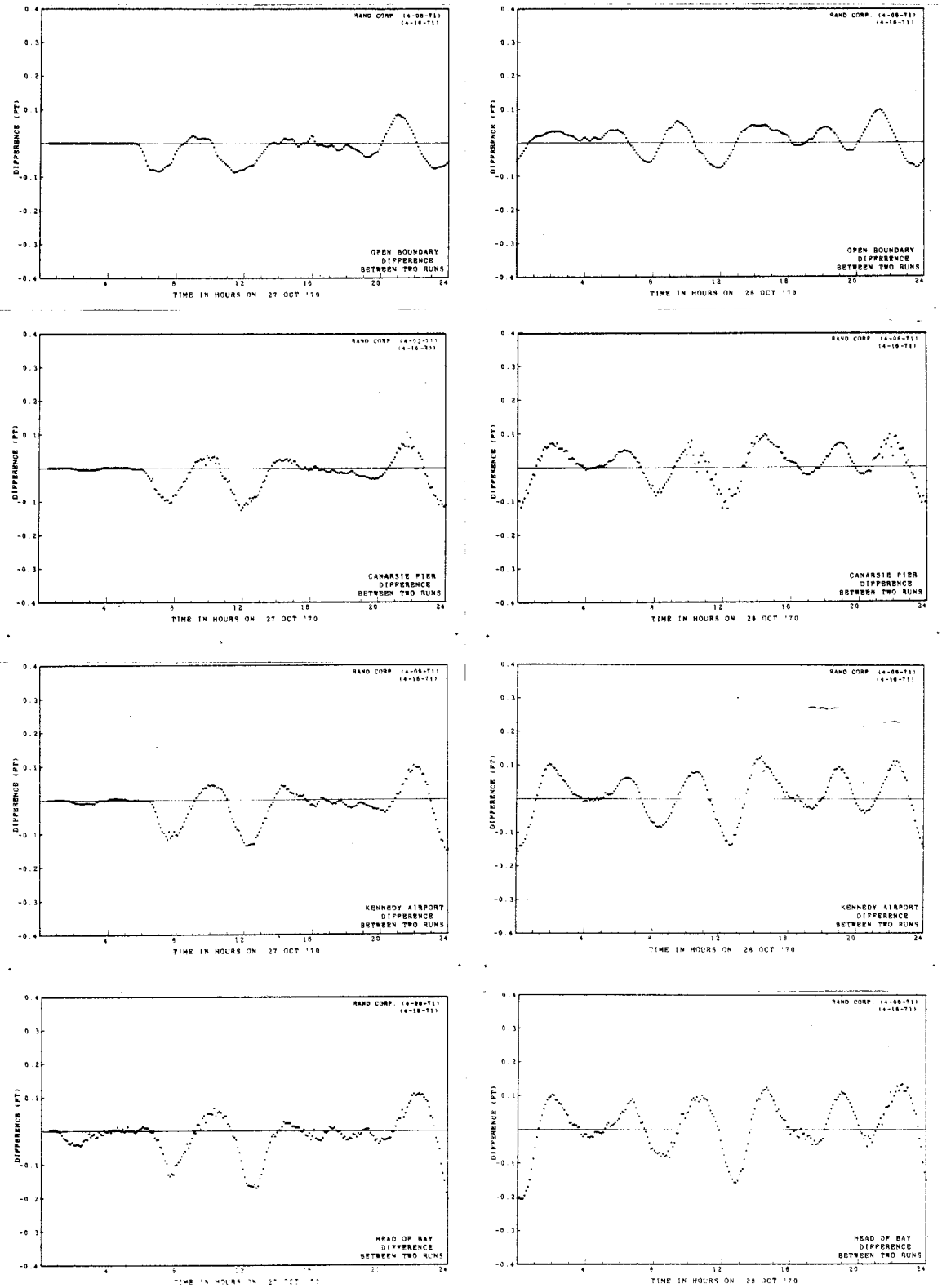


Fig. 11—Differences between inputs and resulting differences in tidal elevation for three stations

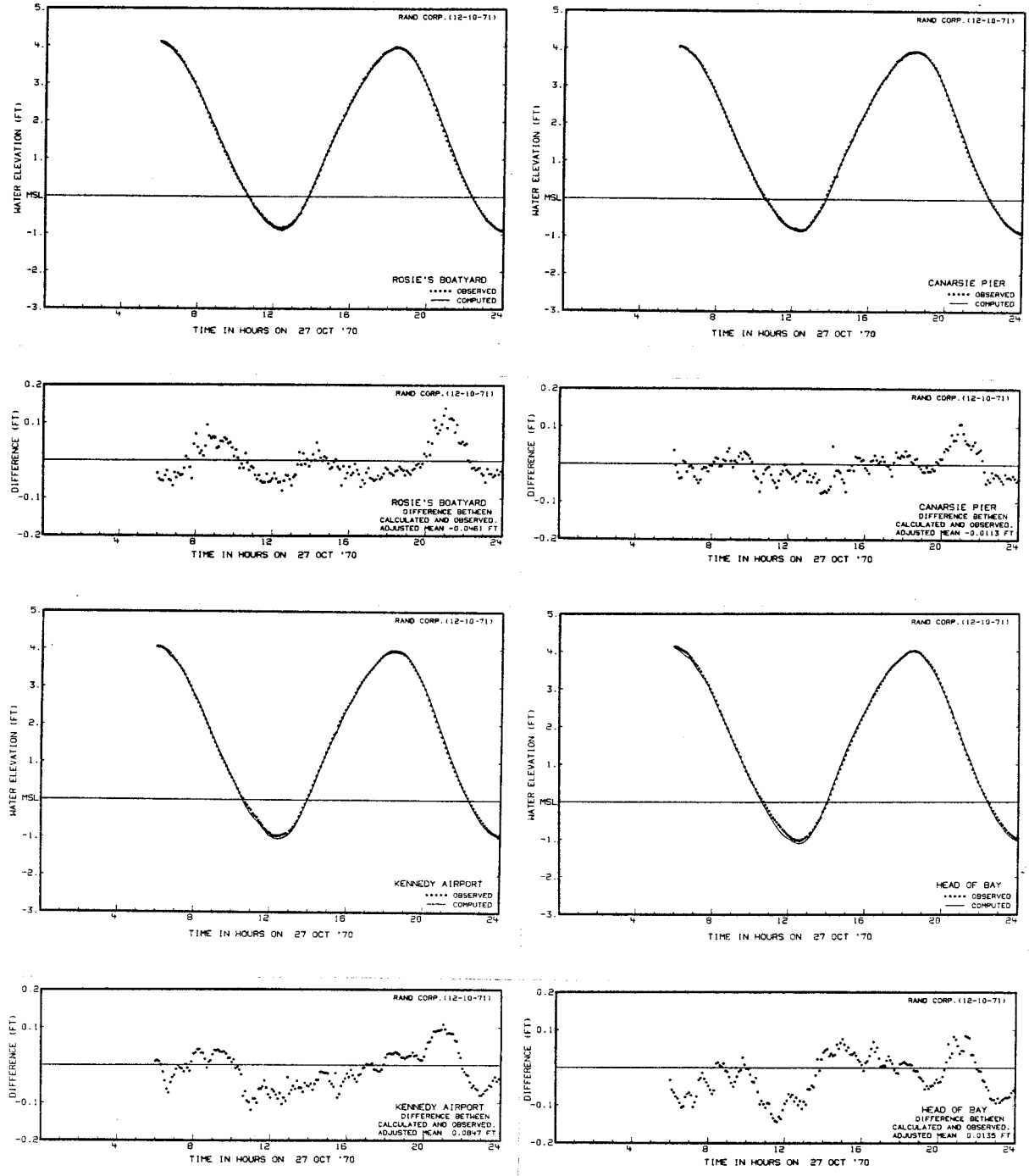


Fig. 12—Comparison between observed and computed data for four stations in Jamaica Bay (after corrections in input for October 27, 1971)

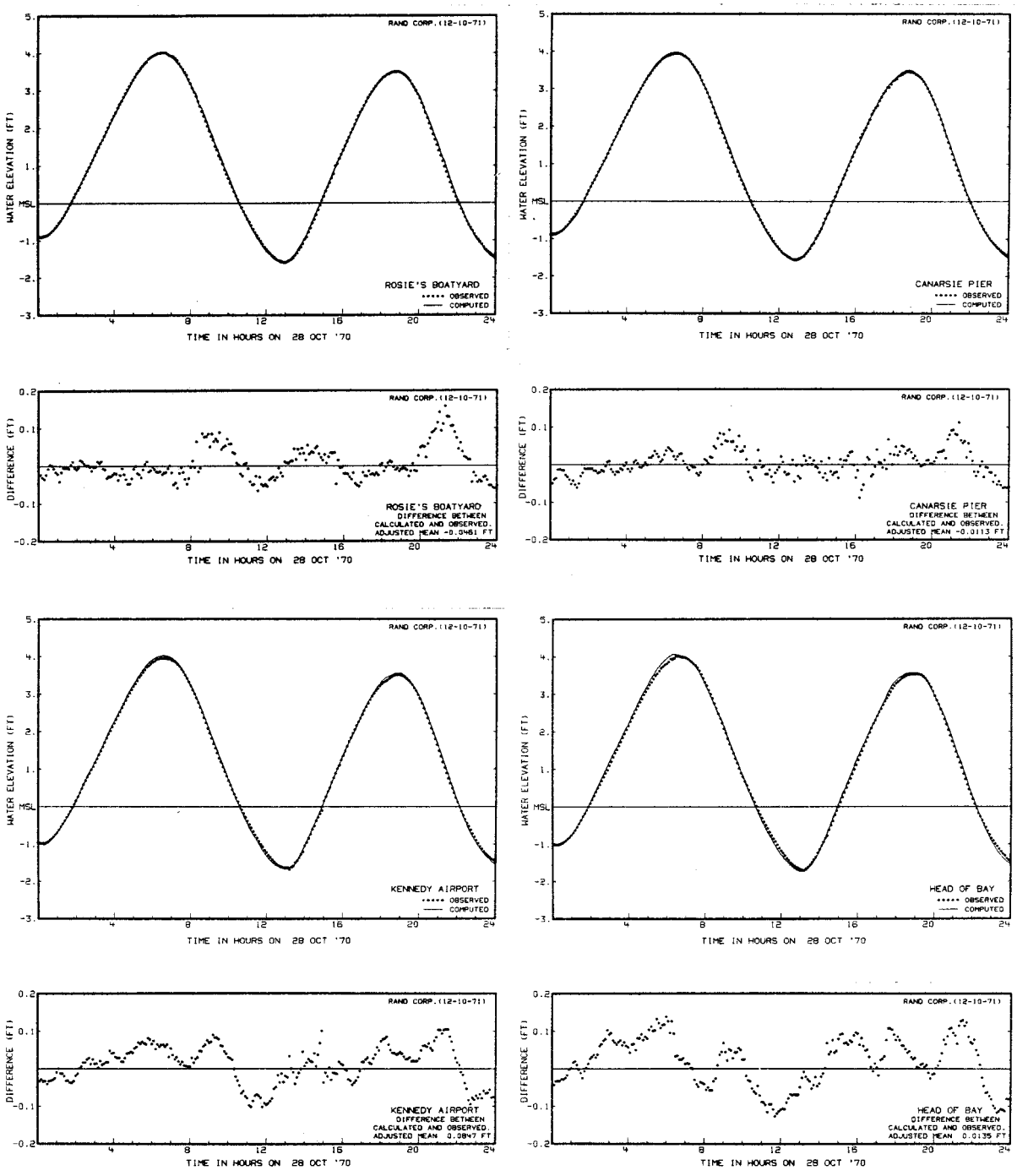


Fig. 13—Comparison between observed and computed data for four stations in Jamaica Bay (after corrections in input for October 28, 1971)

maintained as a fixed level across the inlet. Since small changes in this input become significantly magnified, it can be expected also that this particular assumption may introduce errors in the final results. With the limited data available, however, further adjustments would not be practical.

The influence of the correction in the resonance mode in the input can be seen by comparing Fig. 13 with Fig. 9.

In a numerical model, discharges and vertically integrated velocities can be computed accurately. Thus comparisons between computed values and measured values can be made. In Sec. II we discussed the errors that influence the observed values. There is still another problem that entails the comparison of the different quantities of these two values.

The computed velocities represent a cross-sectional width of the grid size; observed values represent the local time-averaged value. In a cross section of an estuary channel, the velocities are far from uniform, which is already evident in the differences between the three values over the vertical. Considerable variation also occurs in a horizontal direction. One of the striking examples is a HW slack, when the flow in the shallow parts may be ebbing while flood still exists in the channel. As such the velocity analyses have to be carefully executed. A few comparisons are presented in Fig. 14. The graphs show computed velocity magnitude, together with all observed data for that period. The agreement is still quite good.

Stations 1 and 3 are not analyzed because they are considerably influenced by the noise generated by the input. Station 7 was not used either, because of a data input error on the location; fortunately, this information is of no particular interest for this investigation.

The difference graphs, of which a few samples are given in Fig. 15, are particularly interesting, since many of the higher frequencies also occur in the field. Besides the resonance mode induced by the boundary, and possibly also by wind, oscillations of about a 1-hr duration are present in the observation as well as in the computed results. These oscillations become more prominent in the back of the bay, and are possibly in a higher component of the lunar tide. The agreement and behavior of the higher modes of the tidal motion is considered to be of important scientific interest. An analysis using time series may indicate the accuracy of the simulation of energy transfer from one tidal frequency to another and into final dissipation in the very high modes.

The importance of accurate timing of recording gauges has been stressed previously. The influence of a slow clock is illustrated in the gradient (difference) records between Kennedy and Canarsie, and Kennedy and Rosie's Boatyard. The Kennedy recorder is fast by about 1 min a day; as a result, the computed gradient record starts to deviate in phase from the observed record. On October 28 at 1500 the clock is reset and the curves are again in phase. The errors introduced by inaccurate timing mechanisms of stage recorders will be discussed in more detail in Sec. IV.

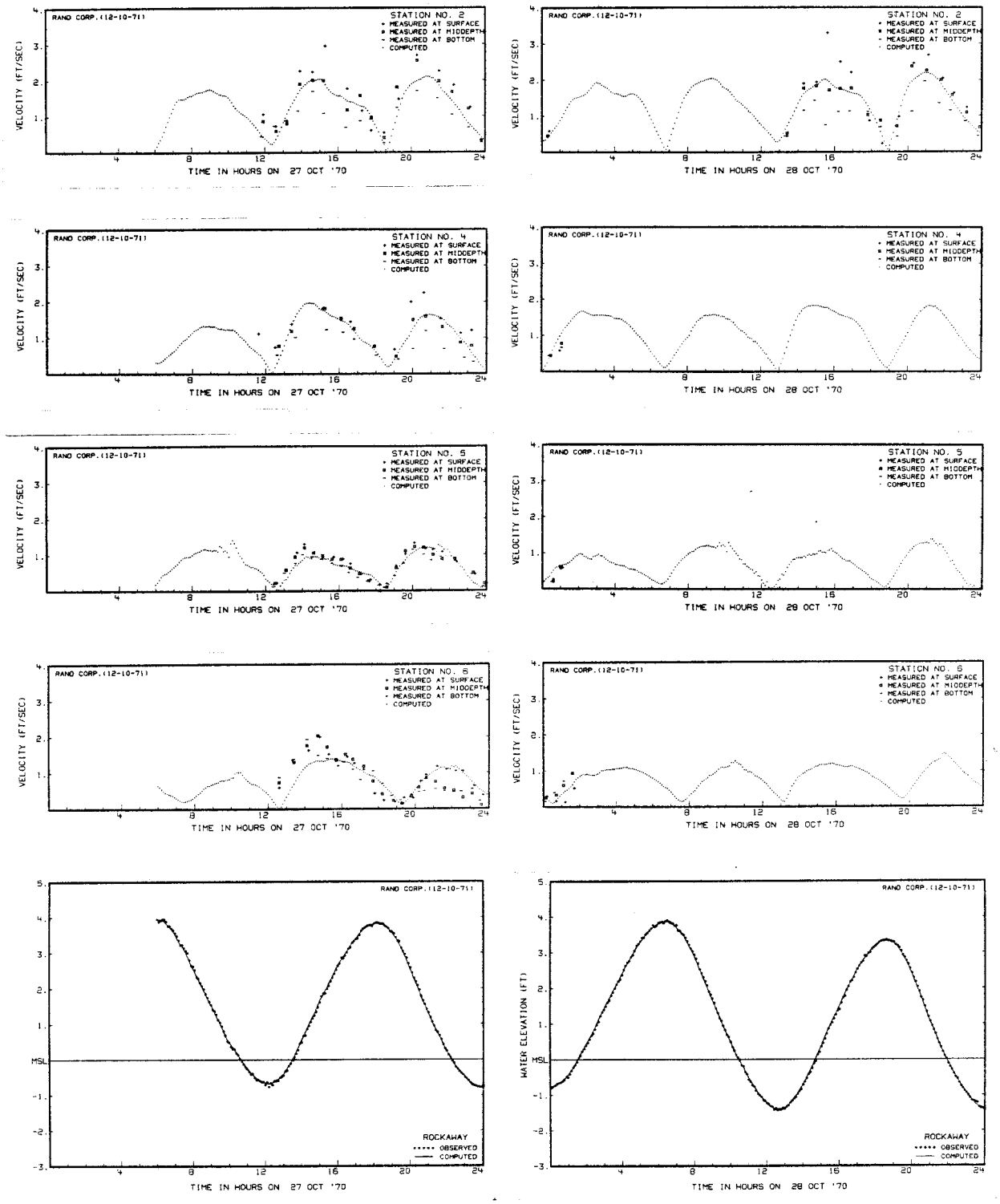
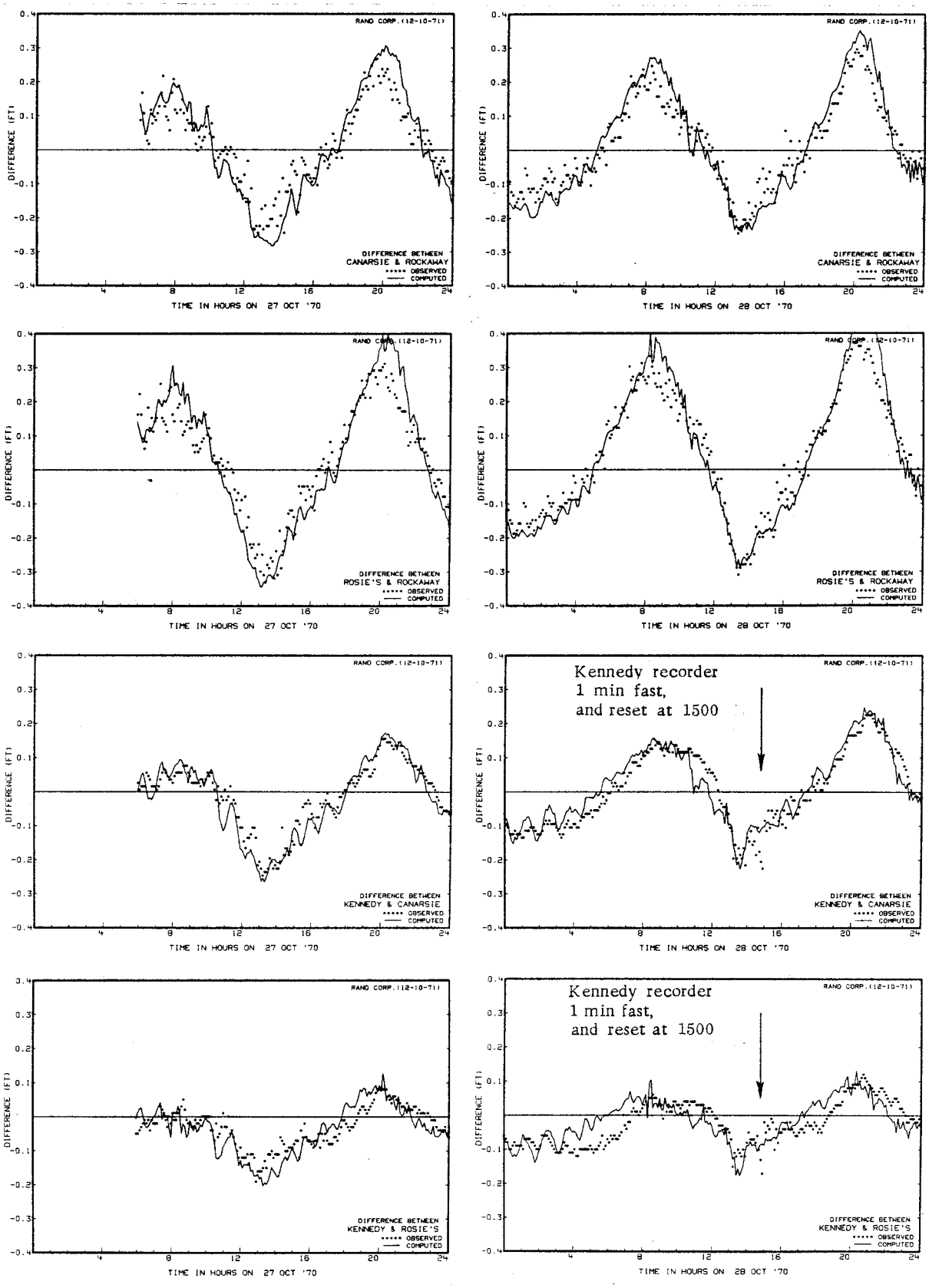


Fig. 14—Computed and observed velocities at four locations, together with the tide at Rockaway



—Comparison between computed and observed differences between stations (after correction for input

IV. PREDICTIONS

The first step in verifying the model was to make a correction in the input tide, as was done for the adjustment 2 days earlier on October 27 and 28. The simulations obtained show a somewhat larger deviation between observed and computed data; nevertheless, the agreement is still very good, as is shown in Table 1 for all stages, and in Table 2 for the velocities. The latter are calculated as the difference between the computed and the average value of the velocities measured at bottom, mid-depth, and near the surface. The tidal amplitude on October 29 was substantially larger than on the two previous days. It is not surprising that the deviations are also larger, as shown in Fig. 16. A complete set of outputs is given in Appendix A.

Most of the deviation is caused by inaccuracies in the clocks of the recorders. The inspection logs of the Kennedy tide-stage recorder indicate that on October 29

Table 1

STANDARD DEVIATIONS BETWEEN OBSERVED AND COMPUTED WATER LEVELS

(In feet)

Tide-gauge Station	October 27 and 28 Adjustment	October 29 and 30 Verification
Rockaway	0.032 (0.035)	0.033 (0.032)
Rosie's Boatyard	0.043 (0.065)	0.053 (0.066)
Canarsie Pier	0.034 (0.053)	0.043 (0.053)
Kennedy	0.050 (0.078)	0.078 (0.082)
Head of Bay	0.064 (0.089)	0.090 (0.100)
Average	0.045	0.060

NOTE: The numbers in parentheses indicate results obtained before correcting for errors introduced by resonance mode.

Table 2

STANDARD DEVIATIONS BETWEEN OBSERVED AND COMPUTED VELOCITIES

(In feet per second)

Current Station	October 27 and 28 Adjustment	October 29 and 30 Verification
2	0.18	0.30
4	0.28	0.22
5	0.14	0.19
6	0.30	0.24
8	0.13	0.15
9	0.17	0.21
Average	0.24	0.26

the clock was about 1 min fast and increased to about 2 min on October 30. A more serious inaccuracy is that of the gauge at the Rockaway station. On October 29 at 0930, the clock was on time; however, at 1200 on October 30, the clock was 4 min slow. Since the information from this gauge is used for driving the model, the errors introduced by boundary information will also show in the deviations between observed and recorded data at all other stations, except at Rockaway. These deviations are taken into account; they reflect not only the effect of the resonance mode, but also timing errors. As a result, the correction for the resonance mode, as described in the previous section on adjustments, was less effective for the period of October 29 and October 30 than for the period of October 27 and October 28.

Since all graphs of the deviations show a gradually increasing slip in the input tide's timing from October 29 to October 30 at 1200, an increasing periodic oscillation with the period of the lunar tide is noticeable (Fig. 16). Naturally, the Rockaway curve is not affected, since this is the information used for driving the model. The periodic deviation is particularly noticeable at the Kennedy gauge, because this recorder was about 2 min fast. The comparison was thus made with a total timing error of about 6 min. A simple computation will show that for a 5-ft lunar tide, the periodic deviation has an amplitude of about 0.02 ft for every minute that a recorder is slow or fast. In drawing the errors in the graphs of Fig. 16, it was assumed that the timing error of the Rockaway recorder increased linearly between 0930 on October 29 and 1200 on October 30.

As a result of the timing problem in the observations used for verification of the model, the standard deviations shown in Table 1 are somewhat larger than those obtained for the adjustment of the model. Although it is possible to make a correction on the timing for the input tide, it was not considered justified in view of the otherwise excellent agreement.

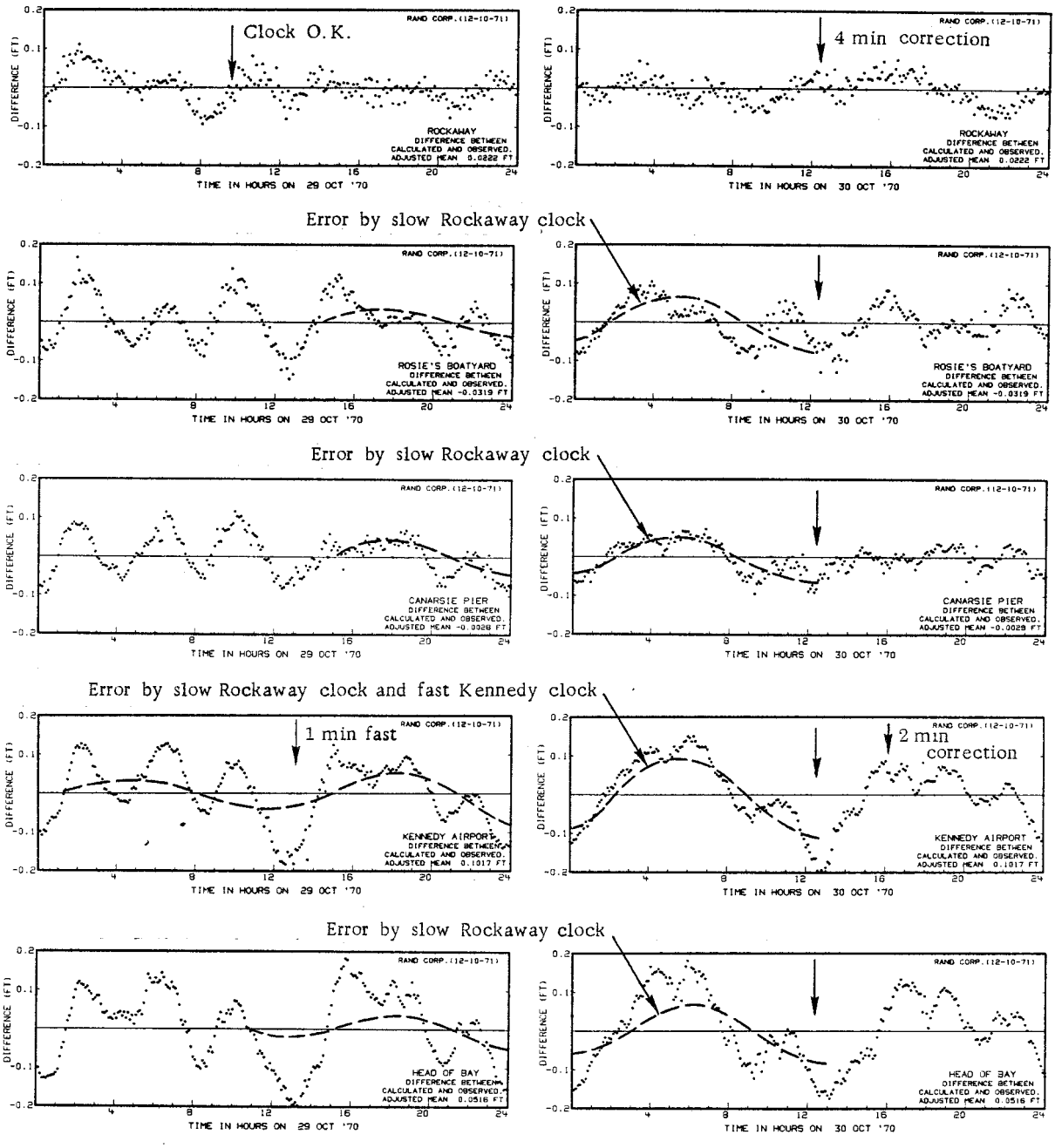


Fig. 16—Comparison between observed and computed data for four stations in Jamaica Bay (after corrections in input), showing errors caused by inaccurate tide-stage recorder timing mechanism

The Head of Bay graphs show a periodic error in addition to the one generated by the input. This is caused by the approximations made for this section of the bay and also by the fact that the point of comparison was located at a shorter distance from the input boundary of the model, while the recorder was situated in a narrow channel some distance from Head of Bay, thus introducing a phase shift.

V. CIRCULATION

In Vol. III of this study [1], it was found that circulation is one of the primary mechanisms by which discharged pollutants are being removed from the back of the bay. Therefore, in the 1970 field-measurement program, an attempt was made to determine the extent of the circulation. Measurements were made over two full tidal cycles in ranges 8 and 9 in predominantly north-south channels connecting Grassy Bay with Beach Channel (Fig. 1). One of the channels had considerable depth—approximately 35 ft; the other was just a minor channel with a depth of approximately 15 ft. The cross sections in which the measurements were made are shown in Fig. 17. In the center of these two channels, measurements were made at 2 ft below the surface, at approximately mid-depth, and near the bottom. In the shallow areas adjacent to the channels, the only measurement made was at approximately mid-depth. All measured velocities were small, generally only a few tenths of a foot per second.

The winds on October 28 were light, approximately 5 kn. This condition continued through the night; but in the morning hours of October 29, the wind speed increased, turning from northerly to easterly, and reaching a maximum of 12 kn about 1200.

For the analysis of currents and transport, each cross section was divided into five subsections, as indicated in Fig. 17. Three of these subsections in each cross section were assigned time-varying areas according to the stage of the tide. In each section, the flow was computed as the product of the current at a particular time multiplied by the surface area, except on the tidal flats where the transport was assumed to be 0.85 times the area times the velocity. The results of our analyses are presented in Figs. 18 and 19, together with the tidal variations and the representation of the wind. The LW at 1300 on October 28 is the same as the LW on October 29 at 0124. The computed average northerly transport during this period is about 400 ft^3/sec. The first HW during the field measurements of the current was at approximately 1830. The next high tide, just before 0800 on October 29, was approximately 0.4 ft higher. Correcting for this difference in water height, we can estimate the average northerly flow during this tidal period to be approximately 1400 ft^3/sec (Fig. 18).

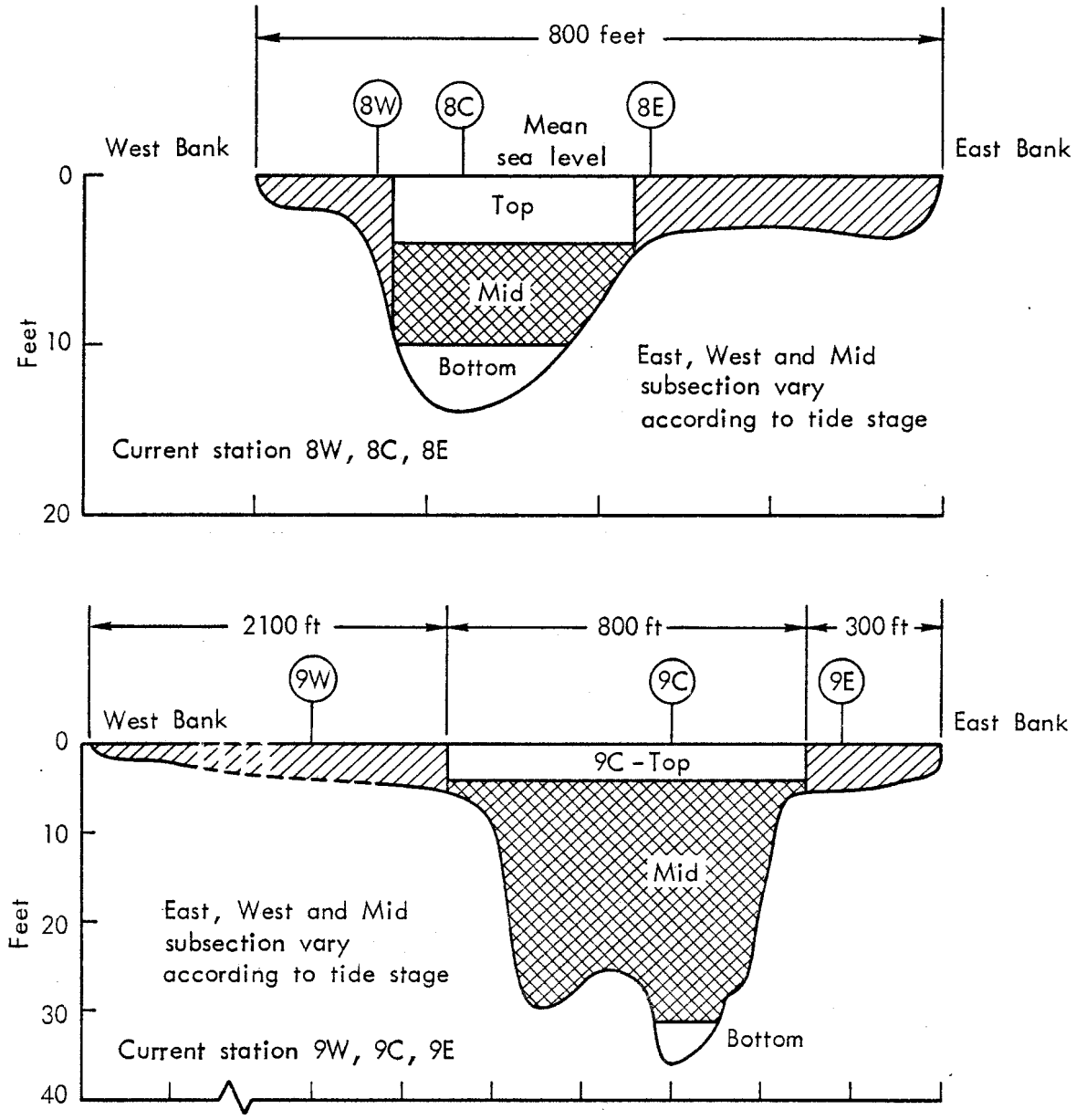


Fig. 17—Cross sections and subsections used for computation of flow

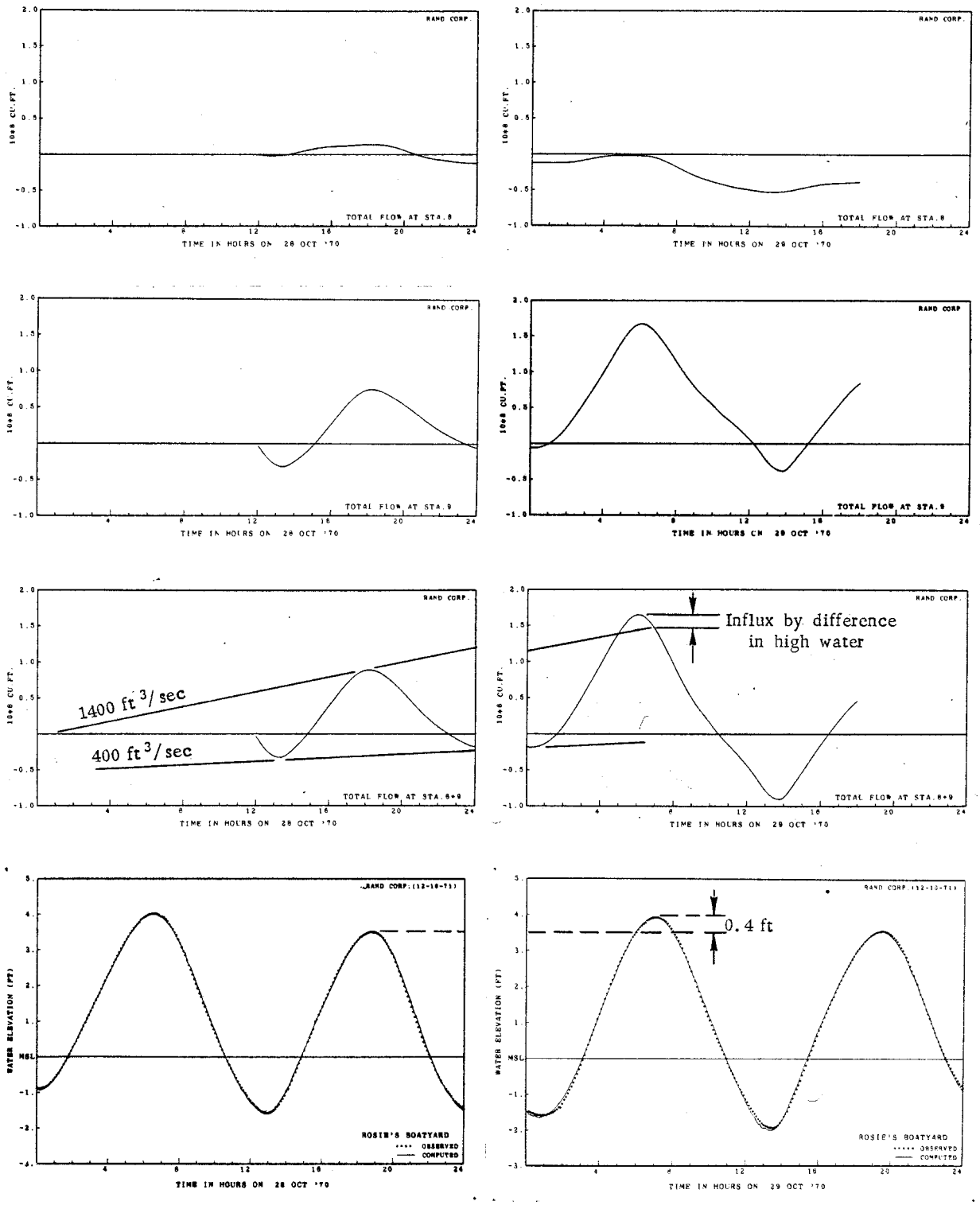


Fig. 18—Net flow through range 8 and 9 computed from field measurements, together with tide data

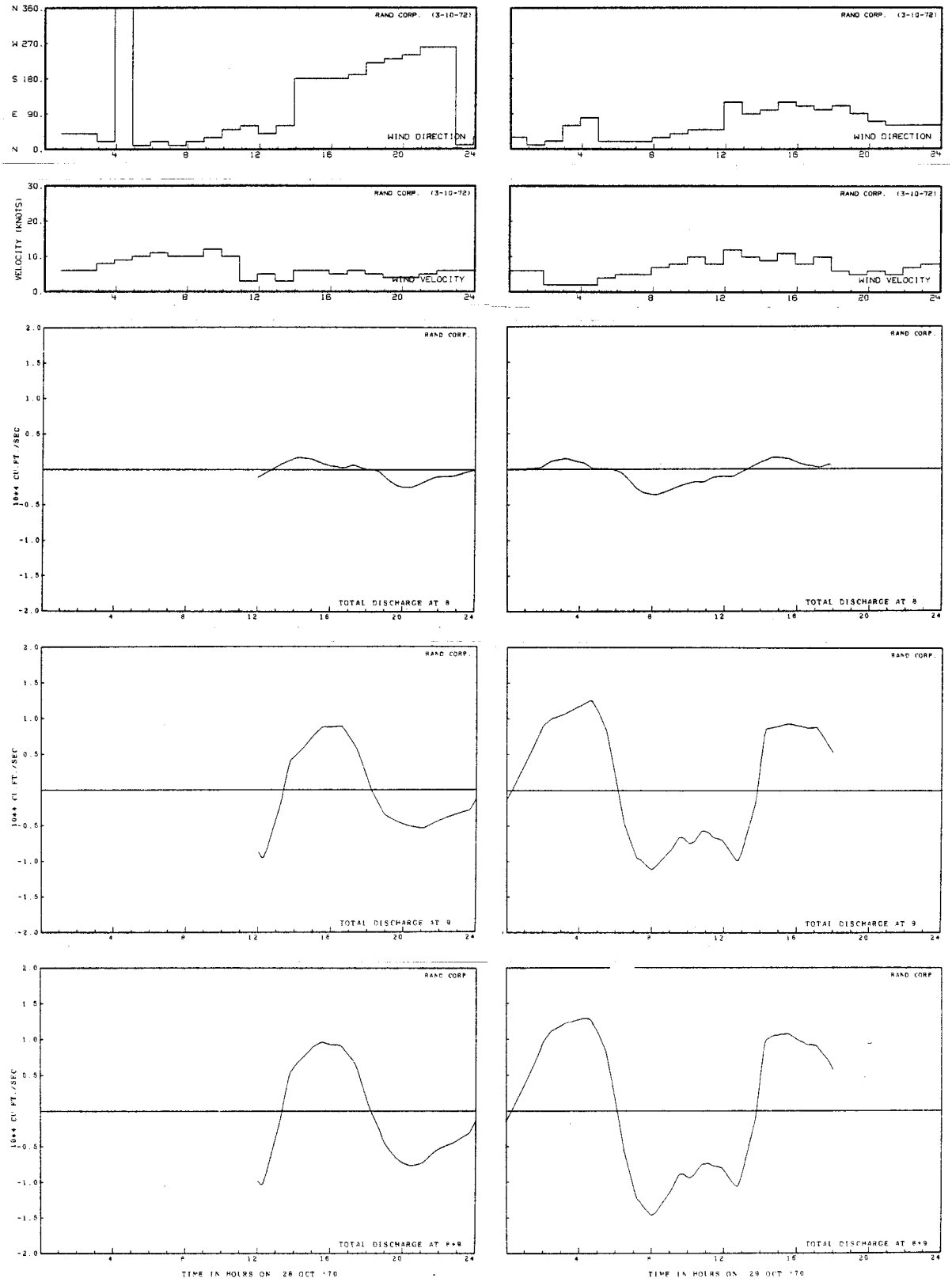


Fig. 19—Discharges through ranges 8 and 9 computed from field measurements, together with wind data

The transports during the period from LW to HW on October 29 were severely affected by the increasing wind, resulting in a reversal of net current. The greatest effect on the transports, however, was the computed transport over the tidal flats, for which only very limited data are available.

The results of the field measurements are not conclusive;[1] the velocities were low, and considerable error in their measurement is indicated in Sec. II. However, in the periods with light wind (until 0800 on October 29), the observations indicate that a weak northerly net current is present.

In the simulations of the tides during the period of current measurement, wind data were changed every 3 hr, using tabulated wind speeds and directions published by the Department of Commerce. At a later time, copies of the wind logs were obtained that showed hourly entries with considerable fluctuations around these values. However, no continuous recording of the wind was available; consequently, no simulation could be made with time-varying wind. Comparisons between our computed and observed velocities are shown in Fig. 20. Considerable deviations do occur, which, for the most part, can be traced back to wind conditions.

It will be noted that at Station 9 on October 29, from 0800 to 1200, the wind-driven surface current was considerably larger than velocities at mid-depth. At the time the simulations were made, the computational program was not capable of computing transports and discharges through cross sections running east-west; thus we cannot make a direct comparison between the observed and simulated total flow computed through the two cross sections.

The gradients between the tide-stage recordings at Kennedy and the stage gauge at Rosie's Boatyard are very small, as shown in Fig. 15. Considerable surging occurs, which will, of course, influence the field measurements.

Varying salinity was one effect we did not simulate in our model. Salinities in Grassy Bay do not show much variation during a tidal cycle. This is not the case for salinities at Broad Beach, where considerable tidal excursion exists. Consequently, the weak gradient in water surface between Kennedy and Rosie's Boatyard is affected by the salinity changes. The pressure gradient introduced by the salinity gradient could be incorporated in the model, but it was not warranted at this time.

Since the wind appeared to influence the circulation to a considerable extent, the results of simulations over a much longer period than the 4 days reported in the study had to be analyzed. The analysis of circulation in the model uses results of a 12-day simulation.

Figure 21 presents the net transport through five cross sections based on actual tides from October 27 to November 7, 1970. Tide and wind inputs are also presented. During 4 of the days (October 31-November 3), a constant easterly wind was simulated. Computations indicated that during the 4-day period (days 5 through 8), the net transport was 2600 ft^3/sec. During the periods in which actual variable winds were simulated, the net counterclockwise transport was about 1400 ft^3/sec, which is in general agreement with the observations.

[1] The analysis of circulation based on field data should require much longer records.

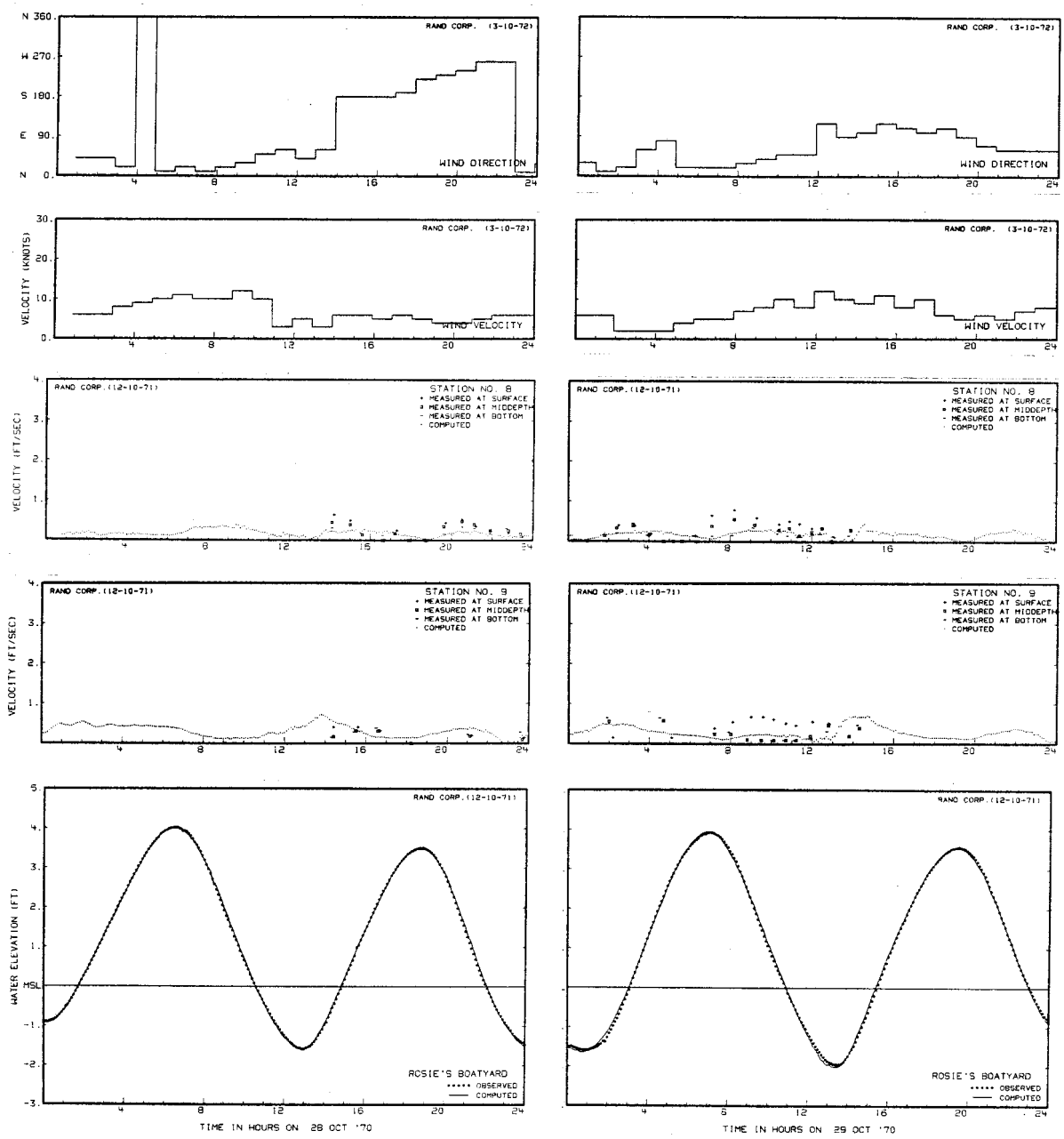
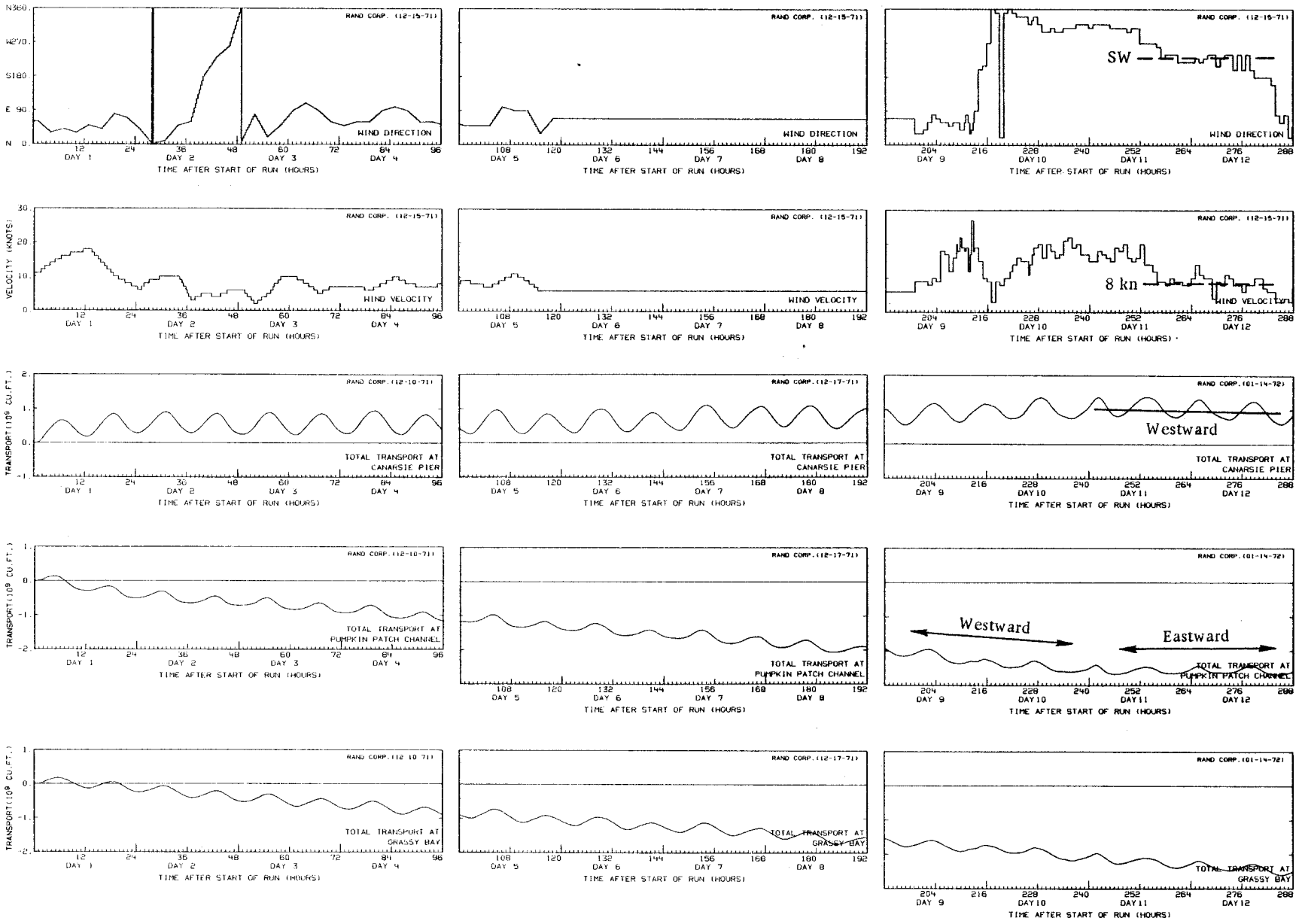


Fig. 20—Observed and computed velocities at Stations 8 and 9, together with wind and tide data


RAND CORP. (12-15-71)
WIND DIRECTION
N360.
E270.
S180
E 90
N 0.
SW
WIND VELOCITY
VELOCITY (KNOTS)
8 kn
RAND CORP. (12-10-71)
RAND CORP. (12-17-71)
RAND CORP. (01-14-72)
TOTAL TRANSPORT AT CANARSIE PIER
Westward
TRANSPORT(10⁹ CU.FT.)
TOTAL TRANSPORT AT PUMPKIN PATCH CHANNEL
Eastward
TOTAL TRANSPORT AT GRASSY BAY
DAY 1
DAY 2
DAY 3
DAY 4
DAY 5
DAY 6
DAY 7
DAY 8
DAY 9
DAY10
DAY11
DAY12
TIME AFTER START OF RUN (HOURS)

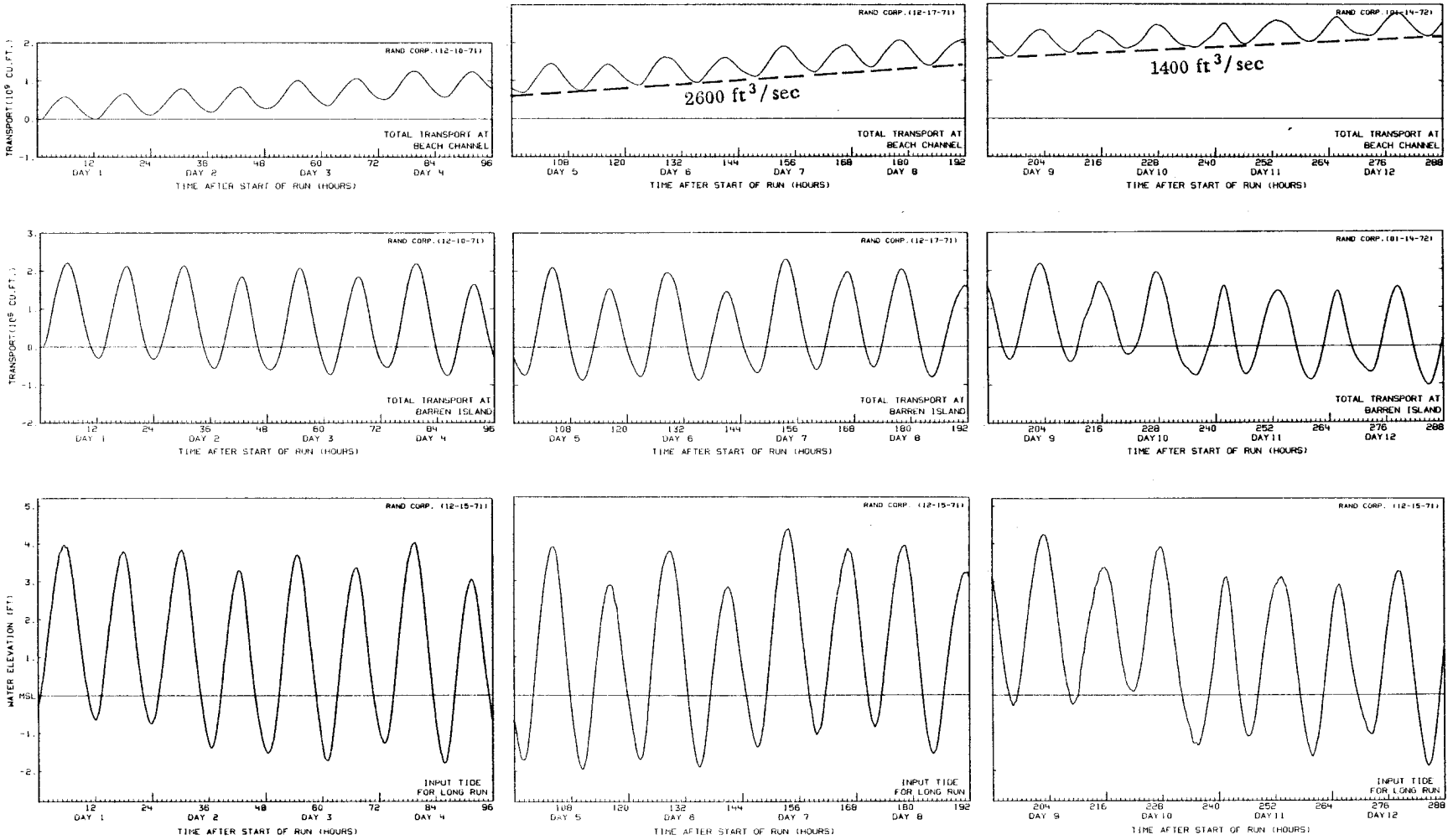
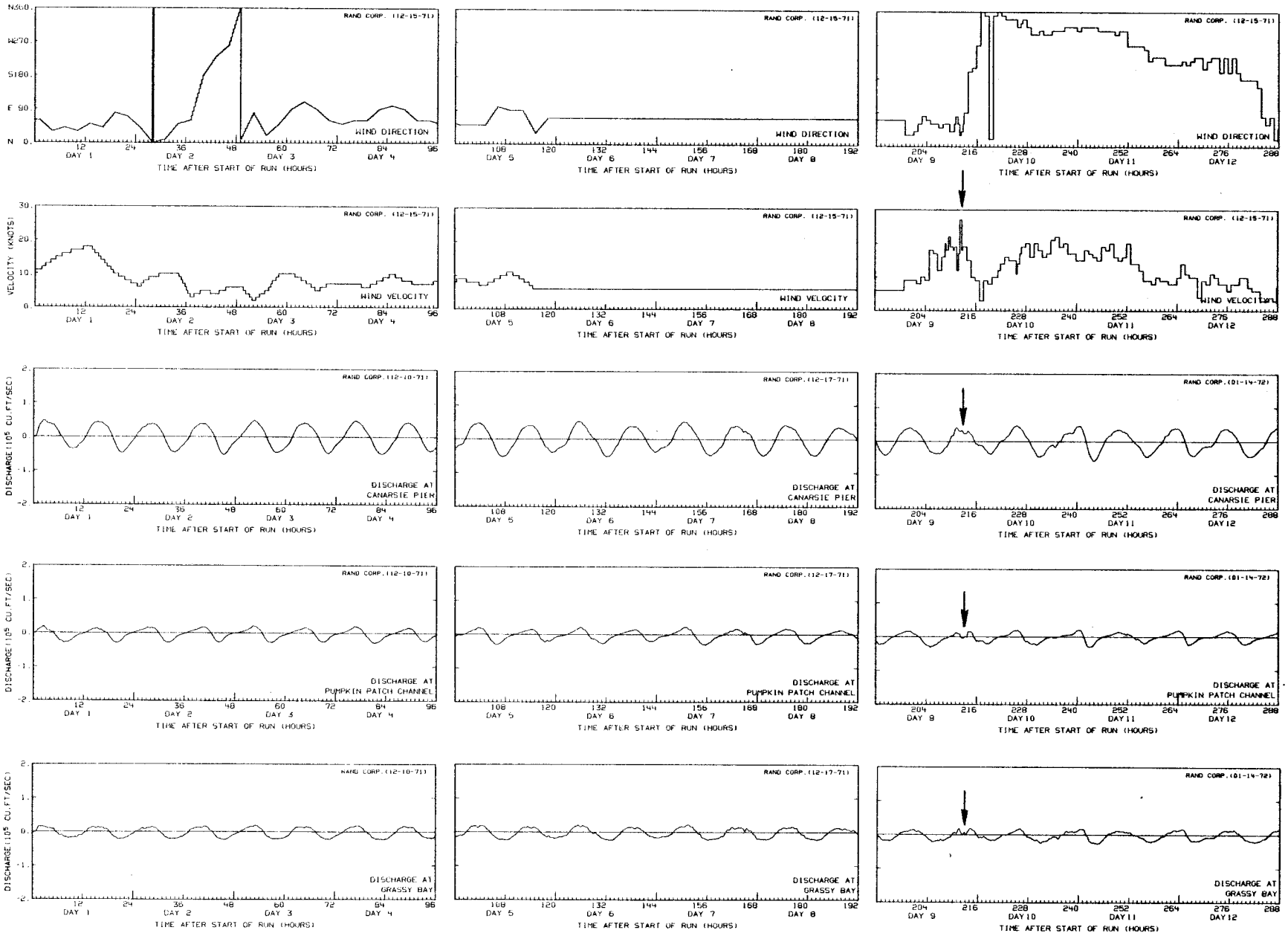


Fig. 21—Wind data, input tide, and computed net transports through five cross sections in Jamaica Bay over a 12-day period


RAND CORP. (12-15-71)
WIND DIRECTION
N 360
W 270
S 180
E 90
N 0
WIND VELOCITY
VELOCITY (KNOTS)
RAND CORP. (12-10-71)
RAND CORP. (12-17-71)
RAND CORP. (01-14-72)
DISCHARGE AT CANARSIE PIER
DISCHARGE AT PUMPKIN PATCH CHANNEL
DISCHARGE AT GRASSY BAY
DISCHARGE (10^5 CU.FT/SEC)
DAY 1
DAY 2
DAY 3
DAY 4
DAY 5
DAY 6
DAY 7
DAY 8
DAY 9
DAY10
DAY11
DAY12
TIME AFTER START OF RUN (HOURS)

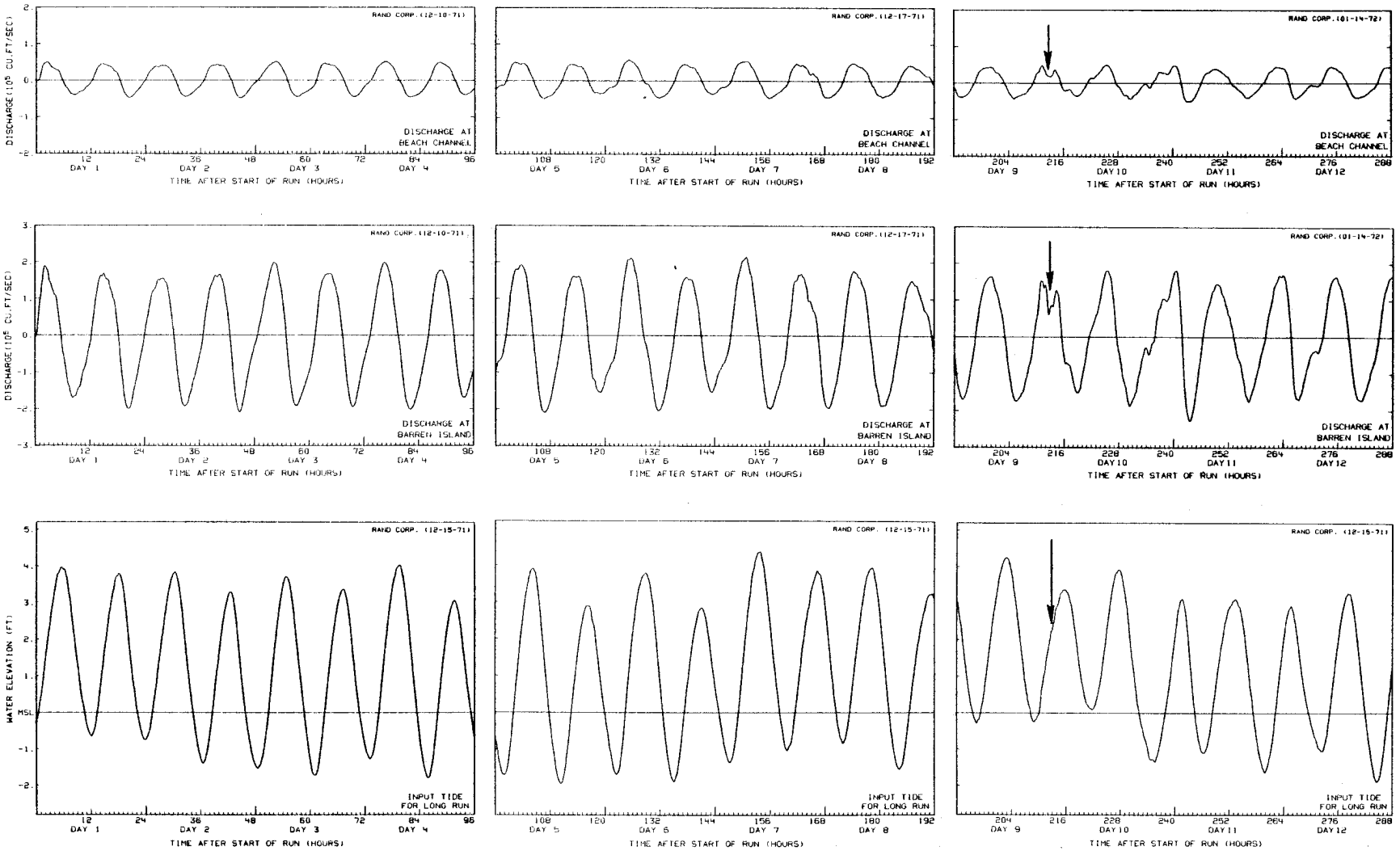


Fig. 22—Wind data, input tide, and computed discharges through five cross sections of Jamaica Bay

The direction of the net transport through sections near Canarsie Pier and through Pumpkin Patch Channel depends on wind intensity and direction.

The discharges are also computed, together with wind and tidal data, in Fig. 22. Of particular interest is the relation between the wind and discharge on days 9 and 10 of the simulation. During flood the current direction was reversed at Pumpkin Patch Channel and at the Grassy Bay cross section around day 9 at 2100. Even the flow in the inlet near Barren Island was reduced to about 50 percent of its normal value at that time.

VI. DISCUSSION

The analysis of the field data and the results obtained with the model indicate that high-quality field data are required to be compatible with the degree of accuracy that can be obtained with the model. Tide-stage recorders using strip charts or circular charts are clearly inadequate, since these cannot be read with an accuracy of 1/100 of a foot in tidal height and within a minute in time. In view of the obvious timing errors introduced by conventional timing mechanisms, use of electronically controlled clocks is desirable.

The velocity measurements taken with conventional stream-gauge current meters are most primitive, but are still extensively used in estuary field-measurement programs. Investigations using numerical models also require velocity records taken at equal time intervals in digital form.

The variability of the velocity field in space is considerable, with the higher velocities being concentrated in the channels. The simulations used for adjustment and verification produced charts with velocity distributions. Figure 23 shows the distribution of the vertically averaged, computed velocities on October 30 at 0559. This distribution is taken during flood about 2 hr before HW. The water surface is nearly horizontal and is at 3.44 ft $\pm$ 0.02 ft above datum, clearly showing the current concentration in the main channels.

It is difficult to assess how successful we have been in our final adjustment of the model in comparison with the models of other studies. The results presented here are possibly the most extensive numerical simulations of an estuary undertaken to date. Consequently, no other numerical tidal simulations could be used for comparison. A survey of the literature concerning physical models did not reveal the existence of an error analysis, expressed in numerical values, as extensive as the one we have presented. Some unsubstantiated information was found in a report on estuarine analysis [4] which indicated that in physical models, it is possible to achieve accuracies of 0.1 ft in tidal stages and a 0.5-ft/sec agreement between observed and simulated velocities. Our results obtained with the numerical model are much better.

Panuzio [5] reported on a study of the Jamaica Bay Hurricane Barrier in which a physical model of the bay was used. This model utilizes a periodic tide with the basic lunar period (12 hr, 25 min), which is called "prototype tide." No information

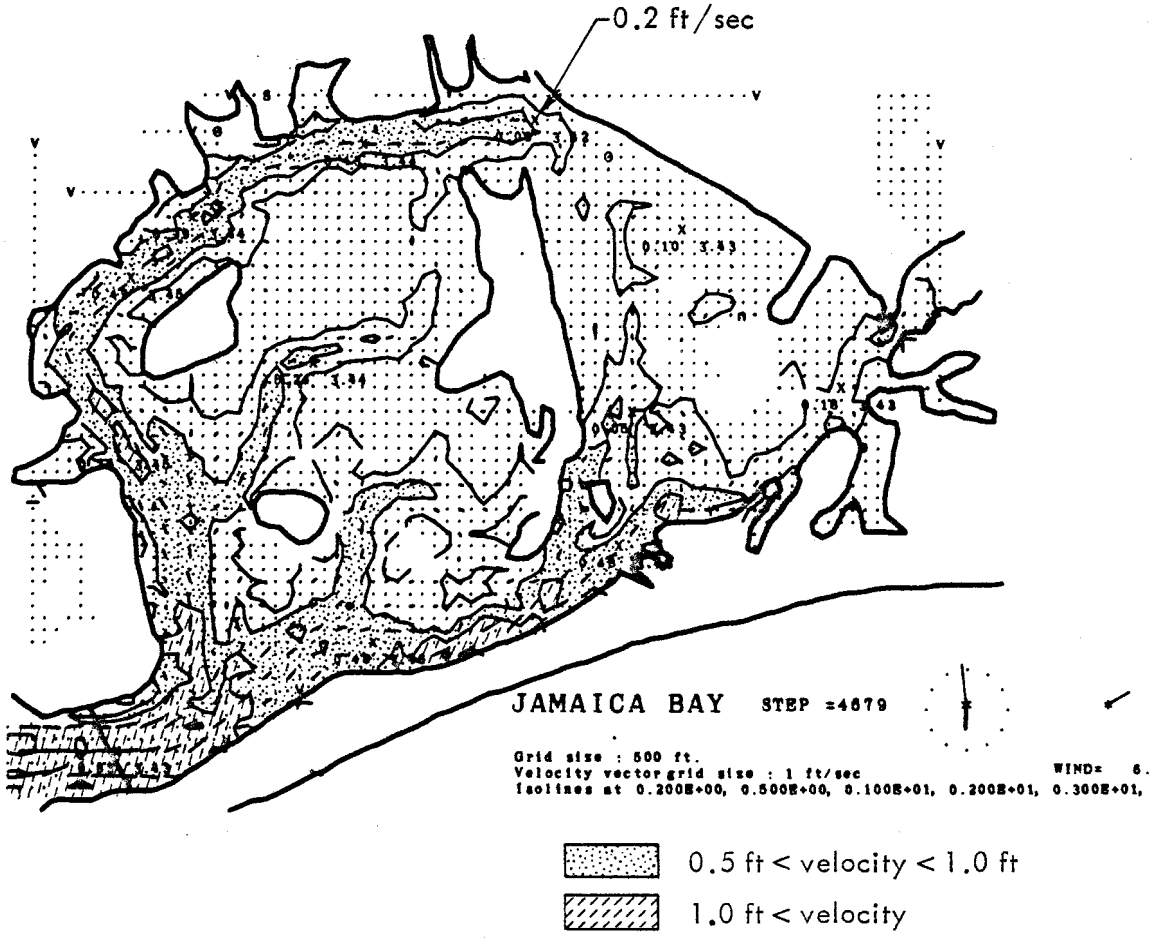


Fig. 23—Computed velocity distribution on October 30 at 0559

is presented to show how this prototype tide is derived from the field records. However, the standard deviation of the difference, taken at half-hour intervals between the prototype tide and the tide simulated, could be computed from plots presented by Panuzio for Canarsie Pier and Head of Bay. These are 0.34 ft and 0.36 ft, respectively, with which the results of the numerical model simulations (0.034 and 0.064 ft, respectively) compare favorably. Only one velocity could be compared, based on the average of the surface, mid-depth, and bottom records. This was the standard deviation for Station 6, which was 0.32 ft/sec for the physical model and 0.22 ft/sec in the verification of the numerical model.

It is emphasized that no direct comparison of the capabilities of physical versus numerical models can be made with the few values presented here. The tidal-stage

data used for our numerical model adjustment are more accurate than the data used for the physical model, which was discussed in a previous report [1].

It is the opinion of the author that by using the 1970 data, the physical model can be more accurately adjusted. Such an effort would be of great practical interest, not so much concerning problems with Jamaica Bay, but in general, since considerable debate has arisen as to the capability of one type of model versus another [4].

Through the Jamaica Bay studies of the proposed hurricane barrier, and of the impact of water-control facilities reported here, two models have become available, each designed and operated independently. Operation of these models under comparable conditions, using the same data, would provide valuable infomation on the performance that can be expected, and would serve as a guide for other investigators in the design of estuarine studies. In such a comparison, however, it should be kept in mind that numerical models are relatively new, and, even with their impressive performance, still need considerable development.

VII. CONCLUSIONS

The tides in Jamaica Bay can be simulated with a very high accuracy. Simulating tidal flow for verification of the model over a 2-day period, with information not used for adjustment of the model, gives an excellent agreement between observed and computed water levels for five locations in the bay. The standard deviation between observed and computed levels ranges between 0.03 ft and 0.09 ft, with an average of 0.06 ft. The standard deviation between computed average velocities and the average of three observations over the vertical ranges between 0.15 ft/sec and 0.30 ft/sec, with an average of 0.26 ft/sec.

Some of these deviations could be traced to a few-minute advance or retardation of the timing mechanism of the tide-stage recorders used in the observation.

Simulations indicate a very weak counterclockwise circulation in the bay of about 1400 ft^3/sec, which is influenced to a great extent by wind. Observations through two cross sections tend to confirm this conclusion. In the northwestern part of the bay, the influence of wind on circulation is considerable and overshadows circulation generated by the tide.

In view of the excellent agreement between computed and observed tidal data, the tidal model is considered properly verified for the simulation of transient movement of constituents discharged into Jamaica Bay.

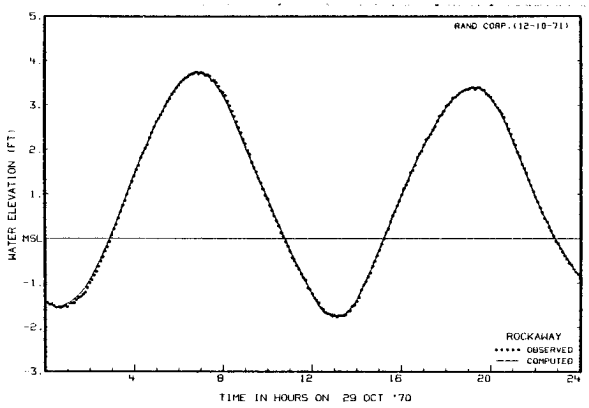
Appendix

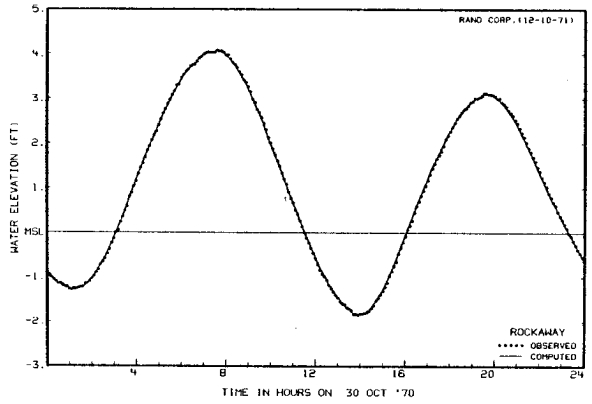
RESULTS OF VERIFICATION SIMULATION

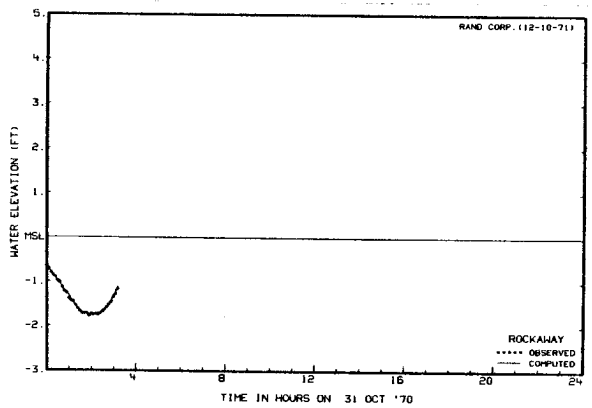
This appendix presents other results as an illustration of part of the output that is generated by the simulation model. Figure A-1 shows computed and observed water levels at five locations. Note that the tide is quite unequal. Figure A-2 shows the differences in water levels between the various stations. An increasing lag of the observed data is evident for the differences involving the Kennedy gauge. As explained in Sec. IV, the main cause for this lag is the advance of the timing mechanism at this station. It will also be noted that seiching is much less pronounced in Fig. A-2 than in Fig. 15, which contains similar data.

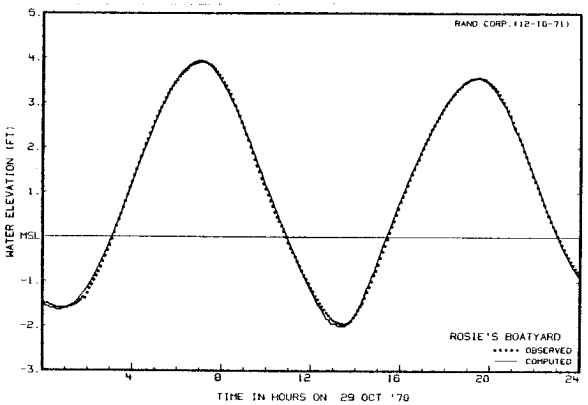
The velocities shown in Fig. A-3 include the results obtained from Stations 1 and 3. The variation from one tidal cycle to another is considerable.

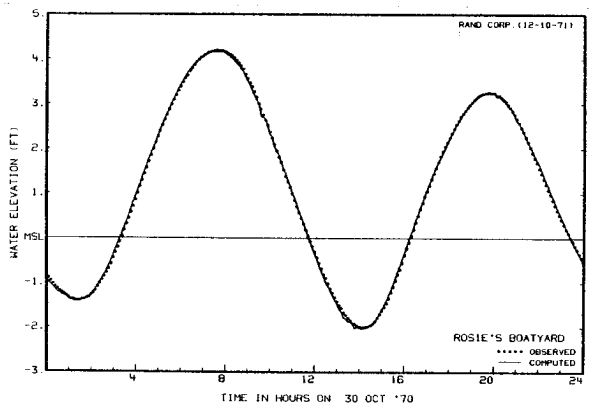
The transports and discharges through the cross section were also computed and included in Figs. 21 and 22 (the third and fourth day), together with the tidal data.

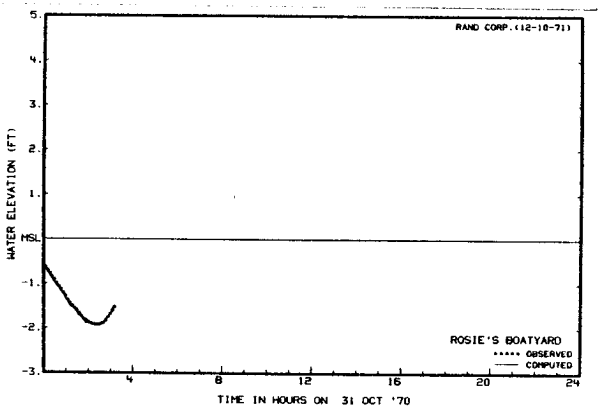

RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
ROCKAWAY
***** OBSERVED
COMPUTED
TIME IN HOURS ON 29 OCT '70

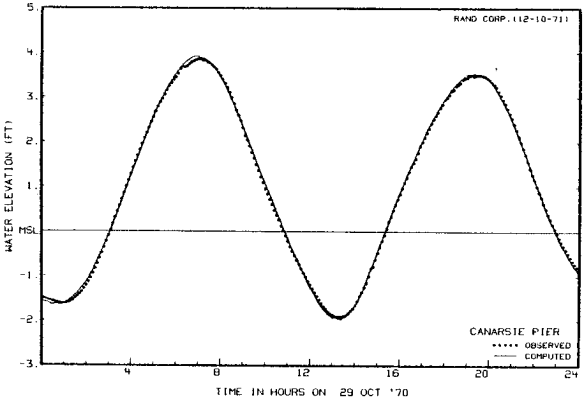

RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
ROCKAWAY
***** OBSERVED
COMPUTED
TIME IN HOURS ON 30 OCT '70

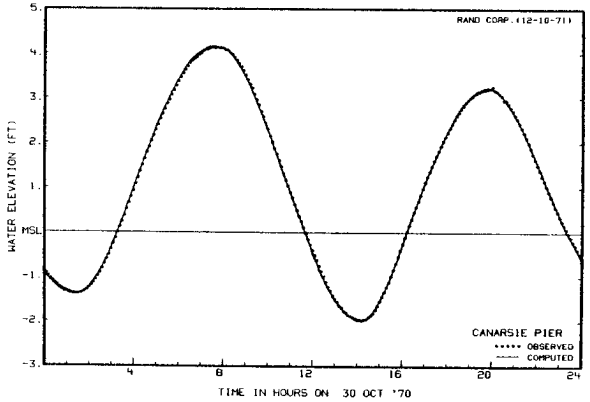

RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
ROCKAWAY
***** OBSERVED
COMPUTED
TIME IN HOURS ON 31 OCT '70

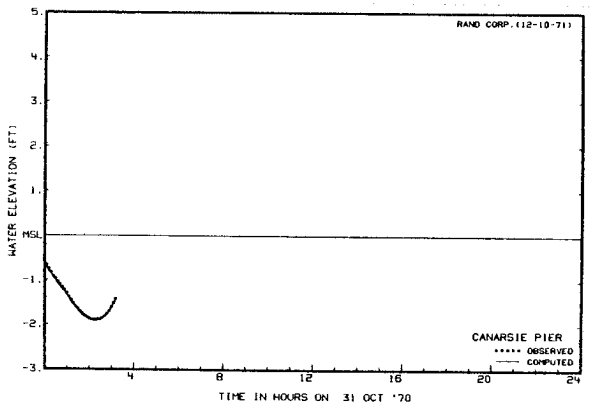

RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
ROSIE'S BOATYARD
***** OBSERVED
COMPUTED
TIME IN HOURS ON 29 OCT '70


RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
ROSIE'S BOATYARD
***** OBSERVED
COMPUTED
TIME IN HOURS ON 30 OCT '70


RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
ROSIE'S BOATYARD
***** OBSERVED
COMPUTED
TIME IN HOURS ON 31 OCT '70


RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
CANARSIE PIER
***** OBSERVED
COMPUTED
TIME IN HOURS ON 29 OCT '70


RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
CANARSIE PIER
***** OBSERVED
COMPUTED
TIME IN HOURS ON 30 OCT '70


RAND CORP.(12-10-71)
WATER ELEVATION (FT)
MSL
CANARSIE PIER
***** OBSERVED
COMPUTED
TIME IN HOURS ON 31 OCT '70

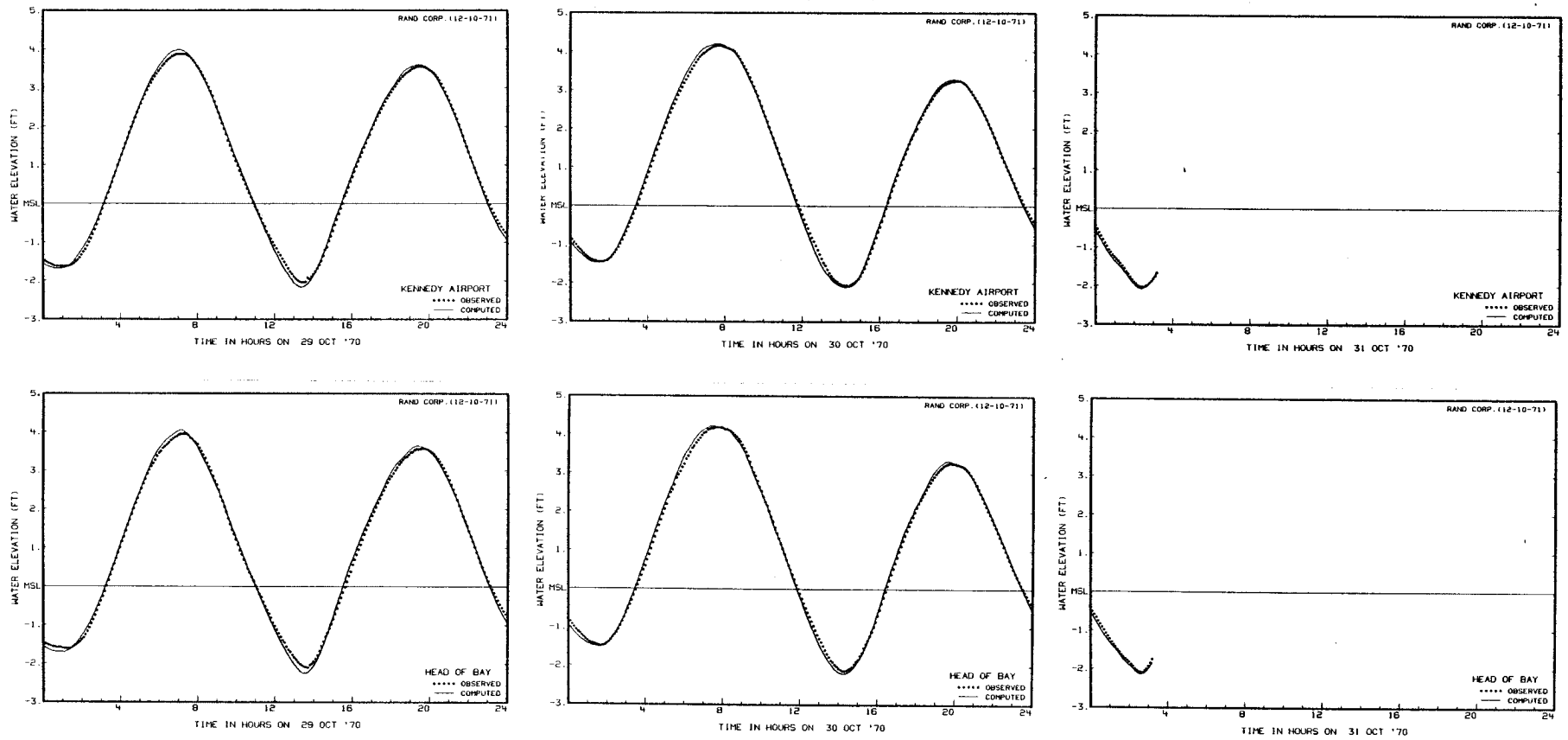
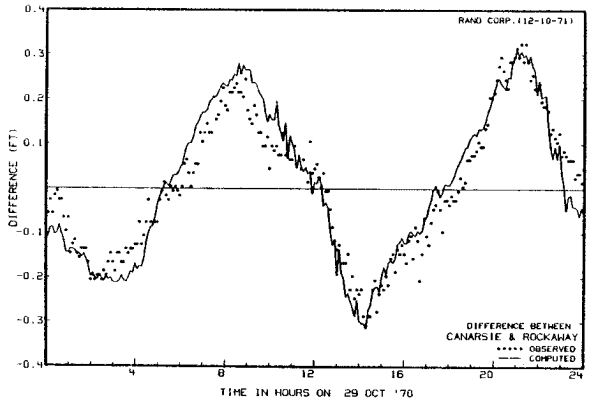
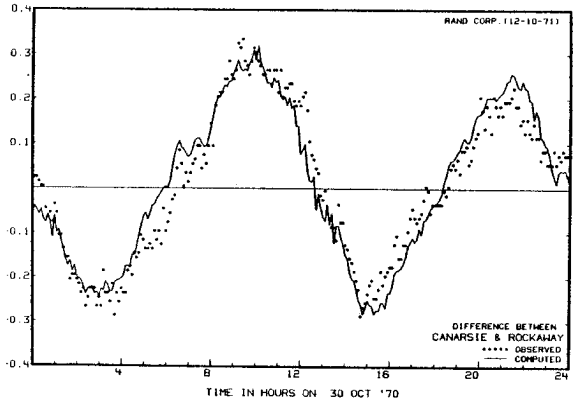
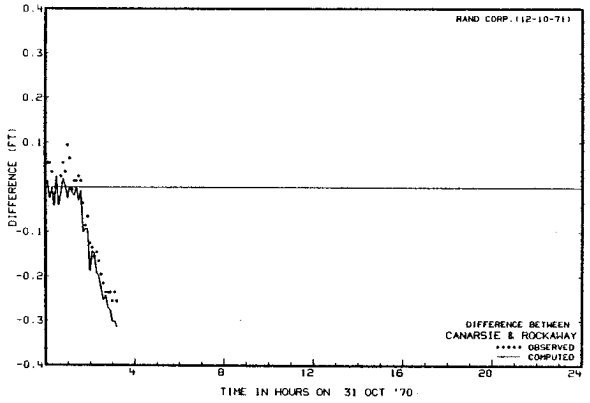
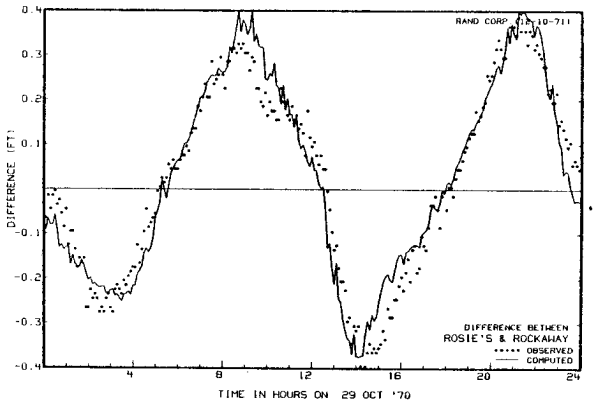


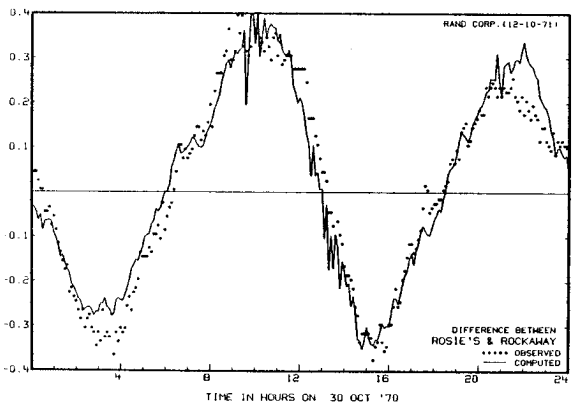
Fig. A-1—Computed and observed water levels for five stations on October 29, 30, and 31, 1970

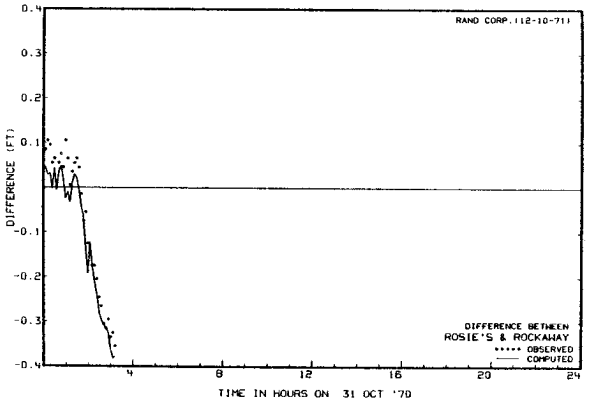

RAND CORP. (12-10-71)
DIFFERENCE (FT)
DIFFERENCE BETWEEN
CANARSIE & ROCKAWAY
OBSERVED
COMPUTED
TIME IN HOURS ON 29 OCT '70

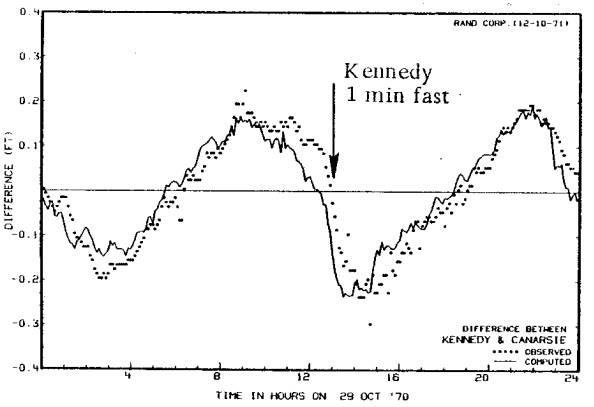

RAND CORP. (12-10-71)
DIFFERENCE BETWEEN
CANARSIE & ROCKAWAY
OBSERVED
COMPUTED
TIME IN HOURS ON 30 OCT '70

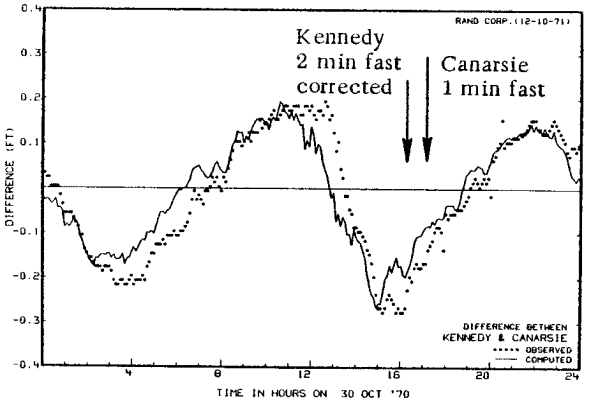

RAND CORP. (12-10-71)
DIFFERENCE (FT)
DIFFERENCE BETWEEN
CANARSIE & ROCKAWAY
OBSERVED
COMPUTED
TIME IN HOURS ON 31 OCT '70

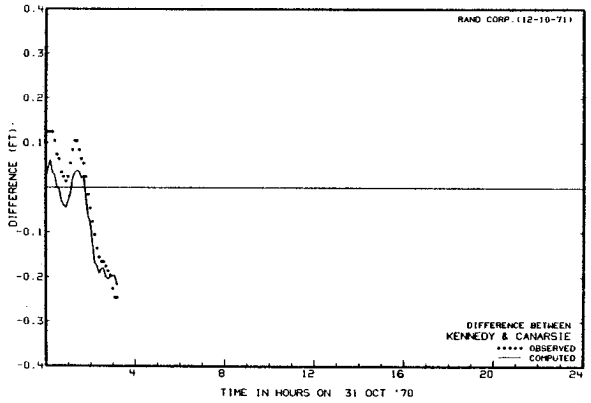

RAND CORP. (12-10-71)
DIFFERENCE (FT)
DIFFERENCE BETWEEN
ROSIE'S & ROCKAWAY
OBSERVED
COMPUTED
TIME IN HOURS ON 29 OCT '70


RAND CORP. (12-10-71)
DIFFERENCE BETWEEN
ROSIE'S & ROCKAWAY
OBSERVED
COMPUTED
TIME IN HOURS ON 30 OCT '70


RAND CORP. (12-10-71)
DIFFERENCE (FT)
DIFFERENCE BETWEEN
ROSIE'S & ROCKAWAY
OBSERVED
COMPUTED
TIME IN HOURS ON 31 OCT '70


RAND CORP. (12-10-71)
Kennedy
1 min fast
DIFFERENCE (FT)
DIFFERENCE BETWEEN
KENNEDY & CANARSIE
OBSERVED
COMPUTED
TIME IN HOURS ON 29 OCT '70


RAND CORP. (12-10-71)
Kennedy
2 min fast
corrected
Canarsie
1 min fast
DIFFERENCE (FT)
DIFFERENCE BETWEEN
KENNEDY & CANARSIE
OBSERVED
COMPUTED
TIME IN HOURS ON 30 OCT '70


RAND CORP. (12-10-71)
DIFFERENCE (FT)
DIFFERENCE BETWEEN
KENNEDY & CANARSIE
OBSERVED
COMPUTED
TIME IN HOURS ON 31 OCT '70

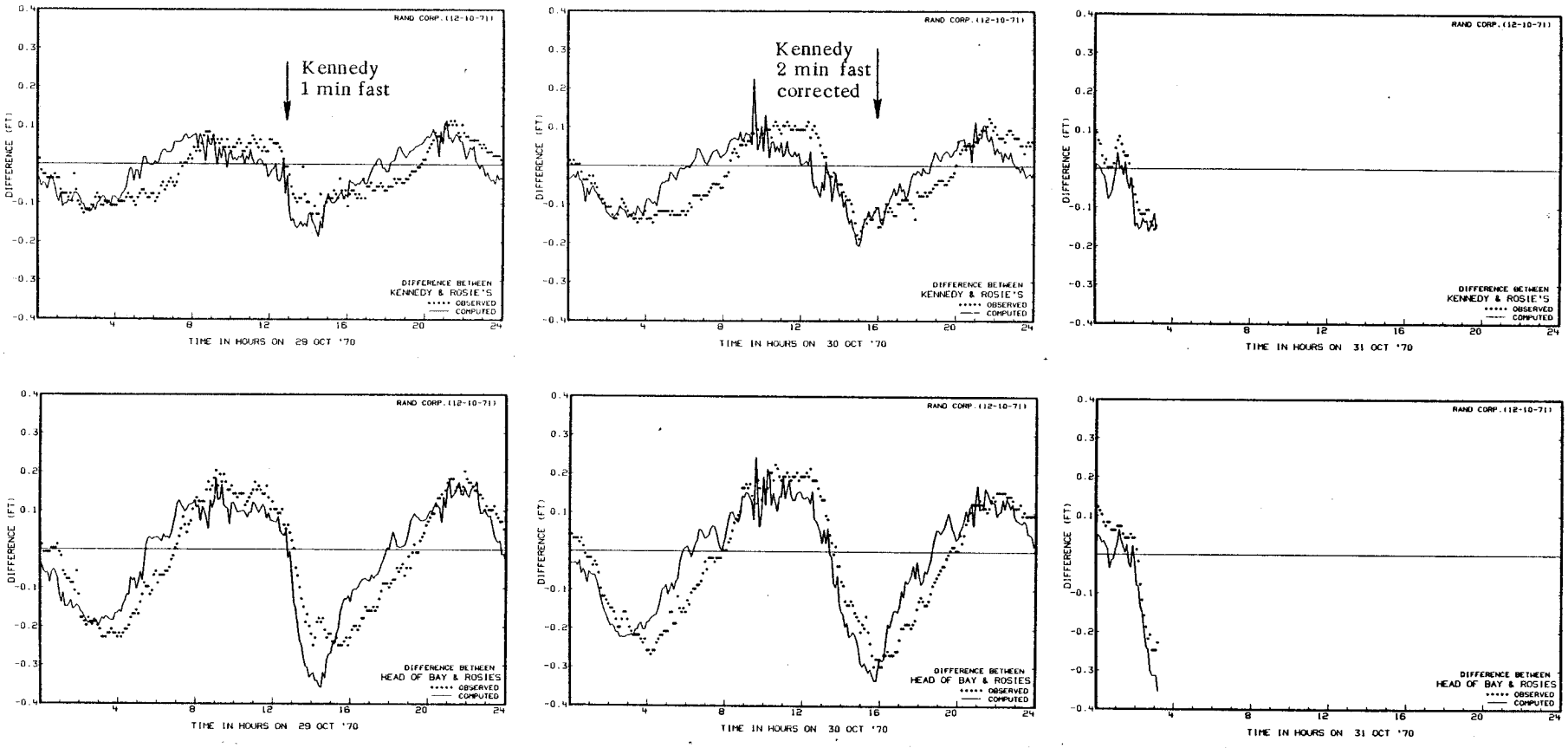
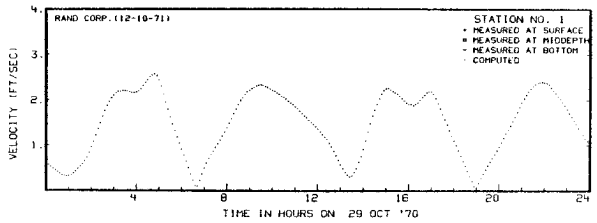
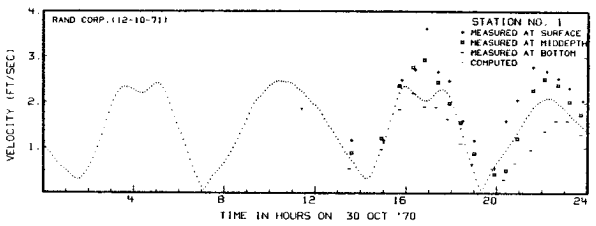
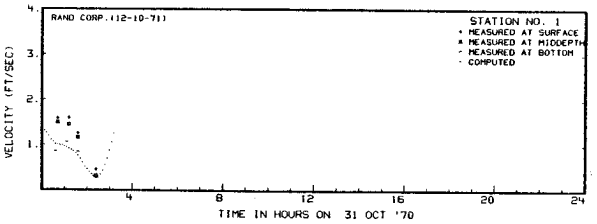
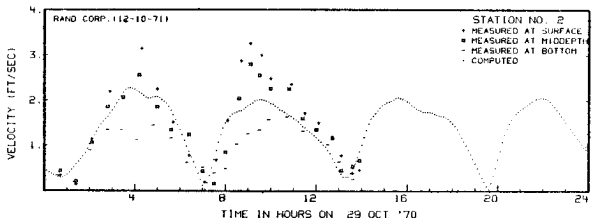


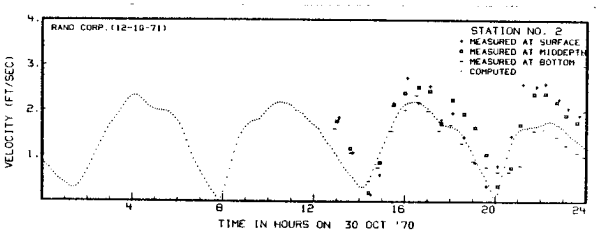
Fig. A.2—Differences in water level between two pairs of stations on October 29, 30, and 31, 1970

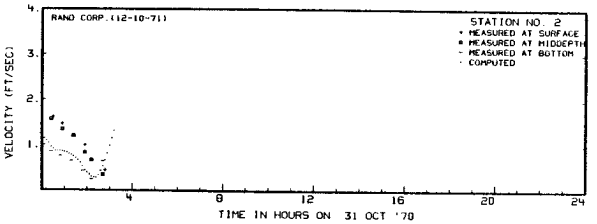

RAND CORP.(12-10-71)
STATION NO. 1
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 29 OCT '70

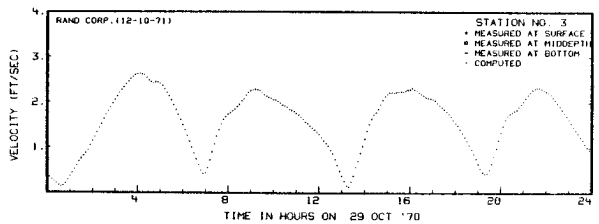

RAND CORP.(12-10-71)
STATION NO. 1
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 30 OCT '70

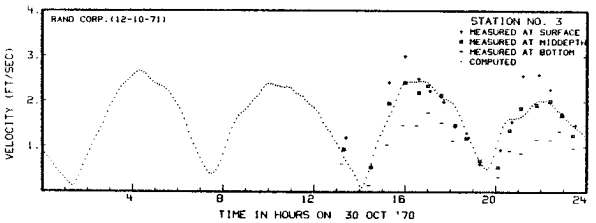

RAND CORP.(12-10-71)
STATION NO. 1
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 31 OCT '70

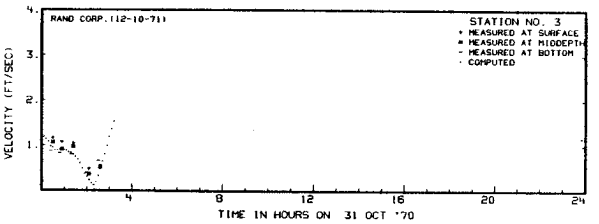

RAND CORP.(12-10-71)
STATION NO. 2
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 29 OCT '70

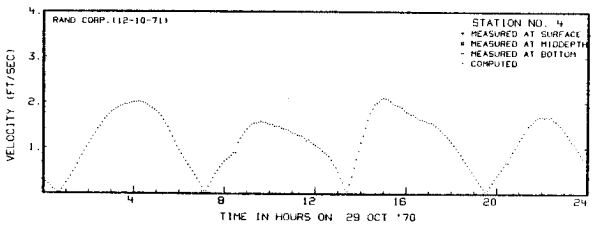

RAND CORP.(12-10-71)
STATION NO. 2
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 30 OCT '70

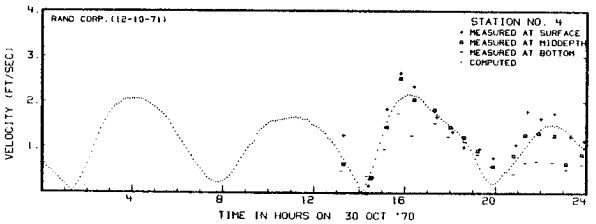

RAND CORP.(12-10-71)
STATION NO. 2
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 31 OCT '70

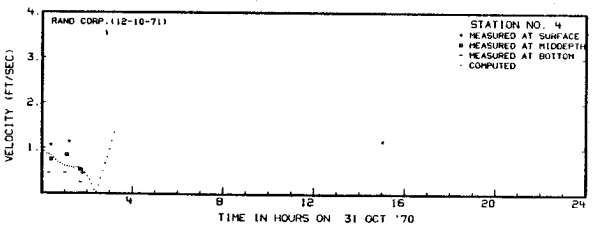

RAND CORP.(12-10-71)
STATION NO. 3
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 29 OCT '70


RAND CORP.(12-10-71)
STATION NO. 3
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 30 OCT '70


RAND CORP.(12-10-71)
STATION NO. 3
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 31 OCT '70


RAND CORP.(12-10-71)
STATION NO. 4
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 29 OCT '70


RAND CORP.(12-10-71)
STATION NO. 4
* MEASURED AT SURFACE
■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 30 OCT '70


RAND CORP.(12-10-71)
STATION NO. 4
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■ MEASURED AT MIDDEPTH
- MEASURED AT BOTTOM
· COMPUTED
VELOCITY (FT/SEC)
TIME IN HOURS ON 31 OCT '70

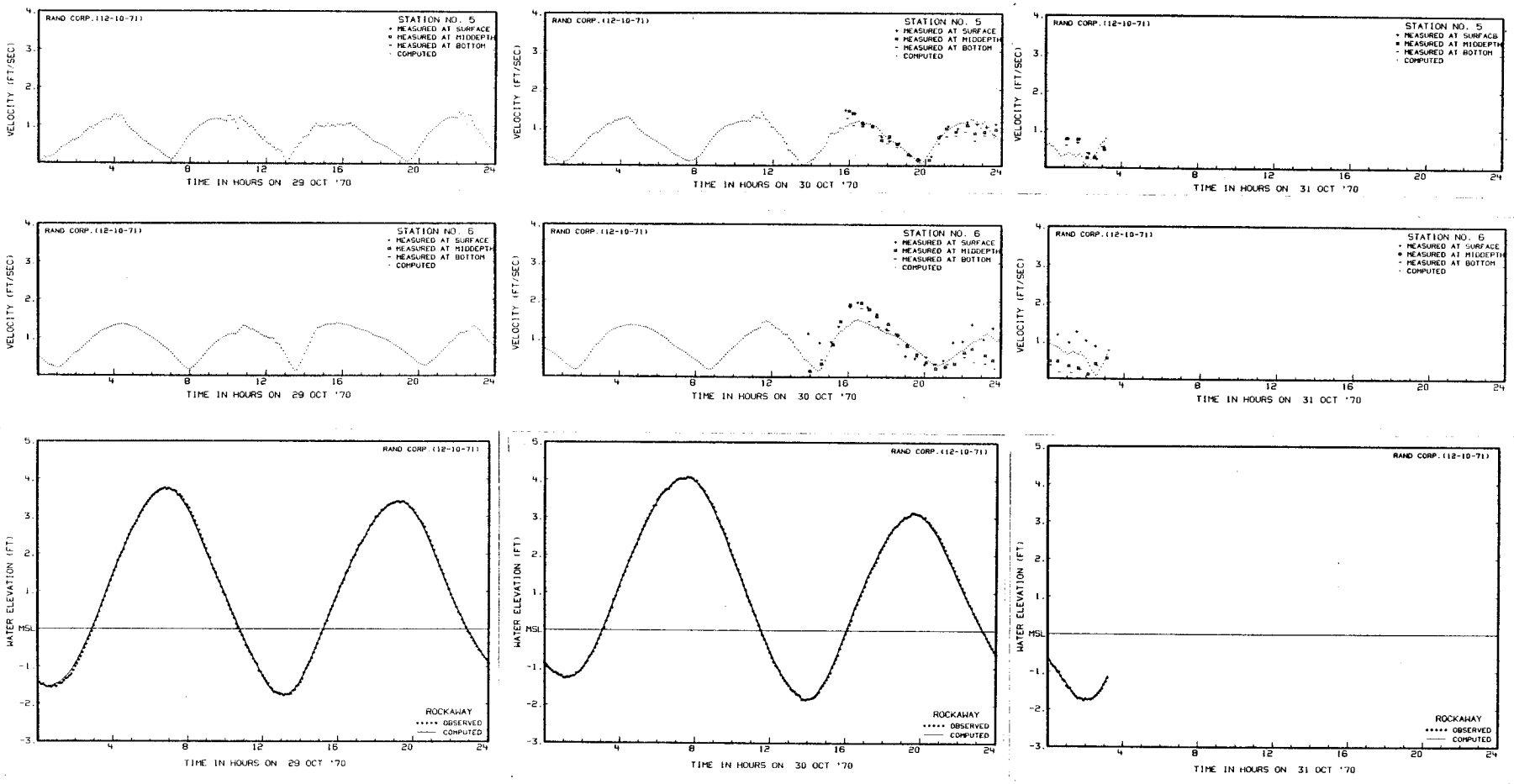

Fig. A.2—Computed and observed velocities for six stations in Jamaica Bay

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2. Kallio, N. A., *Effect of Vertical Motion on Current Meters,* Geological Survey, Water-Supply Paper 1869-B, U.S. Government Printing Office, Washington, D.C., 1966.
3. Leendertse, J. J., and E. C. Gritton, *A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol. II, Computation Procedures,* The Rand Corporation, R-708-NYC, July 1971.
4. Corps of Engineers Committee on Tidal Hydraulics, *Special Analytic Study of Methods for Estuarine Water Resources Planning,* Technical Bulletin No. 15, March 1969.
5. Panuzio, Frank L., *Jamaica Bay Hurricane Barrier,* Proceedings of the Twelfth Coastal-Engineering Conference, Vol. III, Am. Soc. of Civil Engineers, New York, 1970.