September 1991

The Impact of CSOs on Boston Harbor: A New Look Based on 1990 Data

Massachusetts Water
Resources Authority

Environmental Quality Department
Technical Report No. 91-9

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Environmental Quality Department Technical Report Series No. 91-9

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$$c(t) = \frac{M_0}{V} e^{-t/\tau} e^{-\kappa t} \tag{C-2}$$

The flux of mass between channel and harbor is given by

$$F(t) = \frac{cV}{\tau} = \frac{M_0}{\tau} e^{-t/\tau} e^{-\kappa t} \tag{C-3}$$

and the time-integrated flux is given by

$$I = \int_0^\infty F(t)dt = \frac{M_0}{\kappa \tau + 1} \tag{C-4}$$

If we designate the measured residence time as τ_m and the simulated time as τ_s, then the ratio R of simulated to measured time-integrated flux is

$$R = \frac{I_s}{I_m} = \frac{\kappa \tau_m + 1}{\kappa \tau_s + 1} \tag{C-5}$$

For $\kappa = 2\ d^{-1}$ (fecal coliform as used in the model), $\tau_m = 2$ days and $\tau_s = 0.7$ days, then $R \simeq 2$. That is, the simulations overestimate the fecal coliform flux to the harbor by a factor of two.

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Appendix C. Residence Time Calculations for Fort Point Channel

The following calculations provide a way to evaluate simulated concentrations in Fort Point Channel by comparing measured and simulated residence times. MIT/UMassB have performed three tracer studies in Fort Point Channel (Nov./Dec. 1989, May 1990, July 1991). Each involved a slug release of fluorescent tracer at the BOS070 culvert during ebb tide followed by monitoring within the channel for approximately one week. The average residence time from the three surveys was approximately two days, based on the decrease over time of integrated dye concentration.

This residence time can be compared with the residence time inferred from model simulations. The residence time for a conservative substance discharged at the head of a rectangular channel of length L with constant tidal dispersion coefficient D is

$$\tau = L^2/2D \qquad \text{(C-1)}$$

Eq. (C-1) can be derived qualitatively by dimensional analysis or formally by considering a continuous discharge, assuming a boundary condition of $c = 0$ at the mouth and evaluating τ as the spatially integrated concentration divided by the mass injection rate.

For $\tau = 2$ days and $L = 1650$ m (see Table 1), Eq. (C-1) yields $D \simeq 8$ m^2/s which is close to the modeled value of 10 m^2/s. However, the simulated $L \simeq 1100$ m. Combined with the model value of $D = 10$ m^2/s, Eq. (C-1) yields $\tau \simeq 0.7$ d or almost a factor of three lower than measured. As shown below, this faster-than-actual flushing rate results in an overestimate of mass transport between channel and harbor.

Consider that the channel is well-mixed with a volume of V and residence time τ. For an instantaneous release of contaminant with mass M_0 and decay rate κ, concentration will decline with time according to

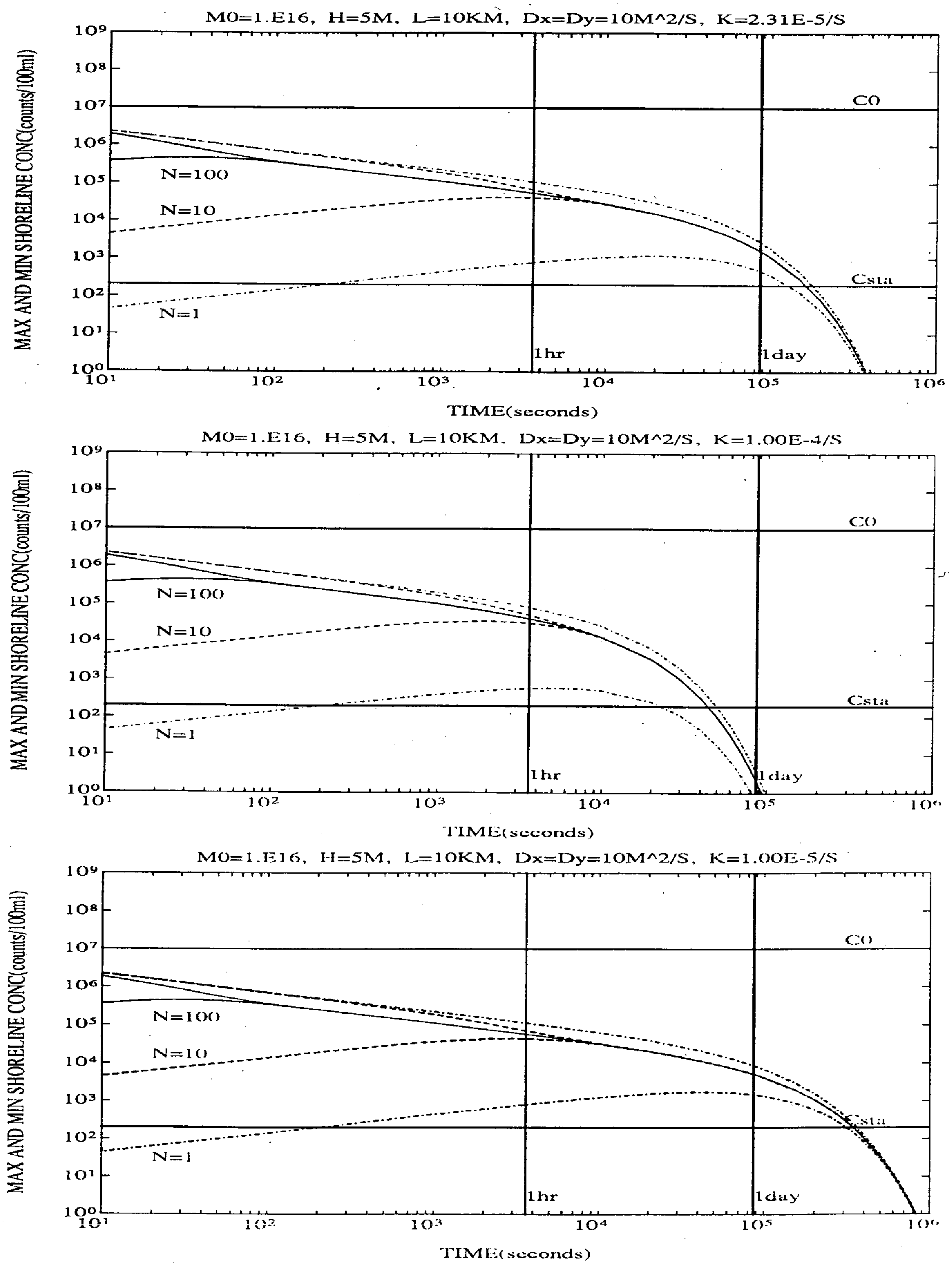

Figure B-2. Maximum and minimum shoreline concentration as a function of time for different levels of aggregation (N = 1, 10, 100 sources)

BACKGROUND

As part of the Combined Sewer Overflow Facilities Plan (CH_2M-Hill Team, 1990) model calculations were made to predict the impact of CSO events on harbor water quality after various levels of control including: 1) existing conditions (i.e., pre-1990), 2) proposed future no action (i.e., improvement to treatment plant headworks, which would increase plant capacity and decrease CSO flows, but no direct CSO control), and 3) various alternatives involving additional CSO storage. Although a range of pollutants was considered, attention was focused on fecal coliform because of its regulatory importance regarding swimming and shellfish harvesting. CSO loadings were computed by the SWMM model (CDM, 1990) using historical data for 1967–72 corresponding to storms with different recurrence intervals: 3 month, 6 month, 1 year, 3 year, and 5 year. Receiving water predictions were made by the two-dimensional transport model ELA (Baptista et al., 1984), driven by the circulation model TEA (Westerink et al., 1985) using tidal and freshwater forcing. For CSOs discharged to the Charles or Mystic Rivers, a modified version of QUAL2E (U.S. EPA 1987) was used to compute receiving water quality and hence loading to Boston Harbor. Model calibration (choice of a horizontal dispersion coefficient of $D = 10\ m^2/s$ and first order coliform decay rate $\kappa = 2\ day^{-1}$) was based on measurements collected following a storm in July 1988 (CDM, 1989b).

The current work is motivated by several factors.

First, since the issuance of the facilities plan, several CSO monitoring activities have been initiated. As discussed below, these tend to indicate that CSO loading may be significantly lower than predicted. If so, this would have an impact on the desired size and perhaps type of CSO control.

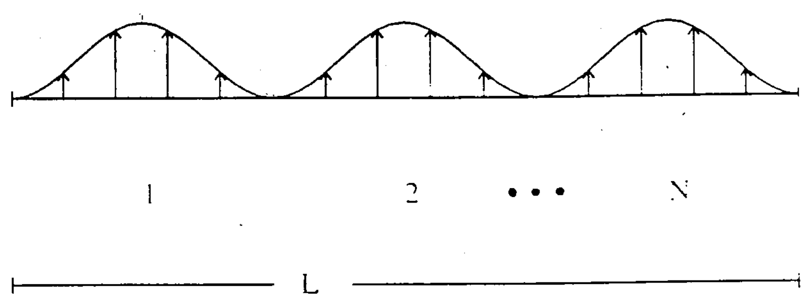

Figure B-1. Definition sketch depicting initial shoreline concentrations

Second, there continues to be interest in the question of the relative impact of particular CSOs on particular receptors; i.e., what is the impact of source i on beach j? This question is of concern if a decision is made to not control all CSO discharges equally.

Finally, compared with the scale of Massachusetts Bay or even Boston Harbor, the CSOs appear as "small" sources discharging to relatively small channels and coves. This disparity of scales presents a challenge for all numerical models and it was felt to be useful to test the adequacy of the source representation in the original calculation. This is particularly useful in light of field measurements currently being collected by MIT/UMassB in Fort Point Channel.

Based on the above considerations, it was decided to re-run the water quality simulations for a small subset of the original scenarios. Depending on the sensitivity, these could be viewed as a first step in a subsequent evaluation of CSO control alternatives.

LOADINGS

Flow Rates

Figure 1 summarizes 1990 volume estimates (column 3) compared with previous model predictions for existing conditions (column 1) and future no-action conditions (column 2). Data are grouped by receiving water—a) outer harbor, b) inner harbor, and c) Charles River—and represent annual volumes. The year 1990 experienced average rainfall (46.5 inches at Logan Airport vs. an annual average of 43.8, BWSC, 1991).

For the outer harbor, the estimates reflect calibrated model predictions made by Camp Dresser and McKee (CDM) using 1990 rainfall data and a modification of the SWMM model. Calibration was based on flow measurements made by Rizzo Associates under contract to Boston Water and Sewer Commission (BWSC). These calculations indicate

Finally, the graphs, themselves, can be used as a very approximate model either to predict actual concentrations, or at least to examine sensitivity. Because of the extreme idealizations being made, one might hesitate to suggest such an analytical solution as a "model." However, despite its approximate nature, it may introduce less uncertainty than the model parameters themselves. For example, there is tremendous uncertainty regarding the value of the bacterial decay rate κ, with literature values ranging from an hour^{-1} or faster to a day^{-1} or slower. An order of magnitude difference in κ translates into almost an order of magnitude difference in the time required for concentration to be reduced below a certain threshold. This can be seen by contrasting the middle and bottom figures where values of $\kappa = 10^{-4}s^{-1}$ (9 day^{-1}) and $10^{-5}s^{-1}$ (0.9 day^{-1}) are used and a particular threshold (swimming standard of 200 counts/100 mℓ) is indicated. For the higher value of κ, the standard is met within less than a day, while with the lower value, nearly a week is required.

On the other hand, assume that the model uncertainty (schematization, representation of transport, etc.) is an order of magnitude in concentration. At a concentration of order 200 counts/mℓ, this represents an error of "only" about 50% in the simulated duration of an exceedance, e.g., $1\frac{1}{2}$ days rather than 1 day or $4\frac{1}{2}$ days rather than one week.

that during 1990 the estimated CSO volume was substantially less than "existing" conditions and indeed about 67% lower than the predicted flow during future no-action conditions. Furthermore, the lower flow was estimated for all three of the outer harbor sub-regions: the Neponset River/Estuary, Quincy Bay, and Dorchester Bay. The reasons for the lower-than-expected flows are thought to include improved operation in the North system leading to greater capacity at the Deer Island Treatment Plant (and hence reduced CSO volume), greater than anticipated in-system storage, and more realistic treatment of tides by the sewer model.

For the inner harbor, the volumes include similar model calculation for BWSC CSOs plus measurements tallied for the Charles River Estuary Facility at Prison Point (MWR203) for the 12-month period October 1989–September 1990 (the most recent data available as of April 1991). Again the flows are substantially less than "existing" predictions and nearly 50% less than the predicted no-action conditions. However, note that not all of the inner harbor CSOs have been measured. The reasons for the lower-than-expected flows are thought to be similar to those for the outer harbor.

For the Charles River, data include measurements for the Cottage Farm Facility (MWR201) for the 12-month period October 1989–September 1990 and measurements reported by the City of Cambridge for the year 1990. While the Cambridge CSOs have apparently discharged less volume than expected, the Cottage Farm Facility has discharged significantly more, with the combined volume being approximately three times greater than the predicted future no-action volume. We note that the Cottage Farm facility does chlorinate its discharge and that many of the big CSOs that discharge to the Charles River (e.g., the Fens Gatehouse) have not been included so "the jury is still out" on the Charles River.

$10^{-5}s^{-1}$ ($2\ d^{-1}$) (same as used in model simulations). The middle figure is the same as the top except $\kappa = 10^{-4}s^{-1}$, and the bottom figure is the same as the top except $\kappa = 10^{-5}s^{-1}$.

Several comments can be made regarding the graphs. First, as $t \rightarrow 0$, $c \rightarrow \infty$. Physically the maximum concentrations should be the discharge concentration c_0 which would equal the loading *rate* (bacteria/time) divided by the discharge flow rate (volume/time). For example, the top horizontal line at $10^7/100\ m\ell$, shown in Figure B-2, corresponds approximately to the loading of $M_0 = 10^{16}$ counts distributed over 12 hours with a flow rate of $2\ m^3/s$.

Second, N represents the number of CSOs. Physically N is approximately 100 for Boston Harbor. However, because some CSOs are bigger than others, the actual distribution could be represented by the superposition (in the sense of a Fourier series) of several sine waves, each with different values of N and M_0. Or, values of $N < 100$ can represent the aggregation of sources. This is useful, for example, in deciding how to represent sources in a numerical model or in interpreting field measurements. In a numerical model it would be cumbersome to represent all 100 sources. These figures show, for given parameter values, how long it takes for adjacent sources to mix together (maximum and minimum concentration to converge). If the time scale of interest is longer than this, there is no reason to represent this number of sources. For example, with the given parameters we see that with 10 sources, mixing occurs over a time scale of order 10^4 seconds or about 3 hours. A similar interpolation pertains to the analysis of field measurements. If data are collected over a finite period of time (e.g., 1 hour as indicated in Figure B-2), and if sources are spaced closer than a critical separation (i.e., N exceeds a critical value), then one can't distinguish which source is contributing to the measured concentrations.

Concentrations

Figure 2 summarizes concentrations of copper, ammonia, total suspended solids, and fecal coliform bacteria reported at five CSOs in comparison with corresponding SWMM model predictions made as part of the facilities plan. Most of the data are from grab samples collected at CSO regulators during overflow events by Rizzo Assoc. and reported in quarterly reports to BWSC (e.g., BWSC, 1991). Several of the fecal coliform measurements reflect MWRA analyses of samples collected at the BOS070 culvert during MIT/UMassB field surveys. In general concentrations of all constituents are comparable with or lower than corresponding model predictions, although it is emphasized that all of the measurements represent grab samples and that substantial variation can be expected throughout a storm (Wallace et al., 1991).

Pollutant loadings are the integral over time of flow rate times concentration. Unfortunately, sufficient data are rarely available to make this integration so loadings are approximated as a single concentration times a volume. Using this latter approach, and the data in Figures 1 and 2, we can estimate, *very approximately*, how the estimated 1990 pollutant loads compare with previously predicted future no-action conditions. Focusing on fecal coliform, and eliminating all measurements reported as "concentration greater than x" leaves four data points for which the arithmetic average ratio of measured to predicted concentration was 0.33. Applying this adjustment of 0.33 to all three receiving waters, we estimate that the 1990 loading to the outer harbor was approximately $\frac{1}{3} \times \frac{1}{3} \simeq 0.11$ times the future no-action predictions, the loading to the inner harbor was approximately $\frac{1}{2} \times \frac{1}{3} \simeq 0.17$ times the future no-action predictions, and the loading to the Charles River was approximately $3 \times \frac{1}{3} \simeq$ the same as the future no-action predictions. Because we have no data for the Mystic River, we will also assume that the 1990 loading was the same as the predicted future no-action loading.

Appendix B. Analytical Model for Bacteria Concentration from Shoreline Discharges

Figure B-1 and the following discussion describe a simple model that may be useful to derive insights about the extent of bacterial contamination from CSO events in Boston Harbor and, in particular, to understand the effects of combining individual sources into a smaller number of aggregate sources. Consider an instantaneous discharge at time $t = 0$ of M_0 bacteria along a straight length of shore L. The spatial distribution is sinusoidal representing the concentration after initial mixing from N evenly spaced sources. Water depth H is constant and there is no net current. All mixing is parameterized by horizontal dispersion coefficients D_x and D_y and the bacteria die-off/settle at a rate κ. The x-coordinate is alongshore and the y-coordinate is positive offshore.

For $t > 0$, concentrations (bacteria count/volume) are given by

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} - \kappa c \qquad \text{(B-1)}$$

with $c = 0$ at $y = \infty$, $\frac{\partial c}{\partial y} = 0$ at $y = 0$, and sinusoidal variation in x. The solution for shoreline concentrations ($y = 0$) is

$$c = \frac{2 M_0 e^{-\kappa t}}{H L \sqrt{4 D_y \pi t}} \left[1 + e^{-D_x k^2 t} \sin kx \right] \qquad \text{(B-2)}$$

where $k = 2\pi N/L$.

The graphs in Figure B-2 present maximum shoreline concentrations ($\sin kx = 1$; i.e., at a source) and minimum shoreline concentrations ($\sin kx = -1$; midway between sources) as a function of time for $M_0 = 10^{16}$, $L = 10^4$m, $H = 5$ m, $D_x = D_y = 10$ m²/s, and $N = 1$, 10, and 100. Units of concentration are counts per 100 mℓ. The top figure is for $\kappa = 2.3 \times$

We emphasize that each of these estimates is very crude, and feel that, because of the sparse data, the estimates for the two rivers are the least accurate. We also note that these factors correspond to annual average flows and, by extension, loading. At this point, we don't know how the loadings from an individual storm would be affected. However, because previous facilities plan calculations were based on discrete storm events, we will assume that factors apply to all storms equally. In particular we will focus on the 1-year and 3-month storms for which previous time-varying loading estimates (pollutographs) have been provided by CDM.

Before proceeding with model predictions, it is worth noting that receiving water bacteria measurements analyzed by the MWRA for 1990 appear to be substantially less than those measured in 1989, and show spatial trends consistent with Figure 1. Figure 3 summarizes MWRA monitoring results for 1990 (A. Rex, personal communication). Plotted values are geometric means and confidence intervals about the geometric mean for transects in a) the outer harbor, b) the inner harbor, and c) the Charles River. In general, geometric mean concentrations are least in the outer harbor and greatest in the Charles River. It should be noted that these figures reflect the actual times at which measurements were taken. Thus it is possible that some of the trend is due to weather—e.g., drier weather during times at which outer harbor samples were collected and wetter weather during the Charles River sampling.

MODEL PREDICTIONS

Figure 4 shows the finite element grid and Figure 5 shows the location of the 14 aggregate sources used in the harbor water quality model simulations. The sources include 13 CSOs, plus the Quincy storm drains. The location of each dot indicates the source location in the model (this will be discussed further) and the diameter of the dot reflects the relative loading. Figure 6 shows a time series of the loadings simulated for each source

Table A-1

Calculated Concentrations as a Function of Distance from Source and Assumed Dispersion Coefficient

	D = 1 km^2/d		D = 0.5 km^2/d	
r (km)	t_{max} (hr)	c_{max} (bact/100 ml)	t_{max} (hr)	c_{max} (bact/100 ml)
0.5	1.3	52000	2.5	47000
1.0	4.4	9700	7.4	6900
2.0	12	1000	19	410
3.0	20	150	30	36
5.0	37	10	54	0.4

under the one-year future no-action conditions (CDM, personal communication). The time step in Figure 6 is one-twelfth of an M2 tidal period or about 1.04 hours.

One-Year Storm

Simulations under future no action. Figure 7 shows computed depth-average fecal coliform concentrations on four days following a one-year storm using loadings from Figure 6 (i.e., future no action). The chosen contours of 1000, 200, 14, and 1 counts/100 ml are the same as used in the facilities plan and reflect regulatory thresholds for marine waters. These contours are virtually identical to those in Figure ES 3-12 of the CSO facilities plan with slight differences attributed to minor changes in the transport model ELA. Focusing on the 200 counts/100 ml contour (which governs beach closures) we see that substantial areas of the outer harbor (e.g., S. Boston, Dorchester, Neponset River, Quincy) were previously predicted to exceed 200 counts/100 ml one day after the storm. Two days after the storm, the predicted region exceeding 200 counts/100 ml includes most of the inner harbor and the Neponset River.

Figure 8 shows corresponding predictions of water column concentration as a function of time for six locations: Fort Point Channel (mouth), Reserved Channel (mouth), Pleasure Bay, Carson Beach, Tenean Beach, and Wollaston Beach. The time step on the horizontal axis is one twelfth of a tidal cycle or 1.04 hours. Note the strong tidal variation in the predicted concentration versus time.

The six parts of Figure 9 show the relative impact of the 14 aggregate sources, as a function of time step, on the six receiving water areas identified in Figure 8. Calculations were made by performing 14 separate runs—each with a single source. In each figure, the source is identified by name only if it contributes more than 5% of the peak concentration in each plot. We see that, in general, predicted water quality degradation is caused mainly

Appendix A. Idealized Model of the Impact of Source i on Receptor j

The fact that highest receiving water concentrations are associated with the closest pollution sources should not be surprising in view of the bacteria die-off rate. The following idealized analytical calculations support this conclusion.

Consider an instantaneous source at location i of magnitude M_i. Consider the receiving water concentration c_{ij} at location j, a distance r_{ij} from the source. If we assume a constant depth H, horizontal dispersion coefficient D, and die-off rate κ, then c_{ij} is given by

$$c_{ij} = \frac{2M_i}{4\pi DtH} \exp\left[\frac{-r_{ij}^2}{4Dt}\right] \exp(-\kappa t) \tag{A-1}$$

Assuming initial concentrations are zero (i.e., neglecting any background concentration), c_{ij} will initially increase until a time t_{max}, given by

$$t_{max} = \frac{1}{2\kappa}\left[\sqrt{1 + \frac{r_{ij}^2\kappa}{D}} - 1\right] \tag{A-2}$$

and then decrease again toward zero. Table A-1 summarizes maximum concentration (units of bacteria/100 ml) as a function of the distance r between source and sink assuming $M = 3.1 \times 10^{15}$ bacteria, $\kappa = 2$ day^{-1}, H = 5 m, and D = 1 km^2/day (12 m^2/s) and 0.5 km^2/day (6 m^2/s). These values of D bracket the value of D = 10 m^2/s used in the facilities plan simulations.

While highly idealized, these calculations show that for a given separation, concentration peaks after a short time and then begins to decay. Because the time to peak increases with separation distance, peak concentration drops off sharply with distance.

by the closest source(s). Thus water quality in Fort Point Channel is dominated by the Fort Point Channel source; Reserved Channel is dominated by the Reserved Channel, Fort Point Channel, and Airport sources; Pleasure Bay is dominated by the South Boston and Reserved Channel sources; Carson Beach is dominated by the South Boston source; Tenean Beach is dominated by the Neponset River and Dorchester Bay sources; and Wollaston Beach is dominated by the Quincy storm drain source. The fact that the nearest sources cause most of the impact should not be surprising in view of the relatively high coliform die-off rate (in comparison with other non-conservative pollutants). This conclusion is supported by analytical calculations presented in Appendix A.

Figure 10 summarizes the source/receptor data after one, two, three, and four days (parts a, b, c, and d respectively), and also allows comparison of the relative impacts.

Simulation under 1990 conditions. Figures 11–14 show corresponding model simulations using the revised (1990) loadings (future no-action loadings for the one-year storm multiplied by 0.11, 0.17, and 1.00 for the outer harbor, inner harbor, and Charles and Mystic Rivers respectively). As expected, receiving water concentrations in Figure 11 are considerably lower than those in Figure 7. For example, one day after the storm, concentrations exceeded 200 counts/100 ml in only a couple of areas of the outer harbor, and two days after the storm concentrations exceeding 200 counts/100 ml are limited to Fort Point Channel and the mouth of the Charles River. This reduced impact can also be seen in the relative impact plots of Figure 14. In general, the previous conclusion regarding the greatest receiving water impact being associated with the closest CSOs is true for the revised loading calculations as well.

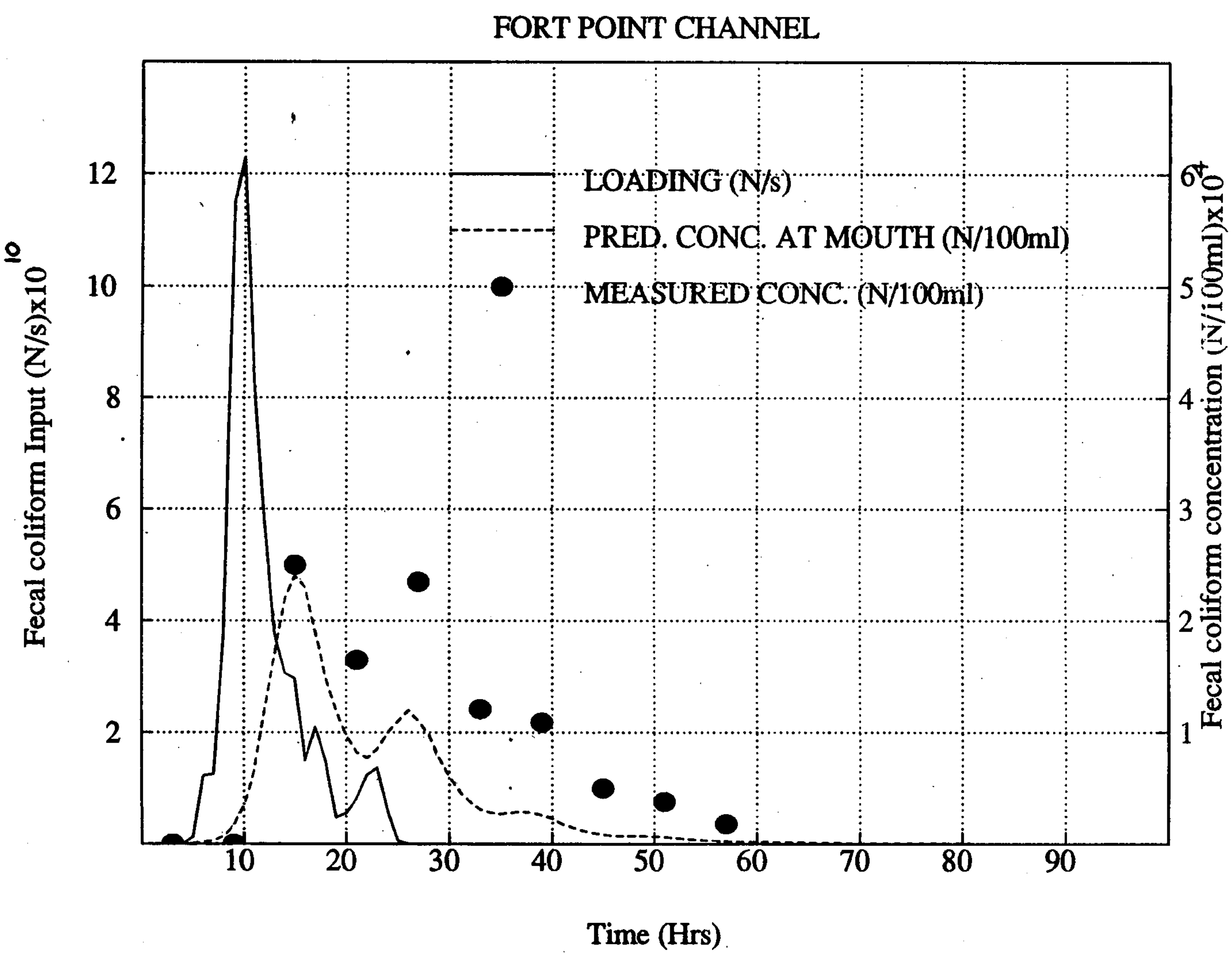

Figure 25. Measured versus modeled fecal coliform concentrations at the mouth of Fort Point Channel based on May 1990 field survey

3-Month Storm

Simulation under future no action. Figure 15 shows a time series of the loadings simulated for each source under the 3-month future no action condition (CDM, personal communication). As with the corresponding Figure 6 (one-year storm), the time step is one-twelfth of an M2 tidal period or about 1.04 hours. Comparisons of Figures 6 and 15 indicate that the duration of the two storms was similar, but that peak loadings for the 3-month storms were generally 25 to 50% of the corresponding peaks for the one-year storm. We note that the total storm volume for the 3-month event was about 45% of the corresponding one-year volume (CDM, 1989a, Table 4).

Figures 16–19 show model simulations for the 3-month storm under future no action conditions. Each figure is analogous to the corresponding Figures 7–11 for the one-year storm under future no action conditions. Because the loadings for the 3-month storm are less than those for the one-year storm, the receiving water impacts are also correspondingly less.

Simulations under 1990 conditions. Figures 20–23 show corresponding model simulations using the revised (1990) loadings (future no action loadings for the 3-month storm multiplied by 0.11, 0.17, and 1.00 for the outer harbor, inner harbor, and Charles and Mystic Rivers respectively.). As expected, receiving water concentrations in Figure 20 are considerably lower than both the 3-month no action simulation (Figure 16) and the one-year 1990 conditions simulation. For example, one day after the storm, concentrations exceeded 200 counts/100 ml in only a few small regions of the outer harbor as well as portions of the inner harbor including Fort Point Channel. On the second day after the storm, no exceedances of 200 counts/100 ml were simulated anywhere. Previous conclusions about the greatest receiving water impact being associated with the closest CSOs are true for these simulations as well.

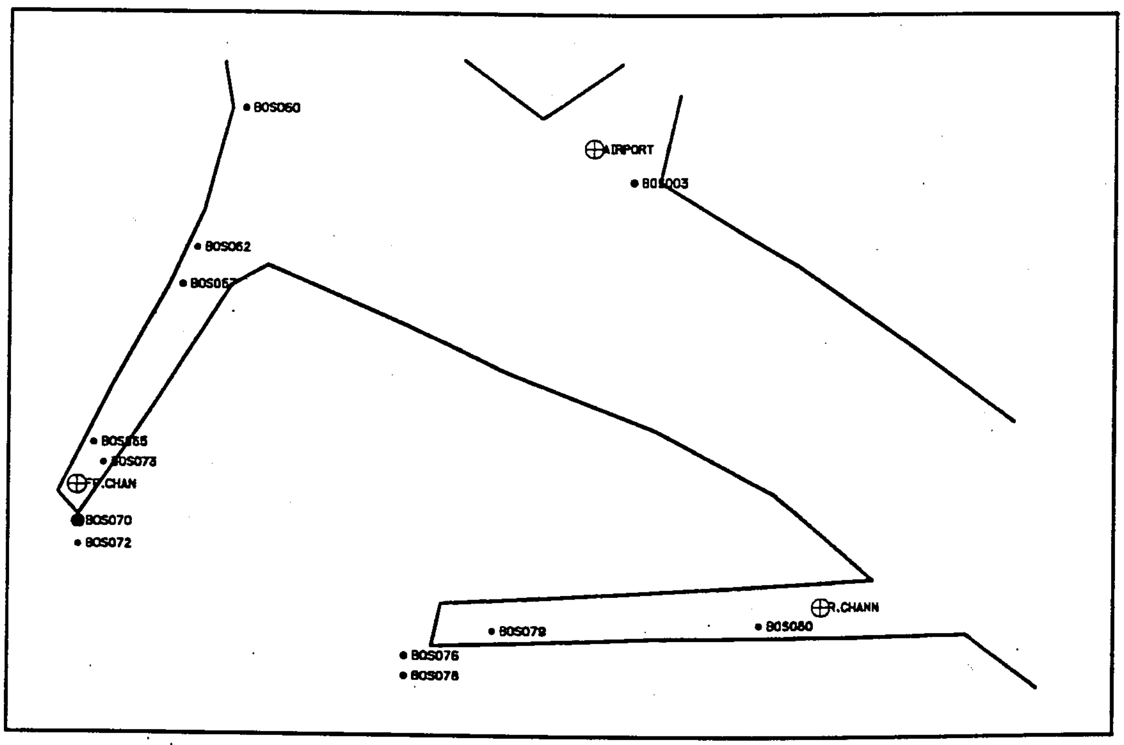

Figure 24. Enlargement of Fort Point Channel and Reserved Channel depicting actual and aggregate sources

Cautionary Note

A major caveat should be mentioned at this point. As predictions of relative impact (associated with the different loading estimates) the calculations described above should be quite reliable because any errors in model assumptions, parameters, etc., are common to both sets of calculations. However, the absolute calculations do reflect uncertainty in model assumptions and parameters. In particular, we note that the model parameters were calibrated to field measurements during July 1988. Predicted loadings for the July 24, 1988, storm were input to the model and model parameters (dispersion coefficient and fecal coliform die-off rate) were adjusted to effect agreement with receiving water bacterial concentration measurements. The validity of the calibrated parameters thus reflects the accuracy of the predicted 1988 loadings. To the extent that some of the improvement we are now seeing between "existing" and 1990 loadings was in effect during July 1988 (for example, lower discharge concentrations) or if the loadings were never as high as assumed under "existing" conditions, then the actual 1988 loadings would have been lower than modeled. As a result, the calibrated die-off rate may have been too high making our current prediction for 1990 too low. Thus we can say with confidence that the model is quite sensitive to loadings, and that the current estimate of loadings is substantially less than previously estimated. However, the receiving water concentrations resulting from these loadings is less certain. It is recommended that if further receiving water calculations are made, perhaps as part of a later stage of CSO study, the model should be re-calibrated based on revised loading calculations. It would appear that the MWRA has collected substantial data since 1988 which would be suitable for this purpose.

NEAR SOURCE REPRESENTATION

As stated earlier, it is difficult in a numerical model to represent small sources in a relatively large receiving water body, especially as regards concentration near each source.

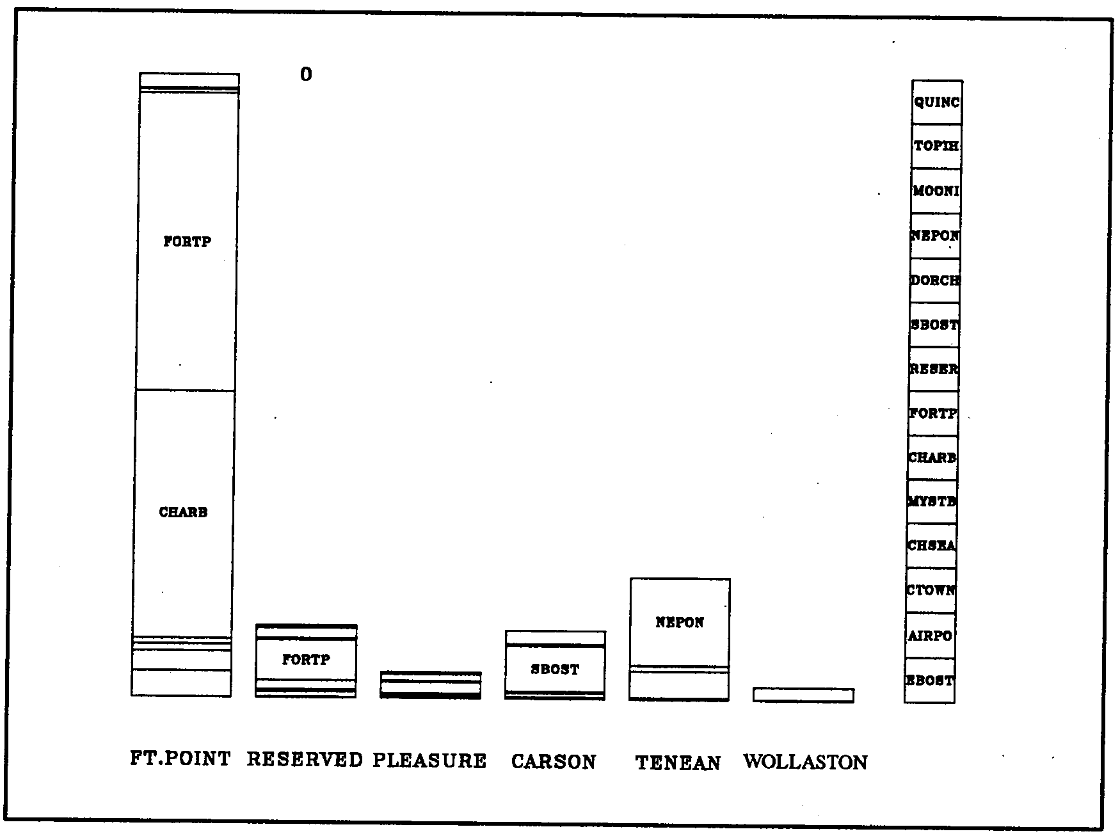

Figure 23d. Four days after storm

Yet the importance of such near source calculations is underscored by conclusions from the previous section that the impact at a given location is dominated mainly by the closest CSOs. In view of this importance, several issues concerning source representation were examined.

Rationale for Source Aggregation

There are 84 permitted CSO discharges (CH_2M-Hill Team, 1990). Although loadings from each are computed by the sewer modeling, it is more convenient to combine these loadings into a smaller number of aggregate sources. The relevant question, then, is how few aggregate sources need to be considered? As part of previous study, we considered this question using a simple analytical model (Appendix B). Conclusions from this analysis, applied to Boston Harbor, suggest that a number of order 10 is sufficient. Thus the chosen number of 14 seems reasonable.

Source Location and Grid Refinement

Figure 5 shows the location of the 14 aggregate sources and Figure 24 shows an enlargement of the Fort Point Channel and Reserved Channel areas, depicting actual and schematized locations. Intuitively, one would expect to see the aggregate source near the center of mass of the contributing individual sources or near the mouth for the case of rivers. With the exception of Reserved Channel, the source locations appear reasonable. We noted previously that although the Reserved Channel source is relatively small, it does affect Pleasure Bay. Hence in future CSO applications it would be appropriate to re-locate the Reserved Channel CSO.

Along similar lines, tidal flow fields (produced by TEA) have been compared with tidal current measurements in Boston Harbor during this and previous model applications. In

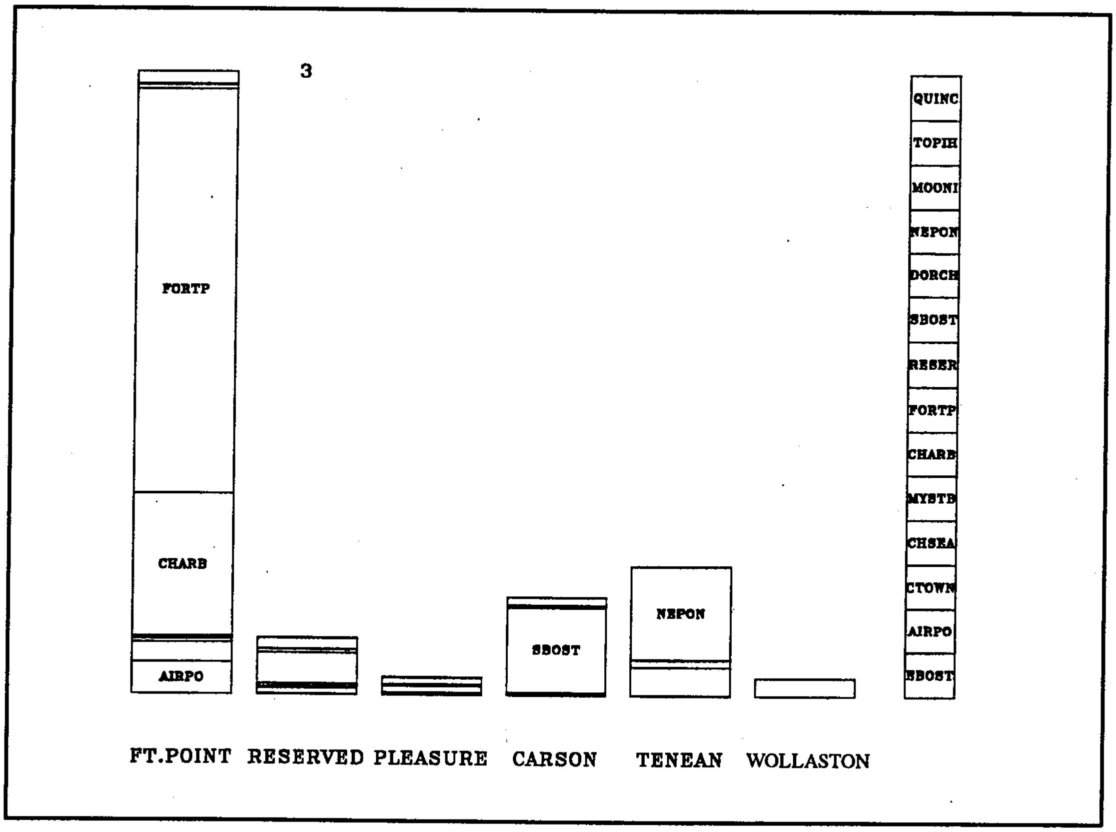

Figure 23c. Three days after storm

general good agreement is obtained in most regions of the harbor. However, it appears that the present grid is too coarse in certain inner harbor locations, such as Fort Point and Reserved Channels, to accurately reproduce observed currents (or currents computed by tidal prism techniques). We estimate that a factor of at least two more nodes would have to be added in each dimension to satisfactorily reproduce currents in the inner harbor channels. This refinement would make the grid resolution (number of nodes across the channel width) in the channels comparable with that in the main section of the inner harbor. (See Figure 4). We would note that most of the transport within the inner harbor is simulated by the model as tidal dispersion rather than advection. Furthermore, the model dispersion coefficients were calibrated using the same grid and flow field used in the model simulation. Hence errors due to coarse discretization should be small. Nonetheless, future simulations should consider greater refinement.

Fort Point Channel deserves further comment, both because of the importance of the source, and the fact that some field measurements are available. Figure 24 shows that, as schematized, Port Point Channel only extends upstream to about Dorchester Ave. (the region between Dorchester Ave. and BOS070 is comparatively narrow). Table 1 compares modeled channel dimensions with those measured from the NOS chart.

The shorter than actual channel length puts the model source too close to the mouth, resulting in an overestimate of fluxes to the inner harbor, and subsequently to the outer harbor. Calculations in Appendix C suggest that the flux of fecal coliform integrated over time may have been overestimated by a factor of about two. On the other hand, the larger than actual channel crossection tends to exaggerate dilution in the model. Figure 25 shows a comparison of modeled versus measured fecal coliform concentration at the mouth of Fort Point Channel. Measurements are based on a fluorescent tracer study conducted by MIT/UMassB during May 1990 and have been adjusted to represent fecal coliform by using the same decay rate (2 d^{-1}) employed in the model. Although measurements were only

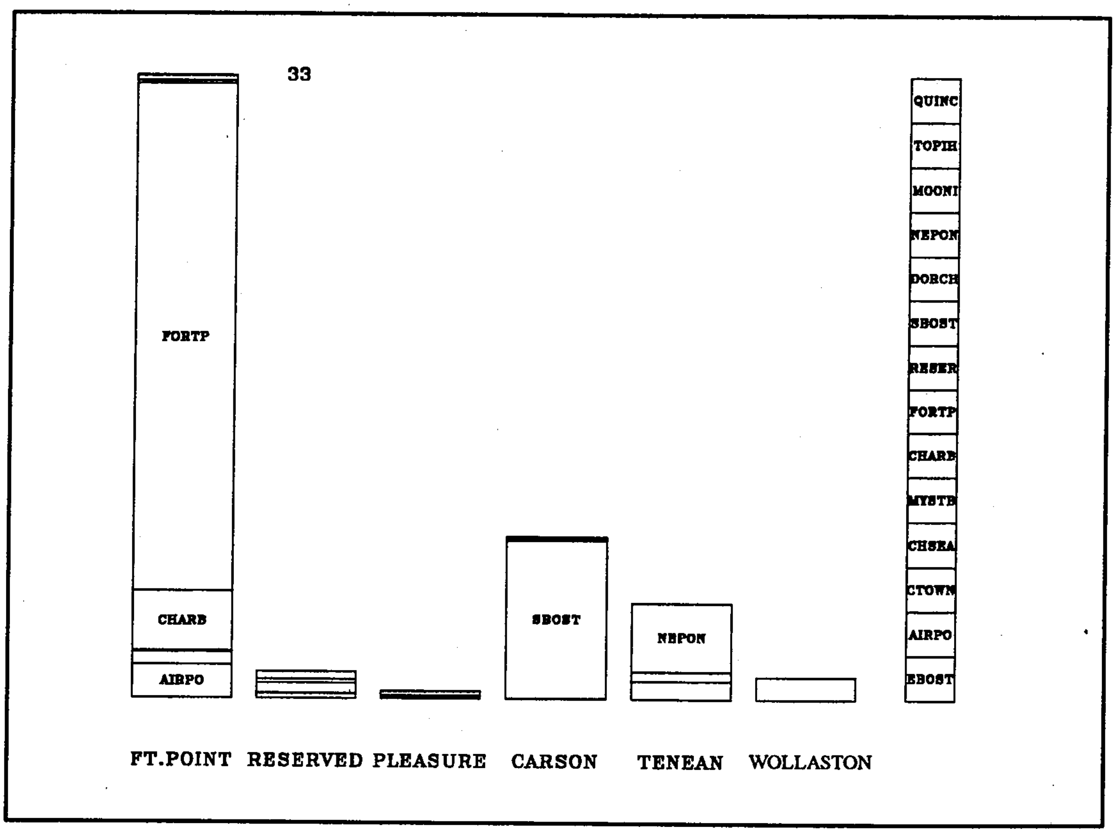

Figure 23b. Two days after storm

taken at low tide, high tide measurements have been estimated by using a 50% return on flood tide. Figure 25 indicates that the shape of the concentration response and the peak concentrations are well predicted but, as hinted above, measured concentrations exceed modeled concentrations by an average factor of about two. Additional field measurements have been collected in Fort Point Channel during July 1991 and it is recommended that more detailed model-versus-measurement comparisons be made.

Particle Representation of Sources

The version of ELA used in preparing the facilities plan simulated near source transport using the superposition of a number of Gaussian puffs which diffused from their source according to a user-input puff diffusion coefficient ($D_p = 1$ m²/s was used). Puffs were tracked over a sufficient time interval (called the puff time step) such that they had grown large enough to be projected onto the finite element grid. For the facilities plan simulation the puff time step = 3 ELA time steps or about 3 hours. The puff representation has been used in several previous ELA applications for offshore sources including MWRA's ocean outfall. For such offshore applications, where the ambient current is relatively uniform over the duration of each puff (e.g., 3 hours), the procedure is certainly reasonable (Adams et al., 1986). However, for narrow channels where flow may be highly non-uniform and boundaries may intefere, the assumption that an individual pollutant cloud remains Gaussian may not be reasonable. Accordingly, we have developed an alternative method of introducing mass. This method uses particles which undergo a random walk in accordance with the same deterministic velocities (from TEA) and diffusion coefficients as were previously applied to puffs. After a specified time (similar to the puff time step), particle positions are converted into nodal concentration following Dimou and Adams (1989) and Dimou (1991). In essence the particle procedure differs from the puff procedure mainly in the fact that the pollutant distribution is not constrained to be Gaussian. The option is

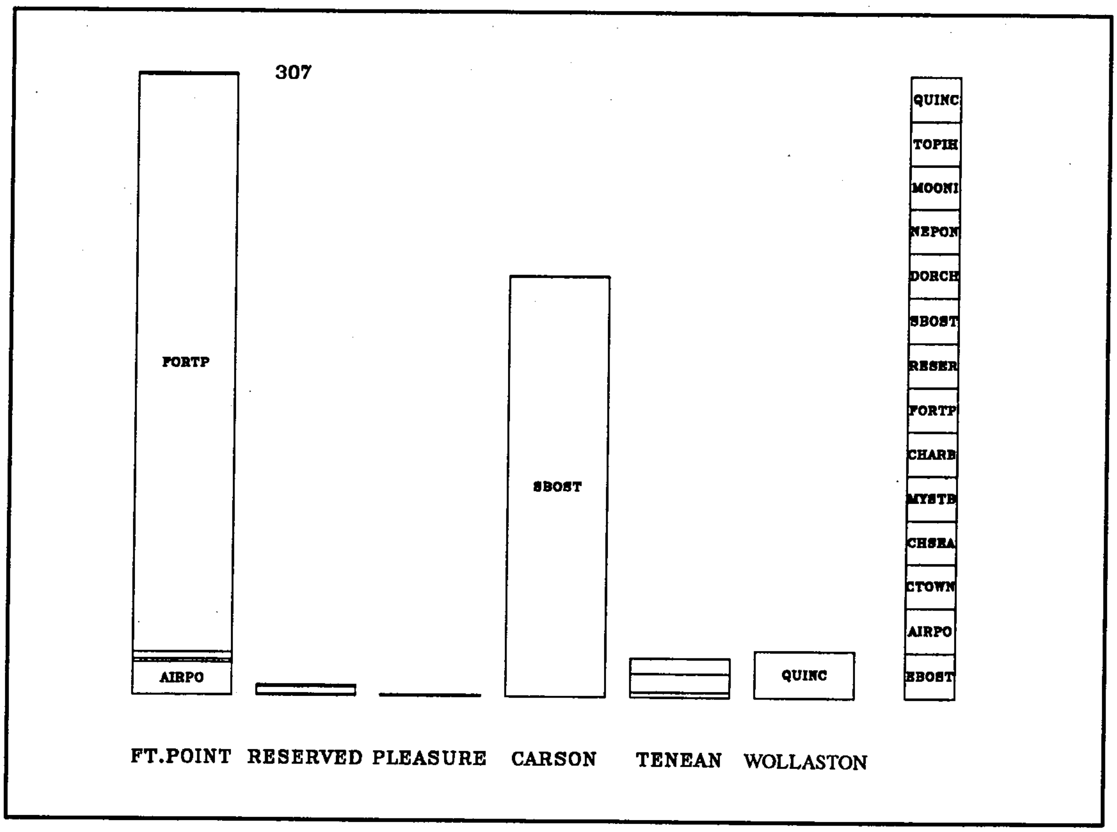

Figure 23. Summary of source impact at six locations following 3-month storm assuming 1990 loading estimates

a) One day after storm

also more computer intensive because many particles (order of 100–1000) have to be introduced and tracked each time step as opposed to about 10 puffs.

Calculations were made with both the puff and particle options, with generally small differences (less than 10% in outer harbor concentration). Compared to the variation introduced by uncertainty in loading, this is almost negligible. Both the puff and the particle methods are now options for ELA and are described in the ELA users manual (Kossik et al., 1991).

SUMMARY AND CONCLUSIONS

Observations during 1990 suggest substantially less CSO volume than previously thought. Suggested reasons include improvements at the North system headworks, greater than anticipated in-system storage, and more realistic treatment of tides by the sewer model. Limited data also suggest somewhat lower than predicted concentration of bacteria and other pollutants. Based on volume and concentration measurements, fecal coliform loading for 1990 was estimated to be about 0.11, 0.17, and 1.0 times the previously computed future no action condition for the outer harbor, inner harbor, and Charles and Mystic Rivers, respectively.

Four simulations of harbor fecal coliform concentration, each lasting four days, were made using two storms (1-year and 3-month) and two conditions (future no action and 1990). The 1990 condition was the future no action condition multiplied by the reduction factors of 0.11, 0.17, and 1.0. Not surprisingly, the water quality simulation showed substantially reduced impact as the loading was reduced from "future no action" to "1990." It should be re-emphasized that these simulations are more valid as measures of relative impact (associated with different loading) than absolute impact. This is because some of the "improvement" that we are now seeing between the "existing" and "1990" loadings

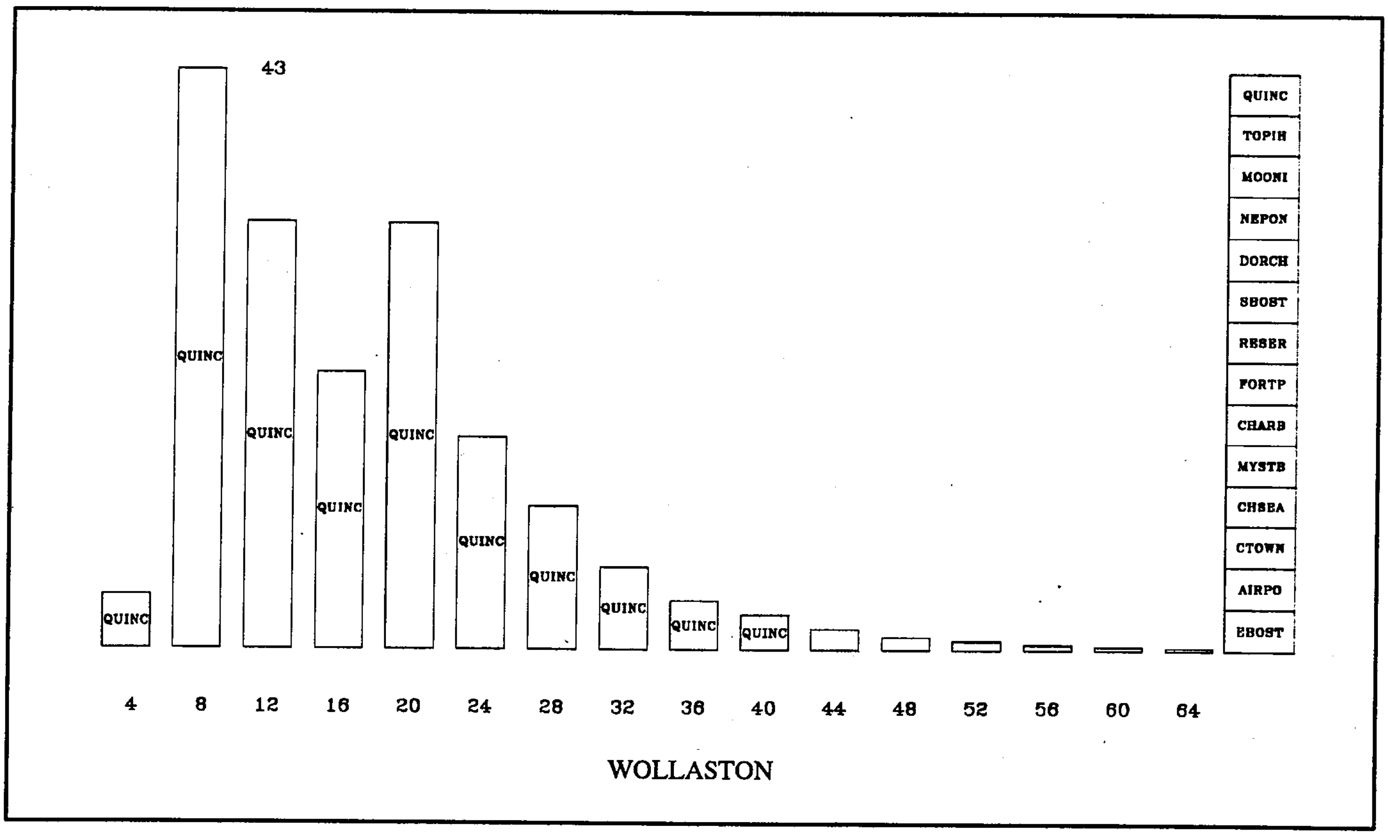

Figure 22f. Wollaston Beach

could already have taken place in July 1988 (the period of time for which the model was calibrated) which would affect the 1988 model calibration and hence the present results. It is recommended that the model be recalibrated if additional simulations are performed.

Simulations also confirm analytical calculations that the greatest impact at a given receptor was generally due to the nearest source, even if the source was small. This is due to the longer transport time (and hence greater bacterial die-off) between more distant sources and receptors. This conclusion may have bearing on the priority for remediation of certain CSOs or groups of CSOs.

The CSOs were simulated as 14 aggregate sources. Several aspects of source aggregation and near-source transport were studied.

- Any errors due to the fact that sources are aggregated, instead of being treated individually, die out with time. Certainly for predicting concentration in Boston Harbor, the choice of 14 sources was adequate.

- The way in which mass was released (as Gaussian puffs diffusing from each aggregate source) was found to be quite accurate (less than 10% difference compared with a more rigorous approach using particles).

- The model location of each aggregate source is reasonable except for Reserved Channel where the source was located too far from shore. Moving the source inshore would reduce concentration in the outer harbor, although the effect would be small due to the small source loading.

- Fort Point Channel is modeled as being slightly wider, deeper, and shorter than it actually is. The combined effect is that the simulated mass flux to the inner harbor (and later to the outer harbor) is exaggerated by a factor of about two.

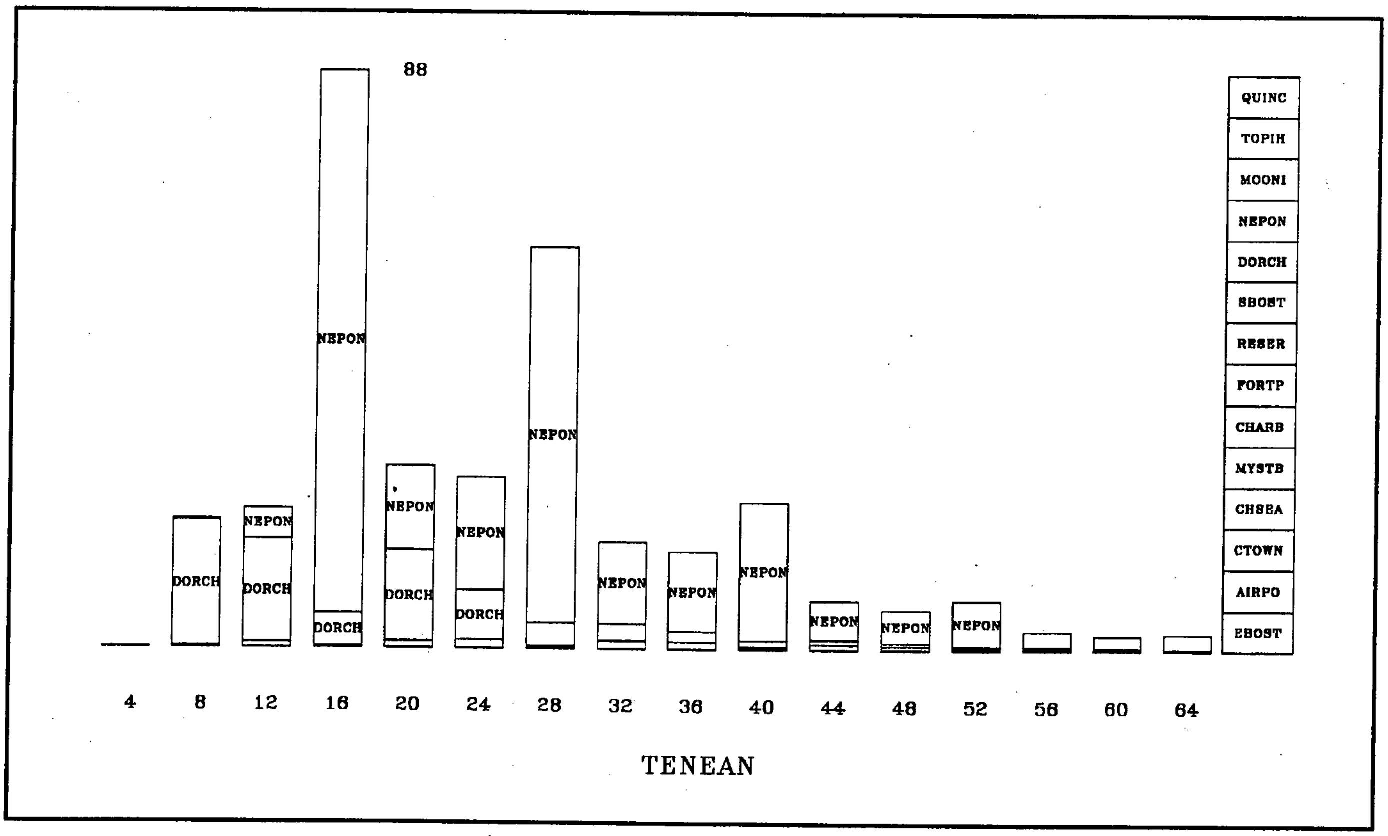

Figure 22e. Tenean Beach

- Despite the refinement made to previous Boston Harbor grids, the present grid is too coarse in certain inner harbor locations (e.g., Fort Point Channel and Reserved Channel) to accurately reproduce observed tidal flow field. Because much of the net transport is actually simulated to take place as tidal dispersion rather than advection (and dispersion coefficients were calibrated using the same grid and flow field as used in model simulation) the error is not large. However future simulations should consider greater refinement.

- The additive uncertainty of all of the "near source" factors is probably about a factor of 2–3 in simulated concentrations, which is significant but somewhat smaller than the factor of 3–10 uncertainty due to loading.

ACKNOWLEDGMENTS

This study was supported by the Marine Studies Group, Sewerage Division, of the Massachusetts Water Resources Authority (MWRA), and supplemented by Marine Center funds from the MIT Sea Grant Program. This support is gratefully acknowledged.

Most of the data upon which the study was based came from outside sources, including the MWRA, Camp Dresser & McKee, Rizzo Associates, Boston Water and Sewer Commission, and the City of Cambridge. We appreciate the use of these data and would like to thank the various individuals from these organizations for their help in digging it up. We accept full responsibility for the interpretation of their data in our report.

The material in the first section of this report was presented by the first author as part of the 1991 John R. Freeman Lecture, entitled "Combined Sewer Overflows in Metropolitan Boston: Structural and Operational Controls." The symposium was held on

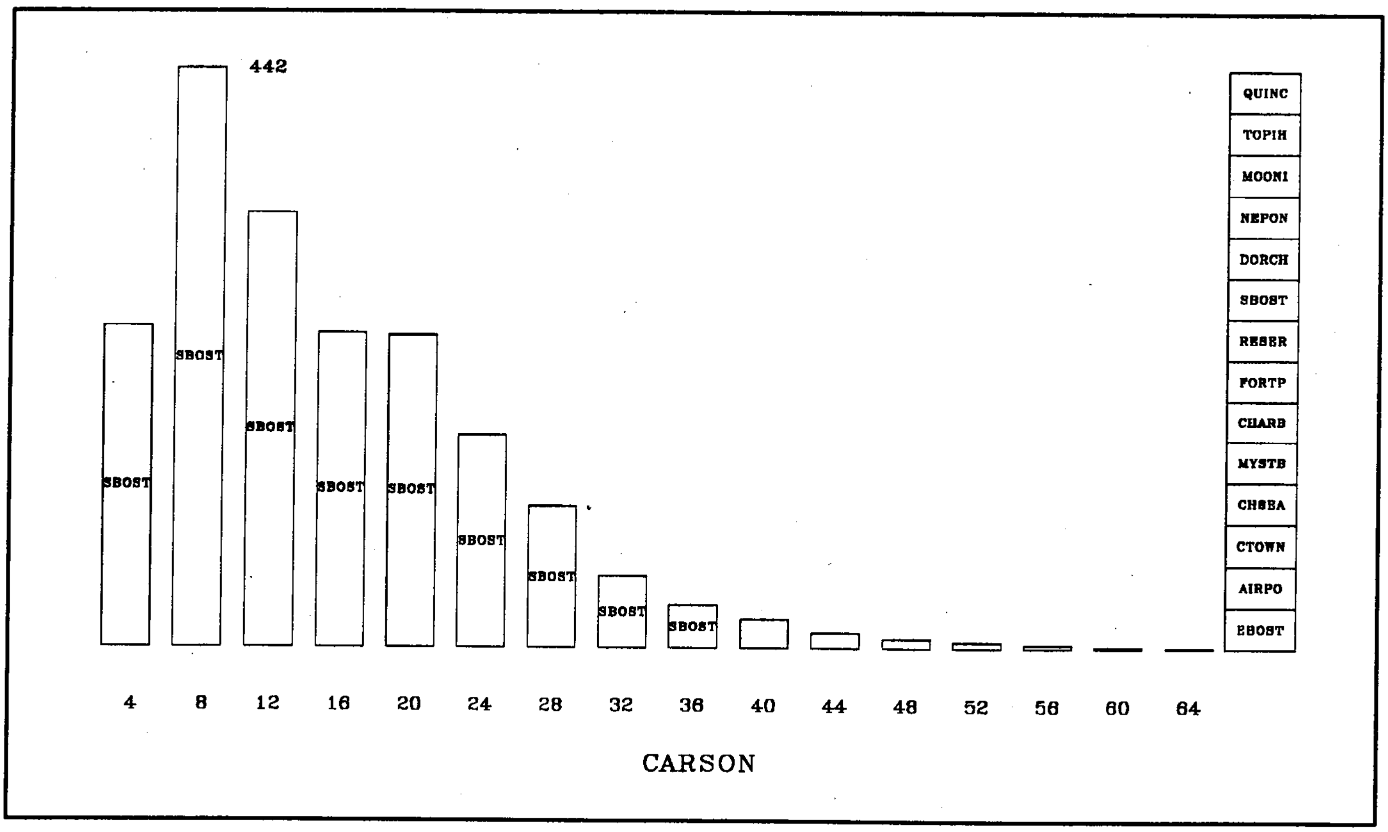

Figure 22d. Carson Beach

April 22, 1991, at MIT and was sponsored by the Boston Society of Civil Engineers Section, ASCE, and the Ralph M. Parsons Laboratory, Dept. of Civil Engineering, MIT.

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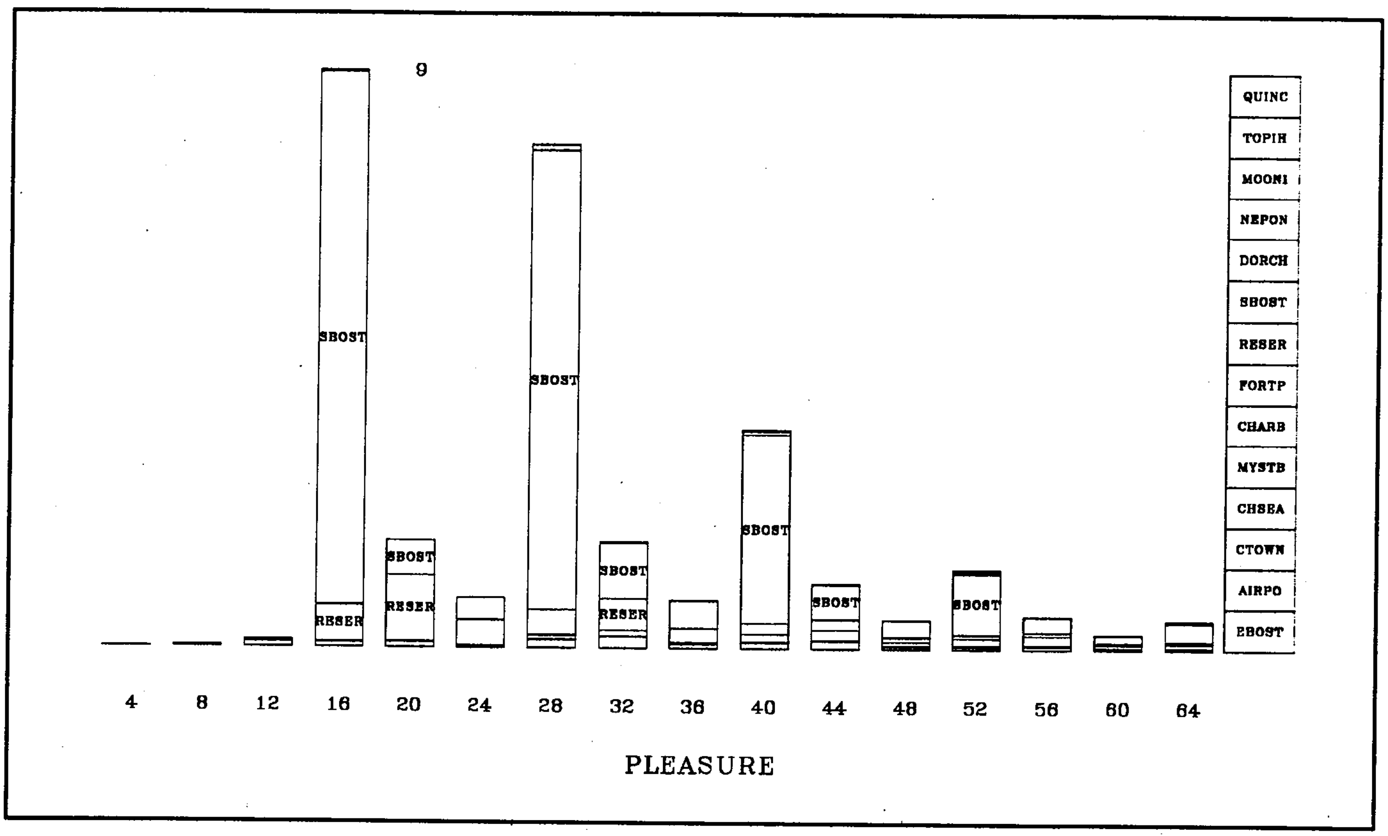

Figure 22c. Pleasure Bay

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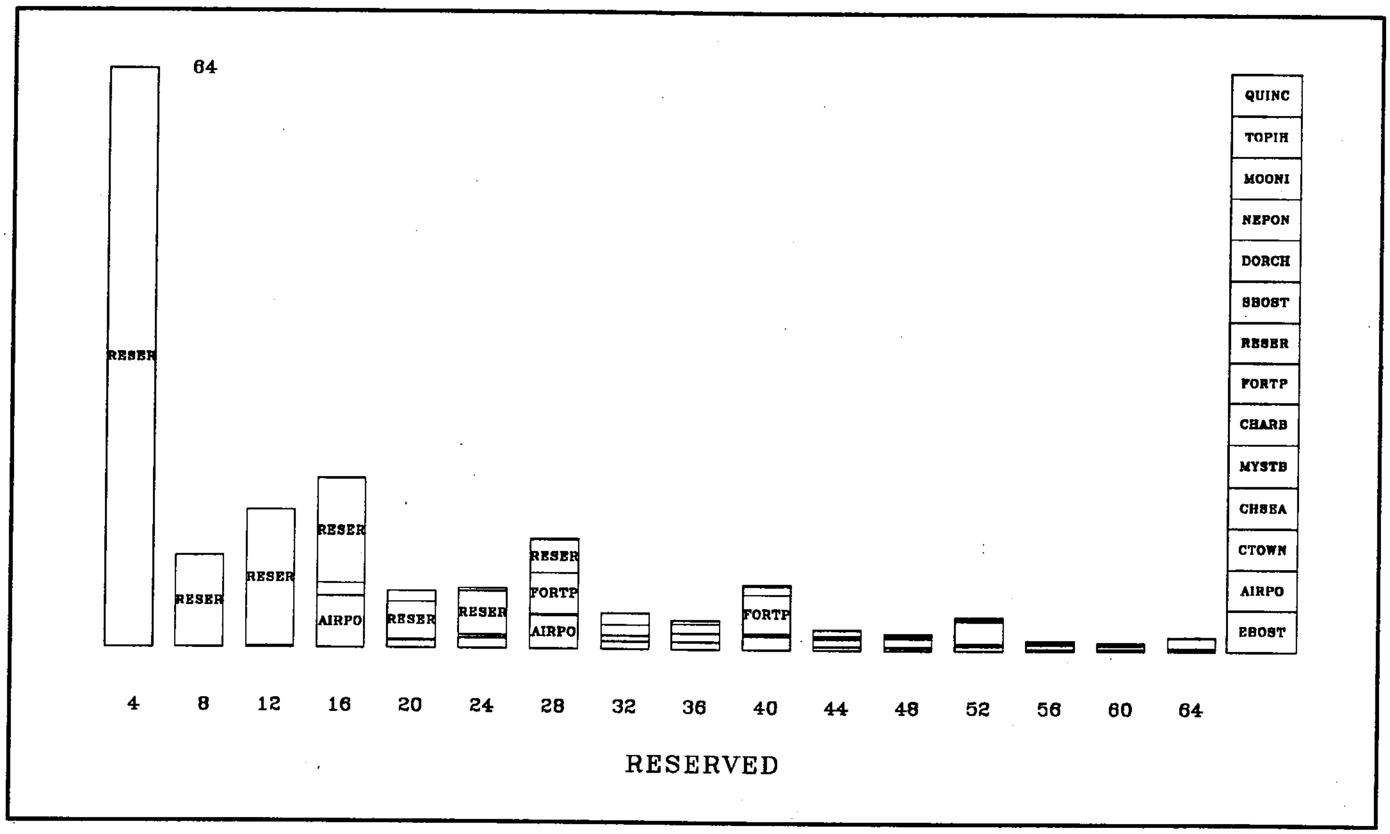


Figure 22b. Reserved Channel mouth

Table 1

Modeled versus Measured Dimensions for Fort Point Channel

	Model	Actual
Length (m)	1095	1650
Ave. depth (m)	7.1	6
Ave. width (m)	180	140

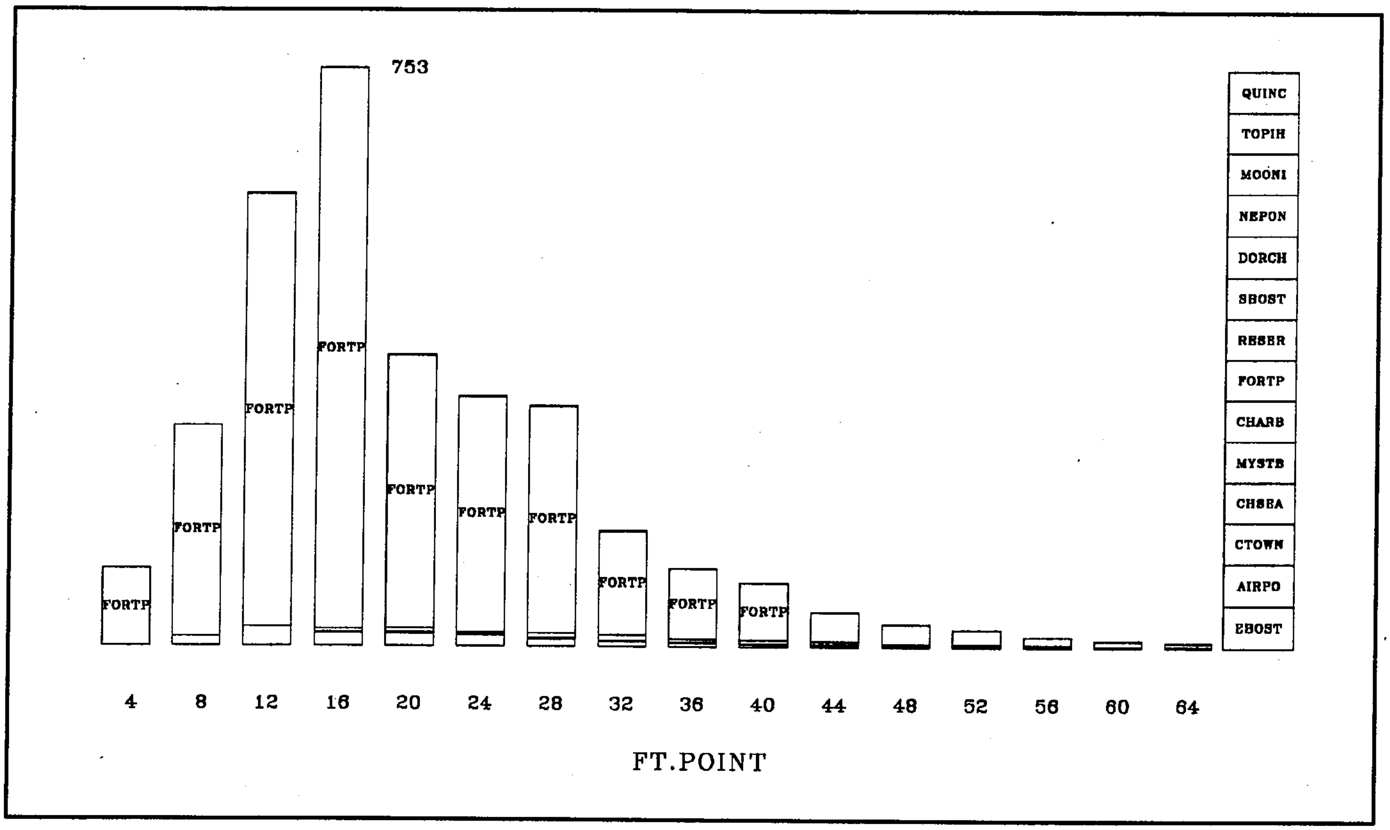


Figure 22. Relative impact of 14 aggregate sources on fecal coliform concentration as a function of time step for 3-month storm assuming 1990 loading estimates.

a) Fort Point Channel mouth

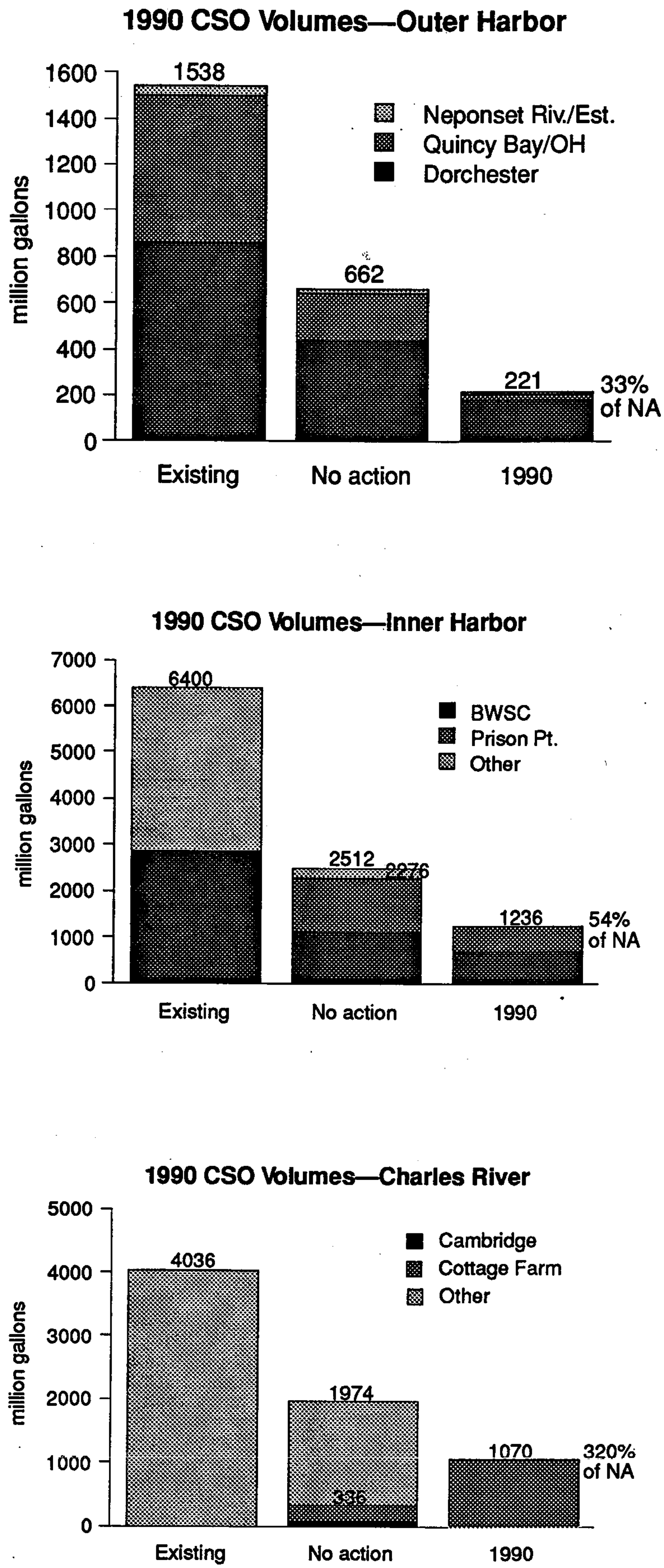


Figure 1. CSO volume estimates

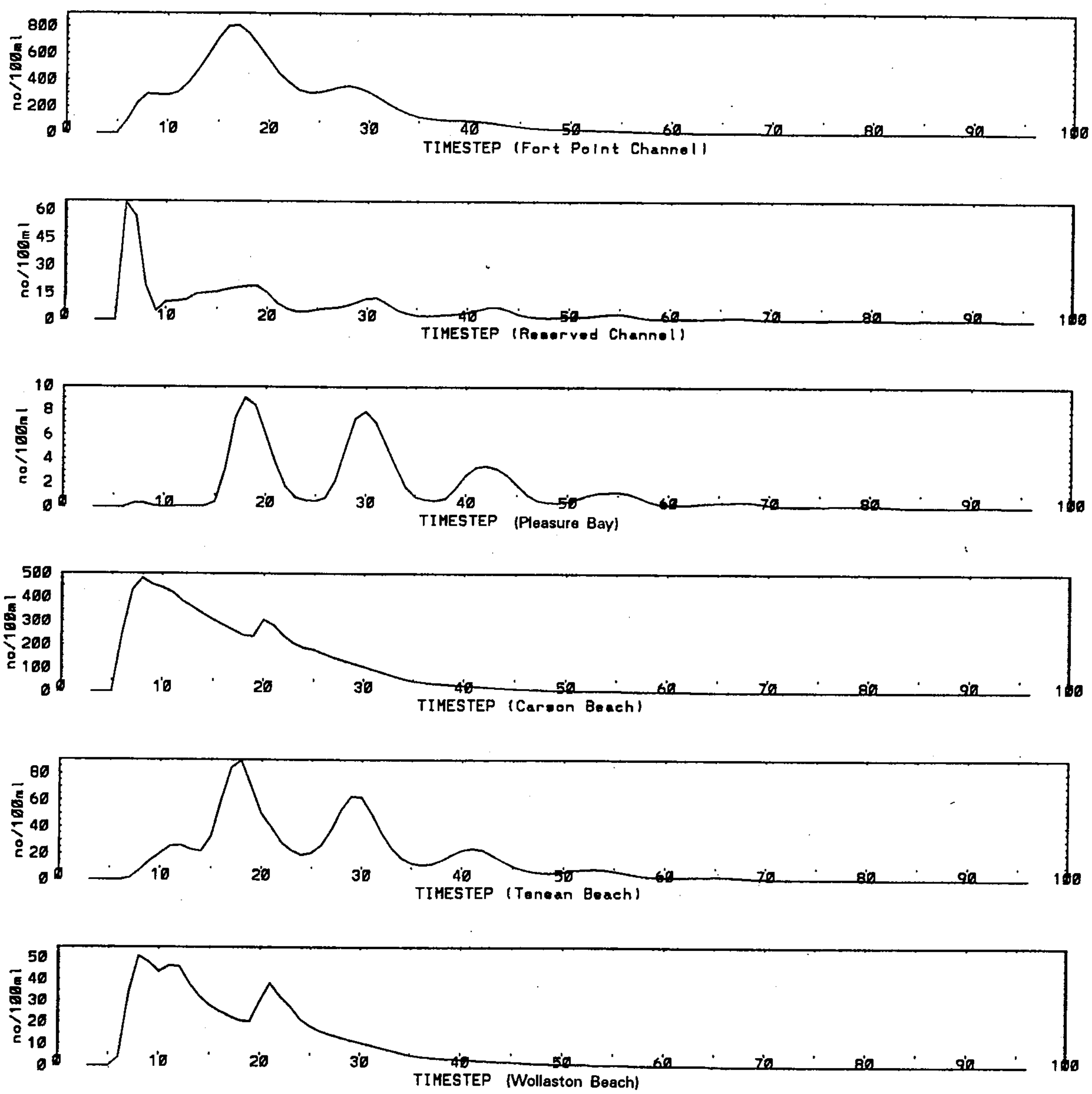


Figure 21. Simulated fecal coliform concentrations versus time at six locations following 3-month storm assuming 1990 loading estimates. Time step equals 1.04 hours.

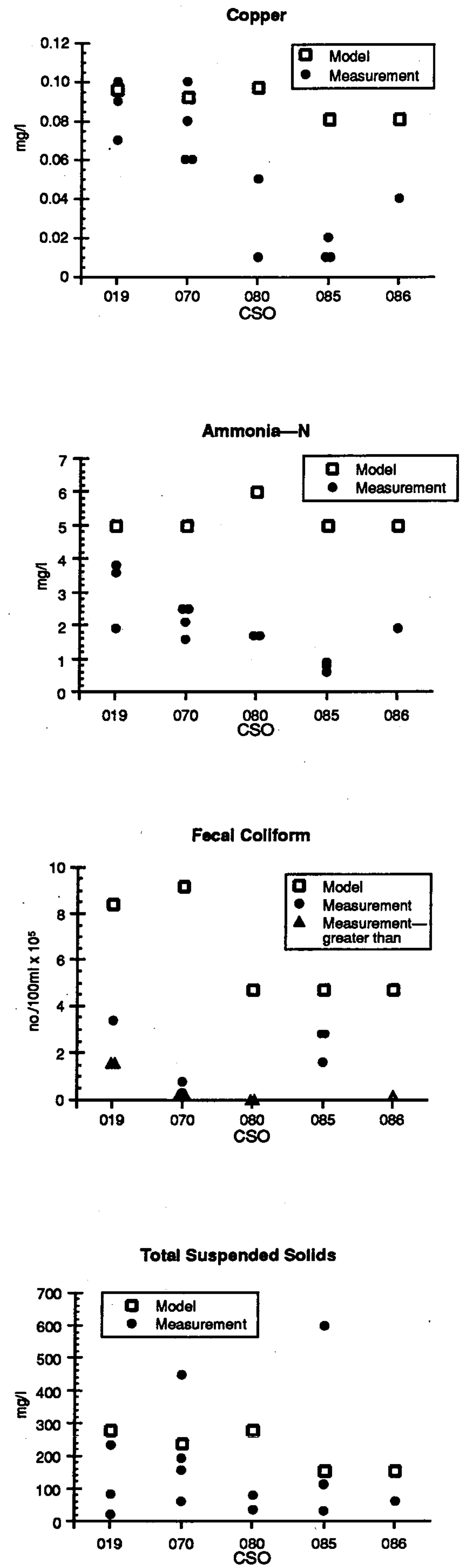


Figure 2. CSO concentration measurements

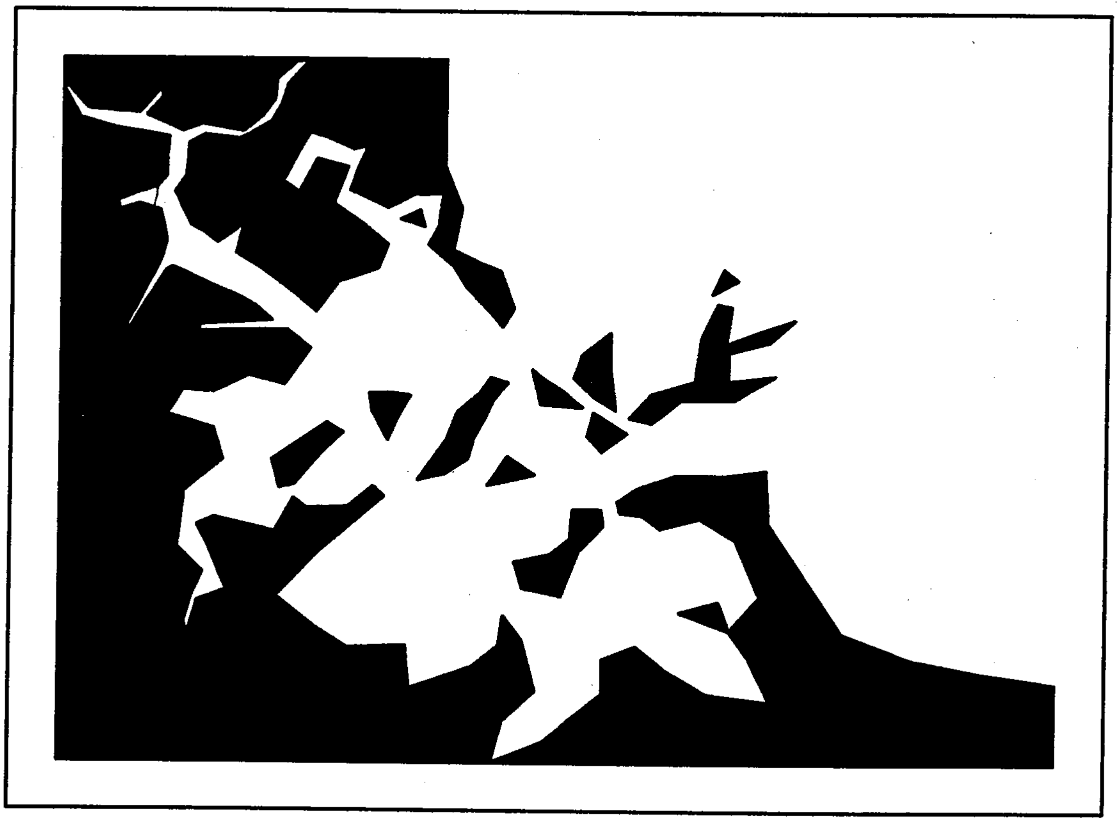
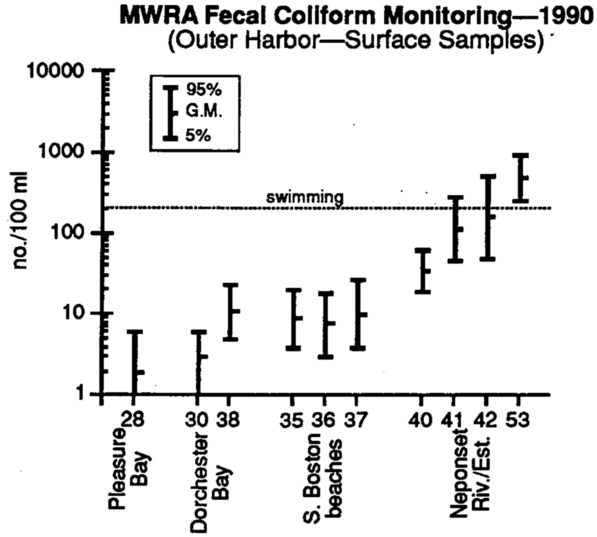
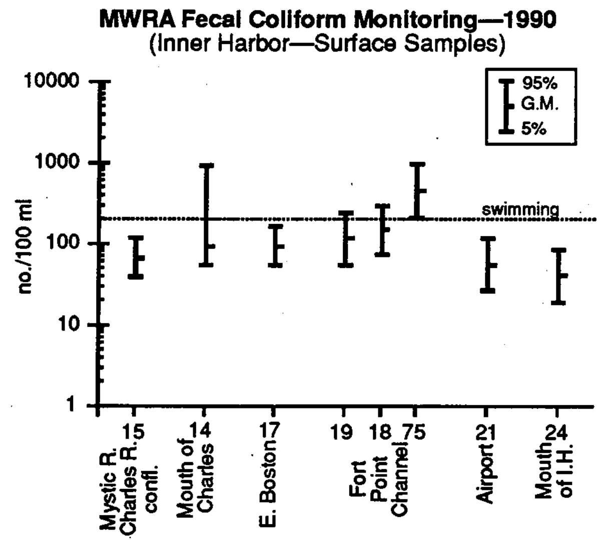


Figure 20d. Four days after storm





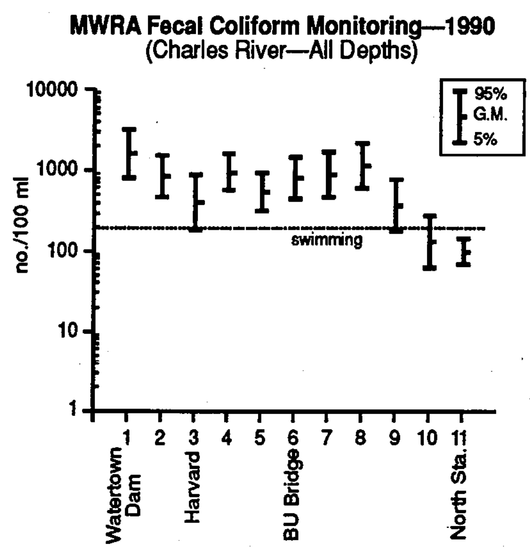


Figure 3. MWRA fecal coliform monitoring results—1990

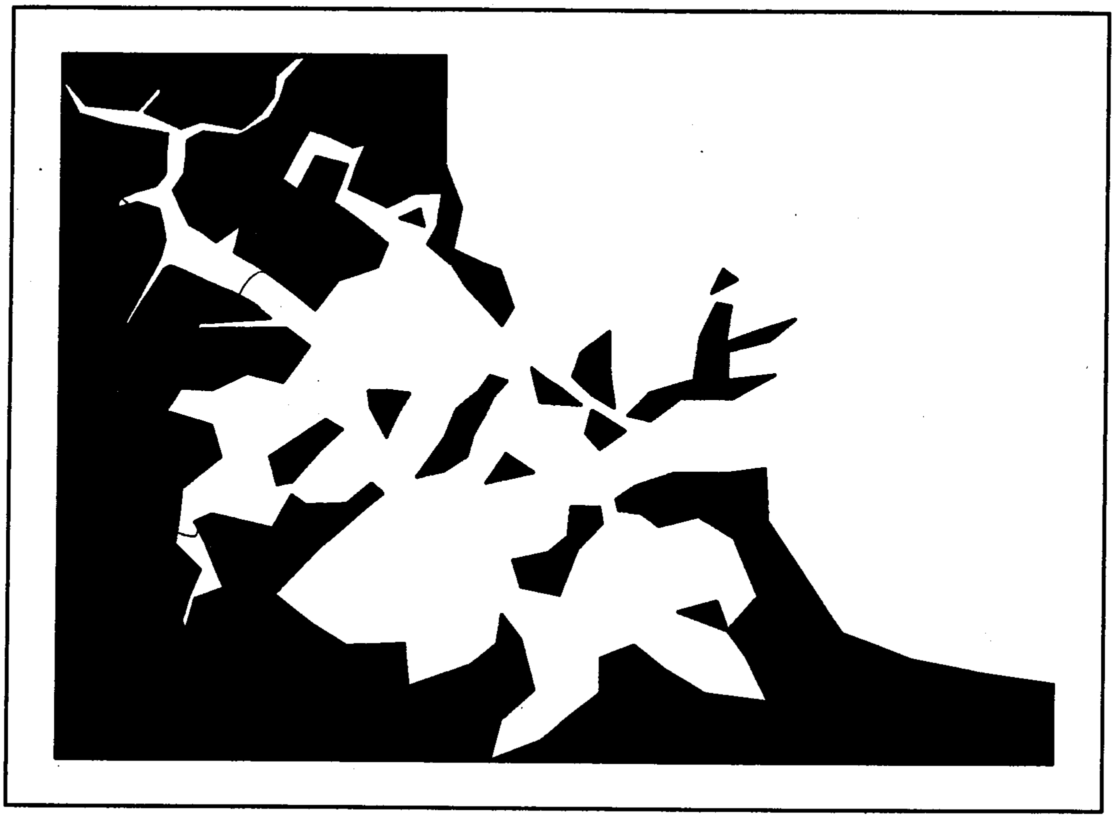


Figure 20c. Three days after storm

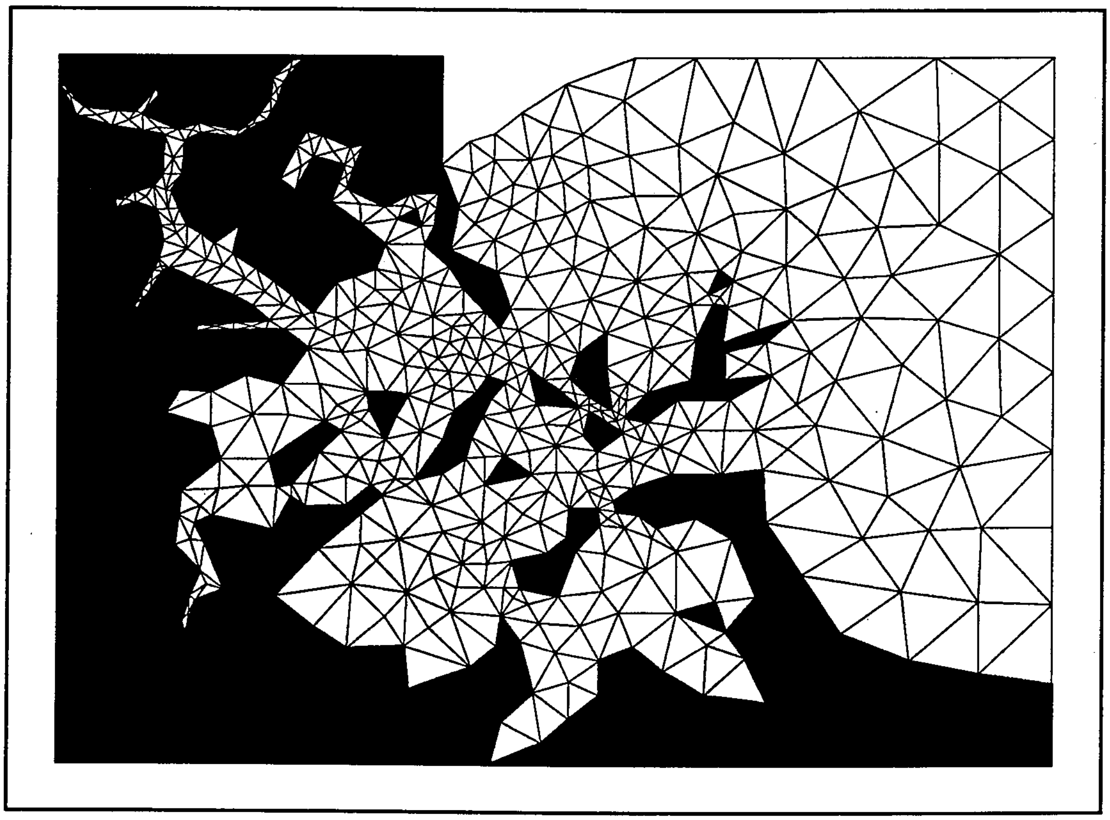


Figure 4. Portion of finite element grid used for harbor water quality simulation

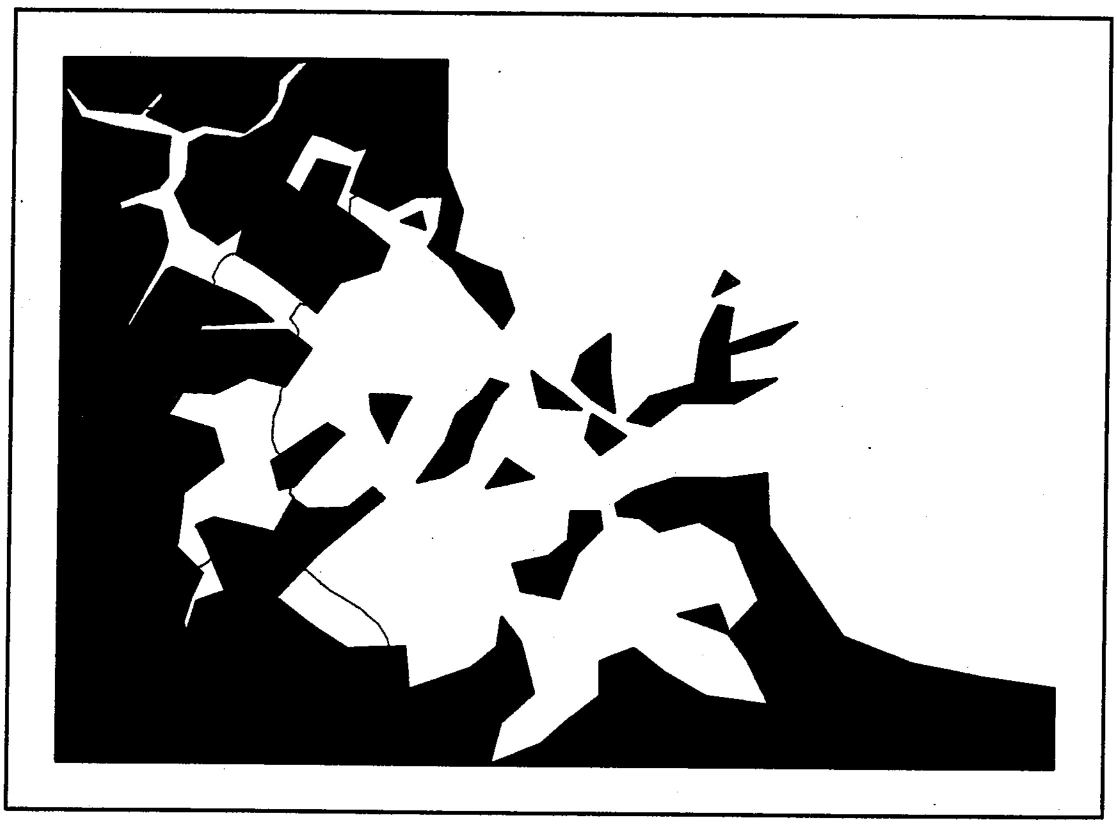


Figure 20b. Two days after storm

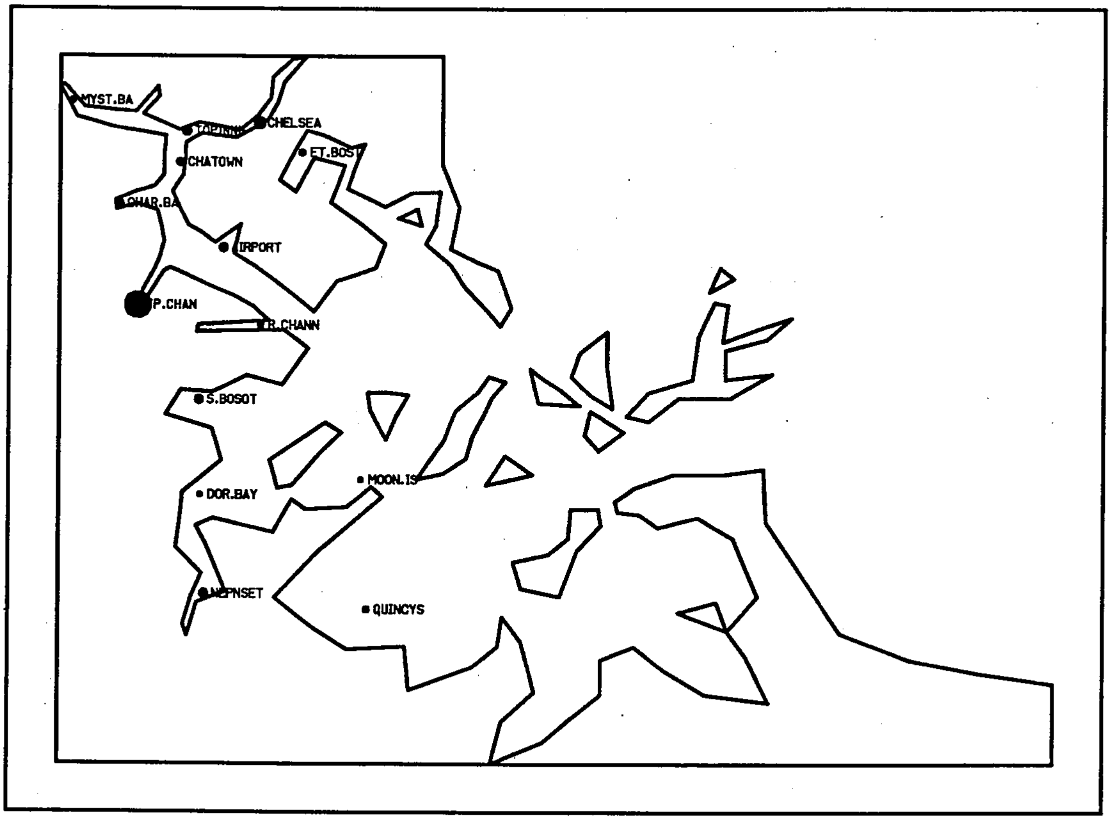


Figure 5. Aggregate source location used in water quality simulations (size of dot reflects source magnitude for one-year storm, future no-action conditions)

Figure 20. Simulated depth-average fecal coliform concentration following 3-month storm using 1990 loading estimates. Coliform intervals from offshore to inshore represent 1, 14, 200, and 1000 counts/100 ml.

a) One day after storm

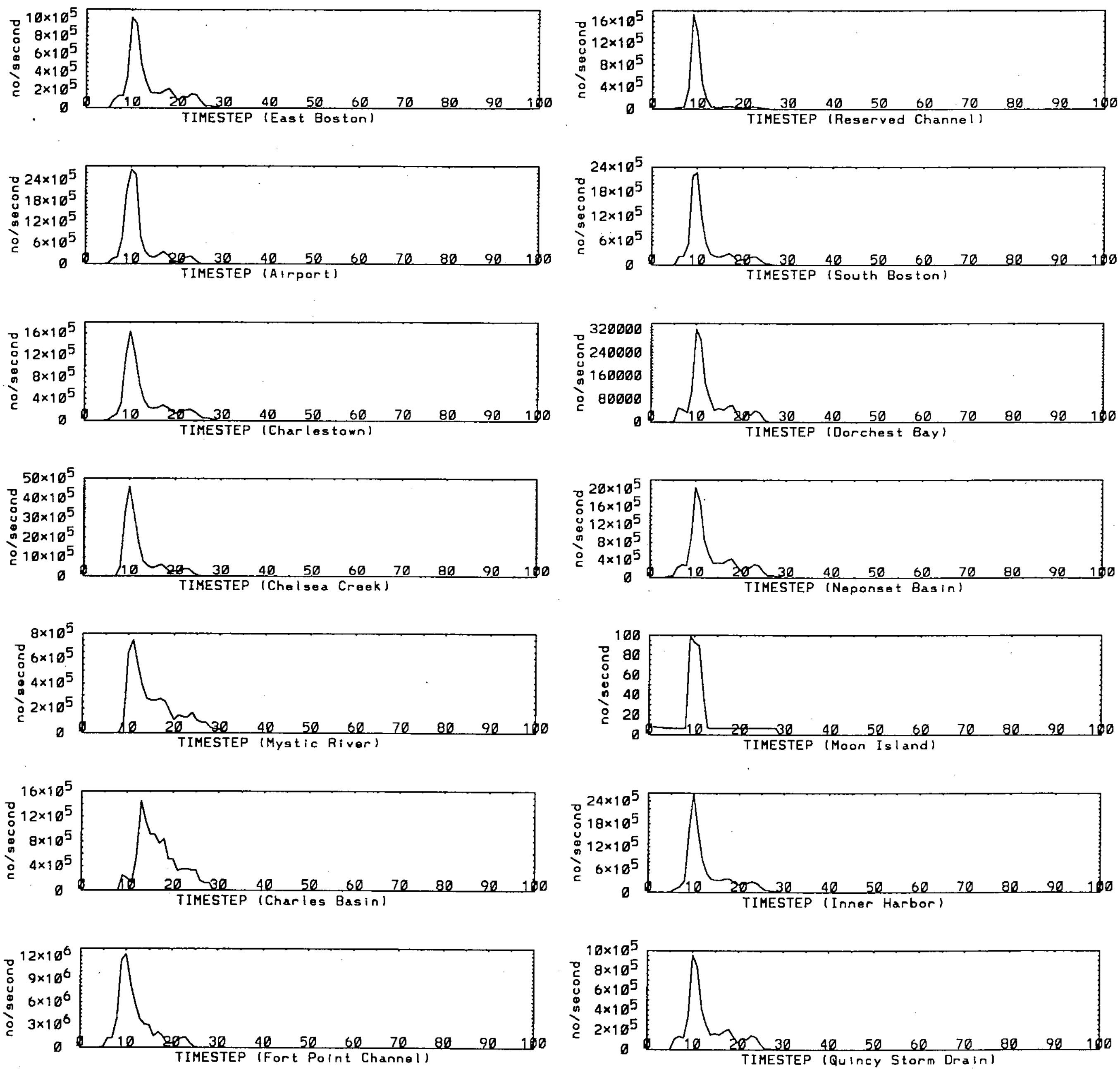


Figure 6. Time series of loading for each aggregate source (one-year storm; future no-action condition). Note that loadings have been divided by 10^4 in order to yield simulated concentrations in no/100 ml rather than no/m^3

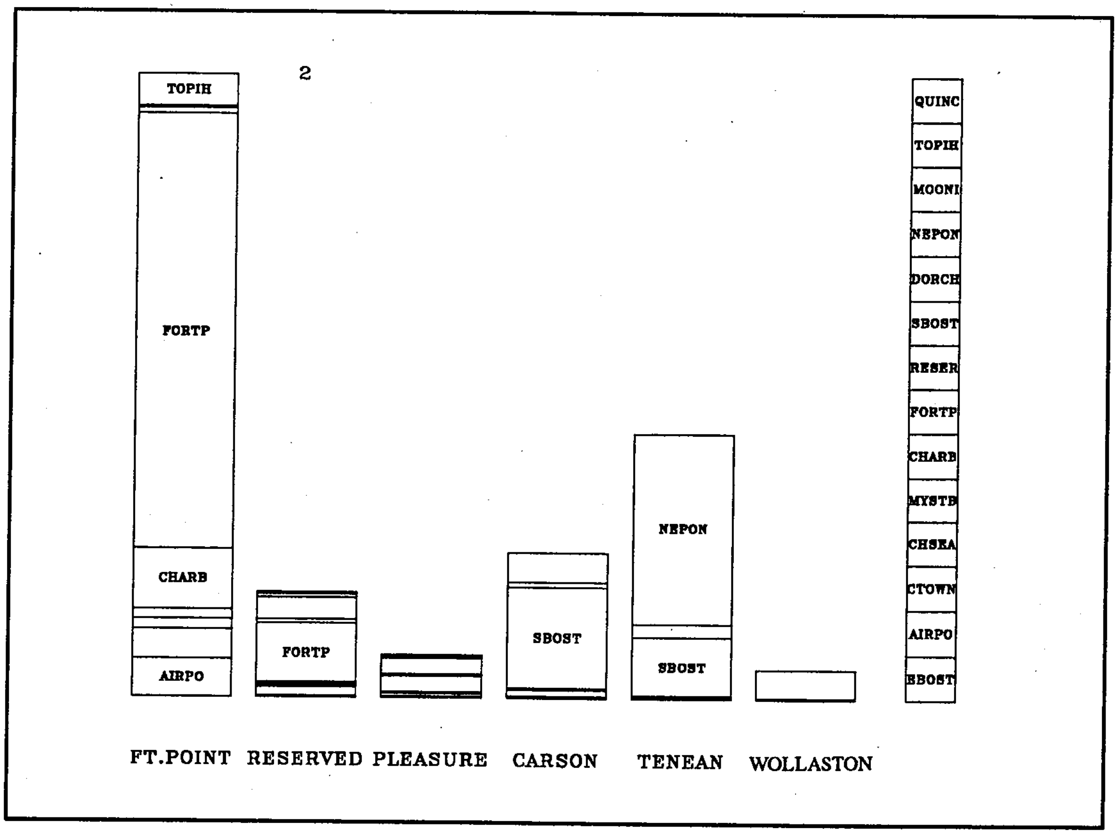


Figure 19d. Four days after storm

Figure 7. Simulated depth-average fecal coliform concentrations following one-year storm under future no-action conditions. Contour intervals from offshore to inshore represent 1, 14, 200, and 1000 counts/100 ml.
a) one day after storm

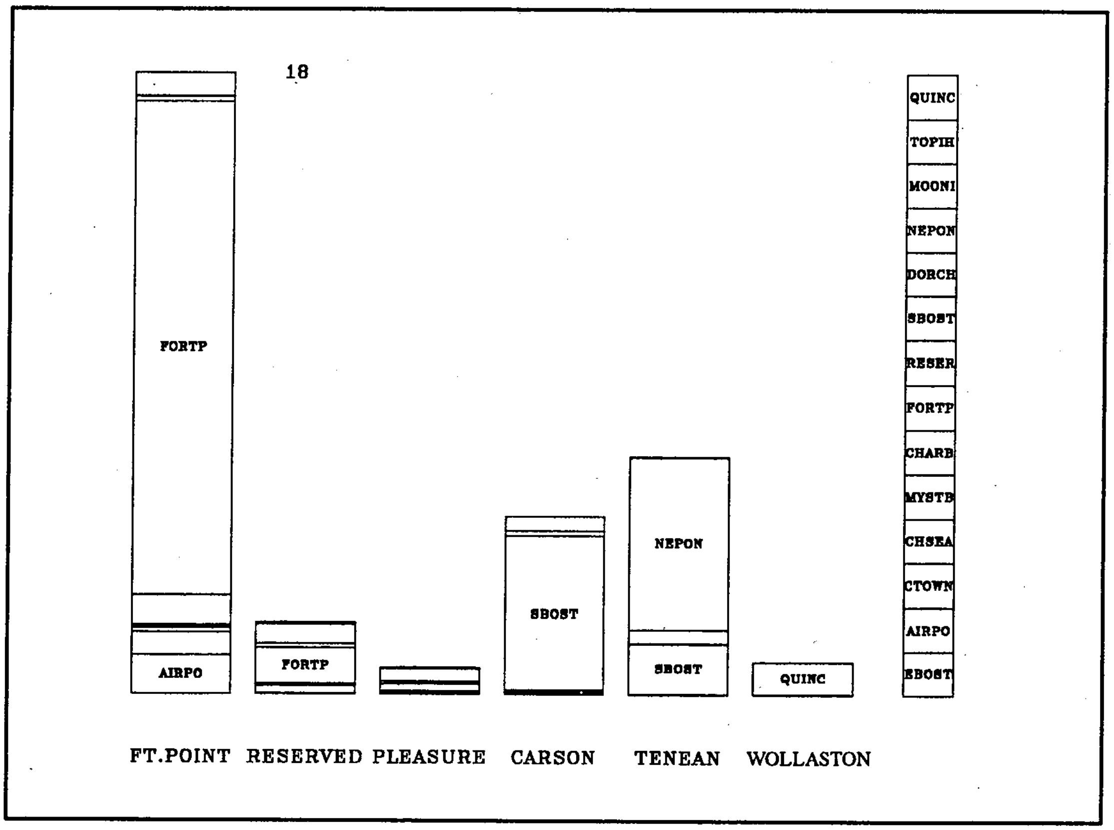


Figure 19c. Three days after storm

Figure 7b. Two days after storm

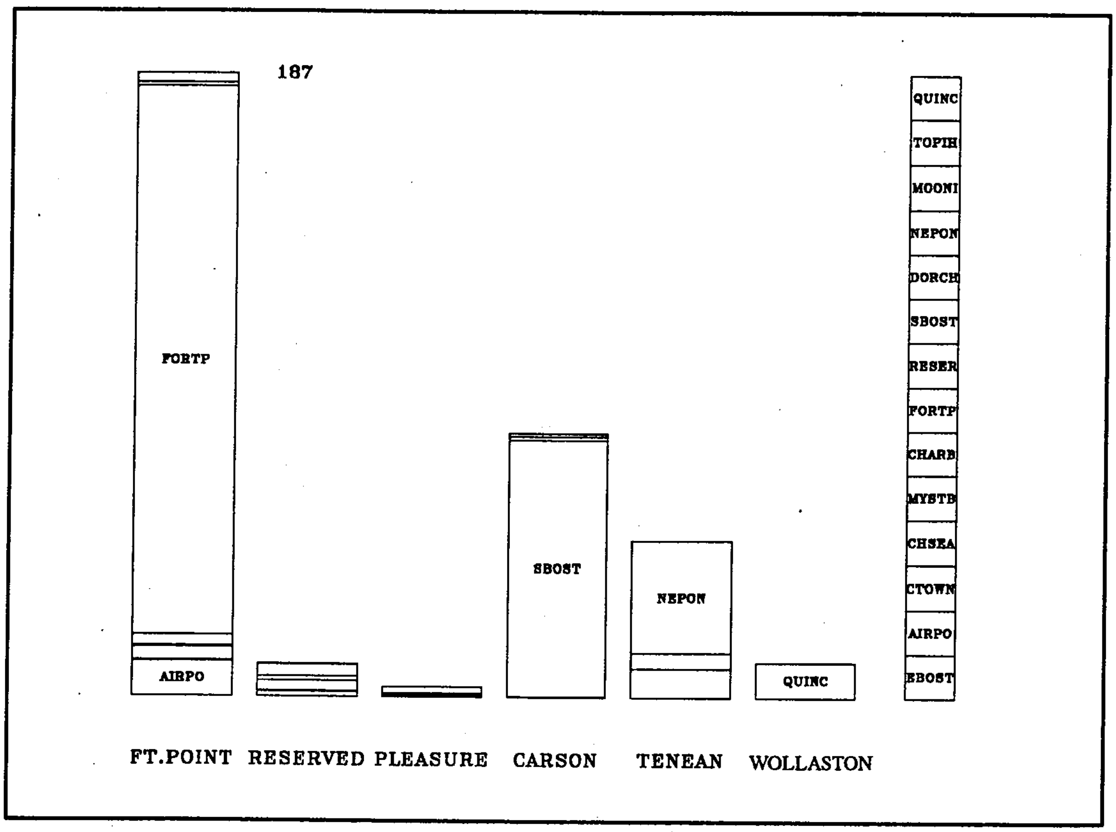


Figure 19b. Two days after storm

Figure 7c. Three days after storm

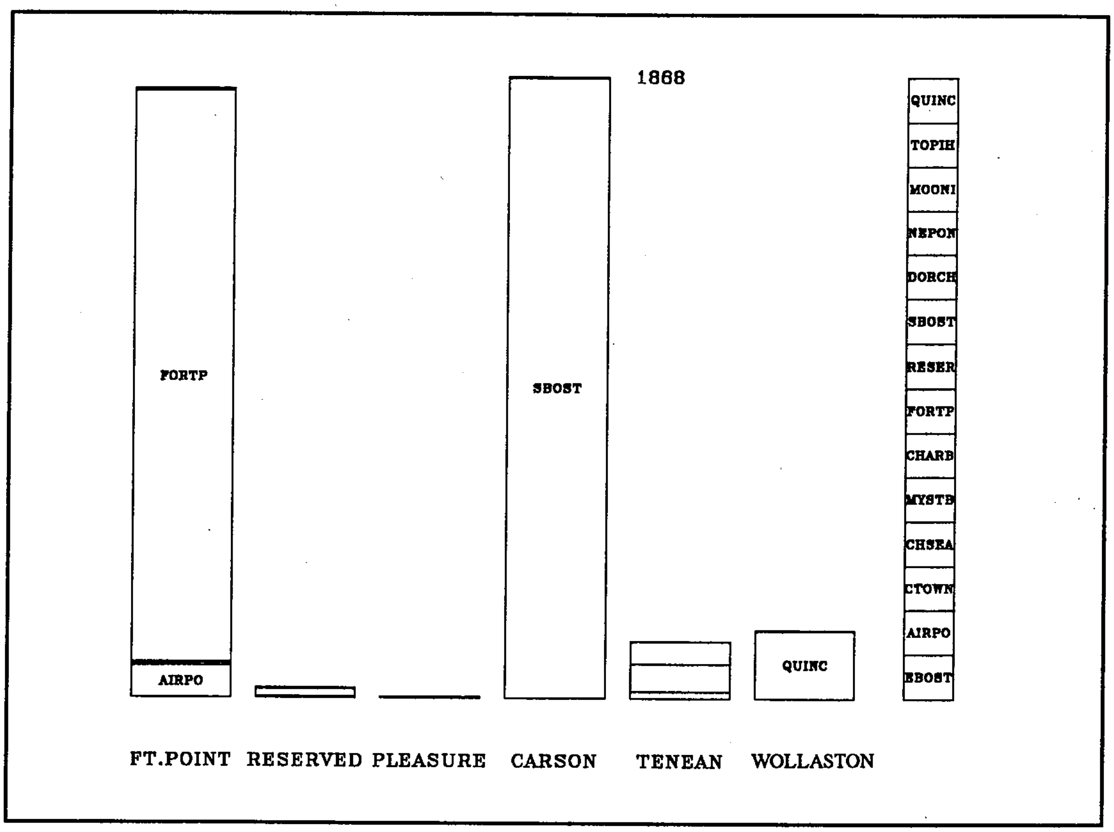


Figure 19. Summary of source impact at six locations following 3-month storm under future no-action conditions.

a) one day after storm

Figure 7d. Four days after storm

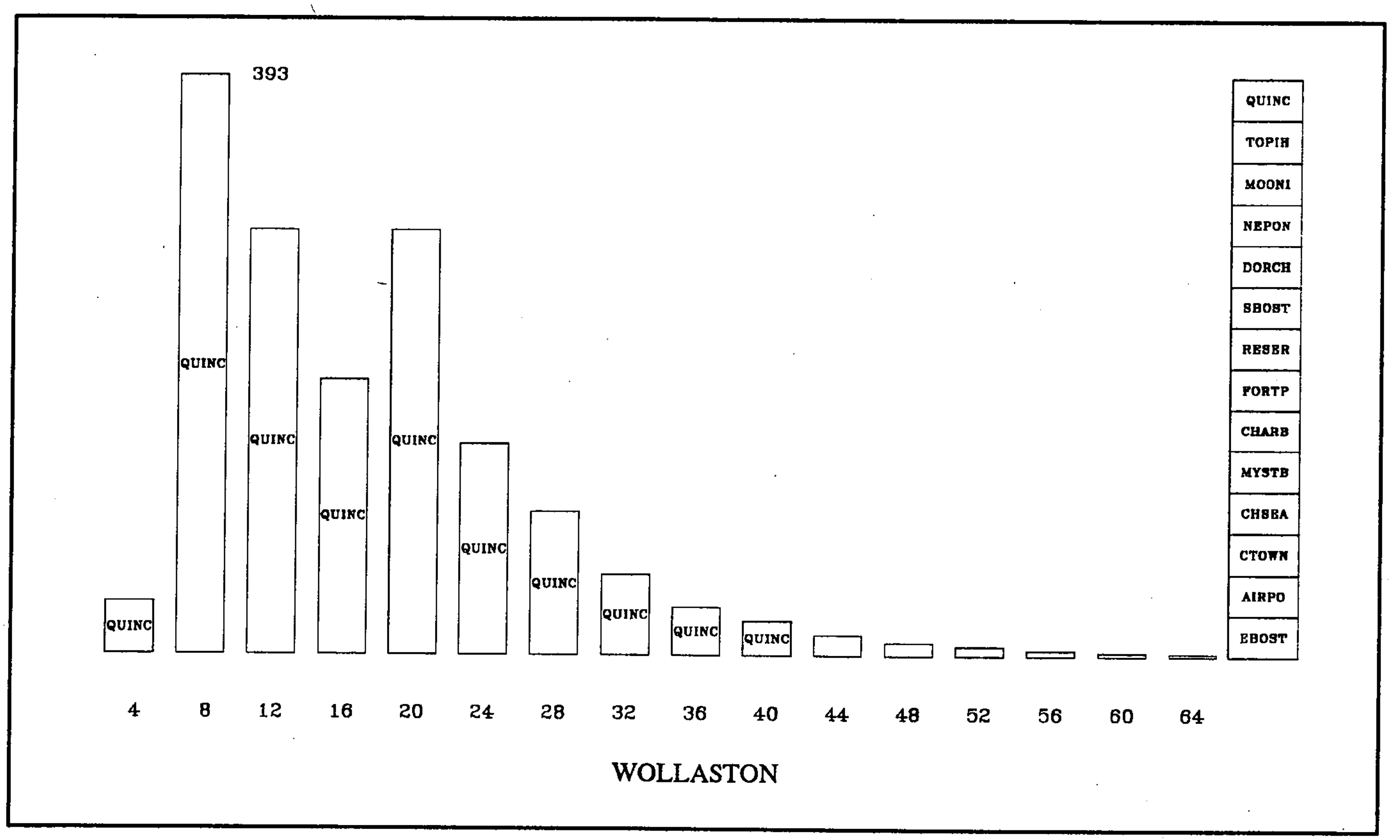


Figure 18f. Wollaston Beach

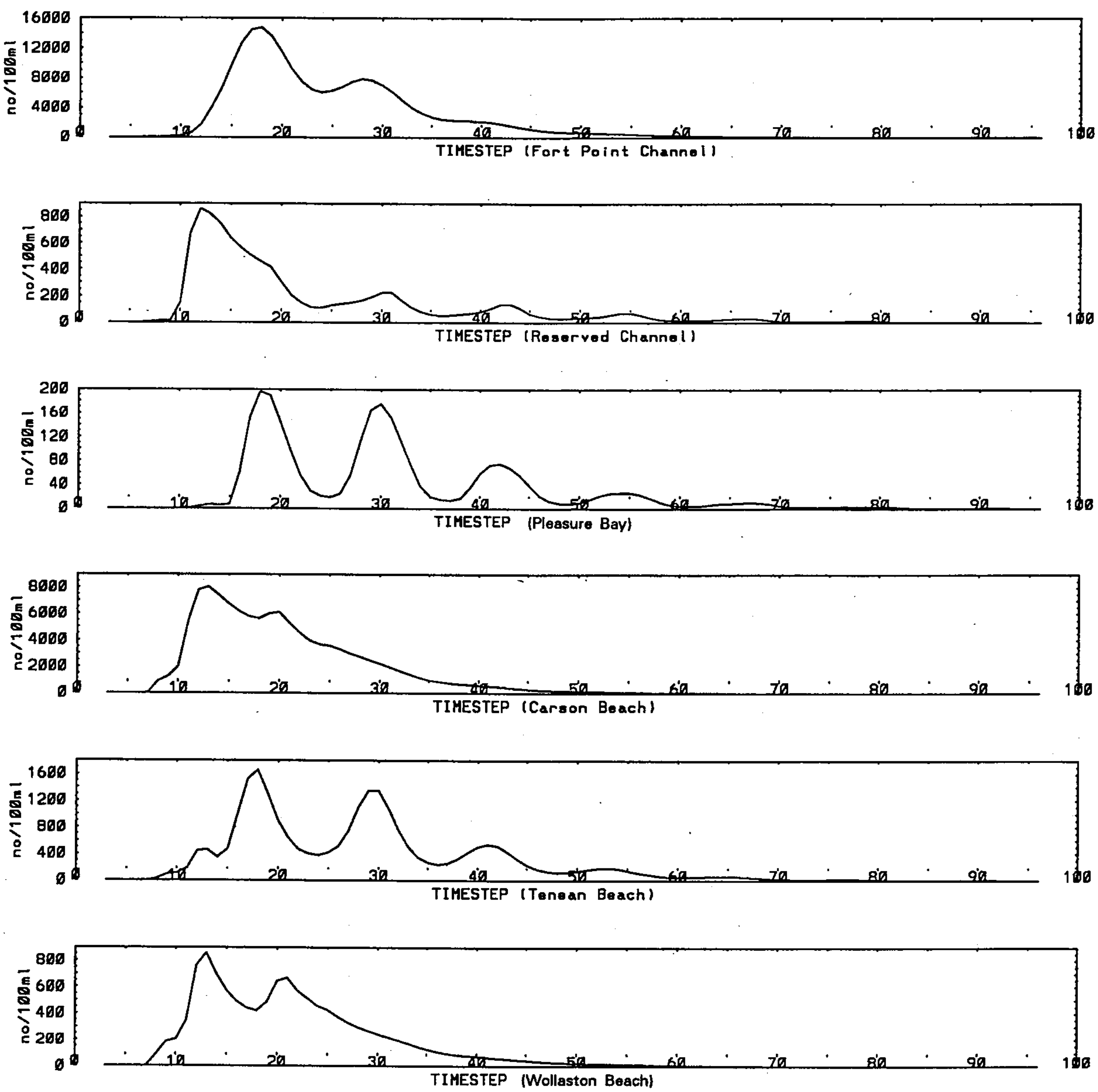


Figure 8. Simulated fecal coliform concentrations versus time at six locations following one-year storm under future no-action conditions. Time step equals 1.04 hours.

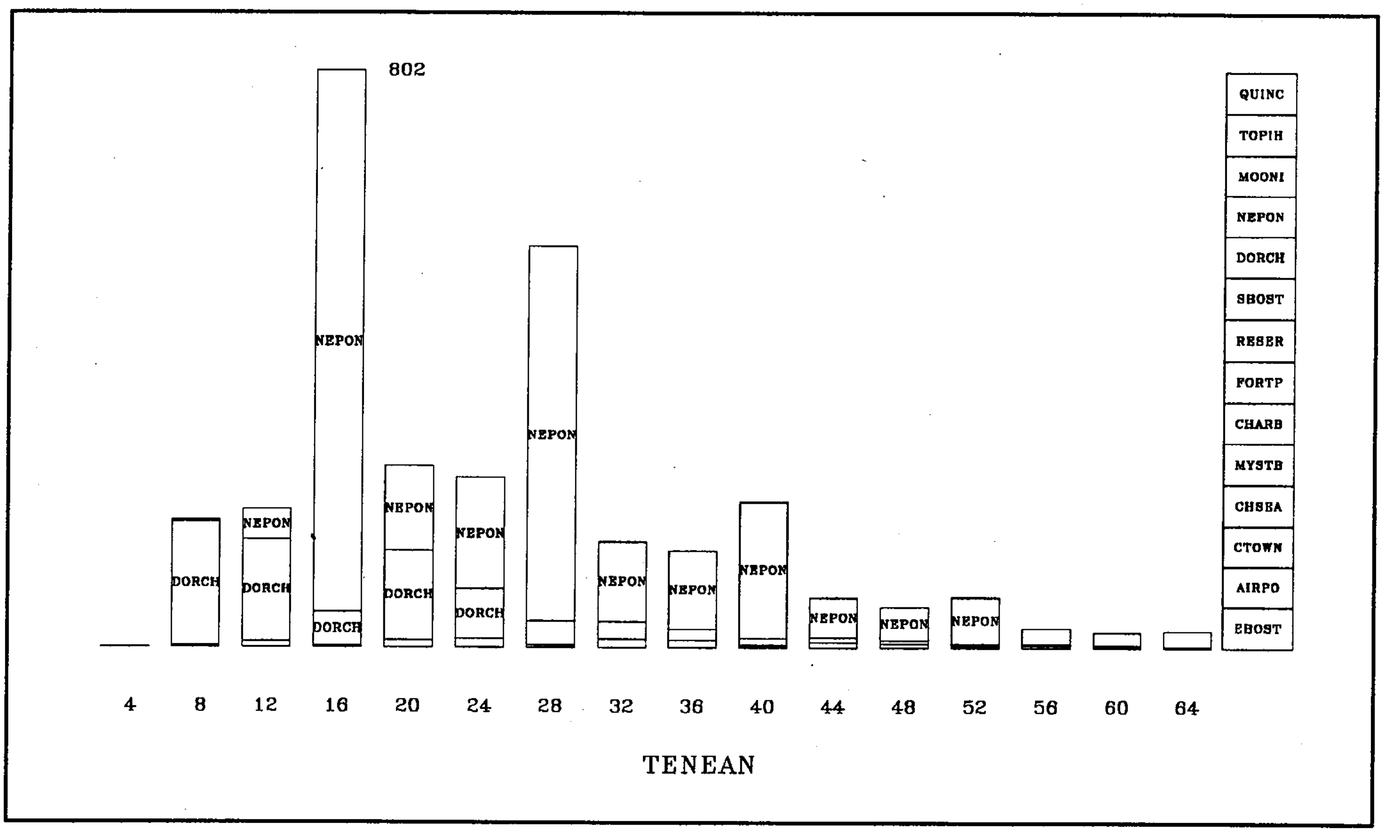


Figure 18e. Tenean Beach

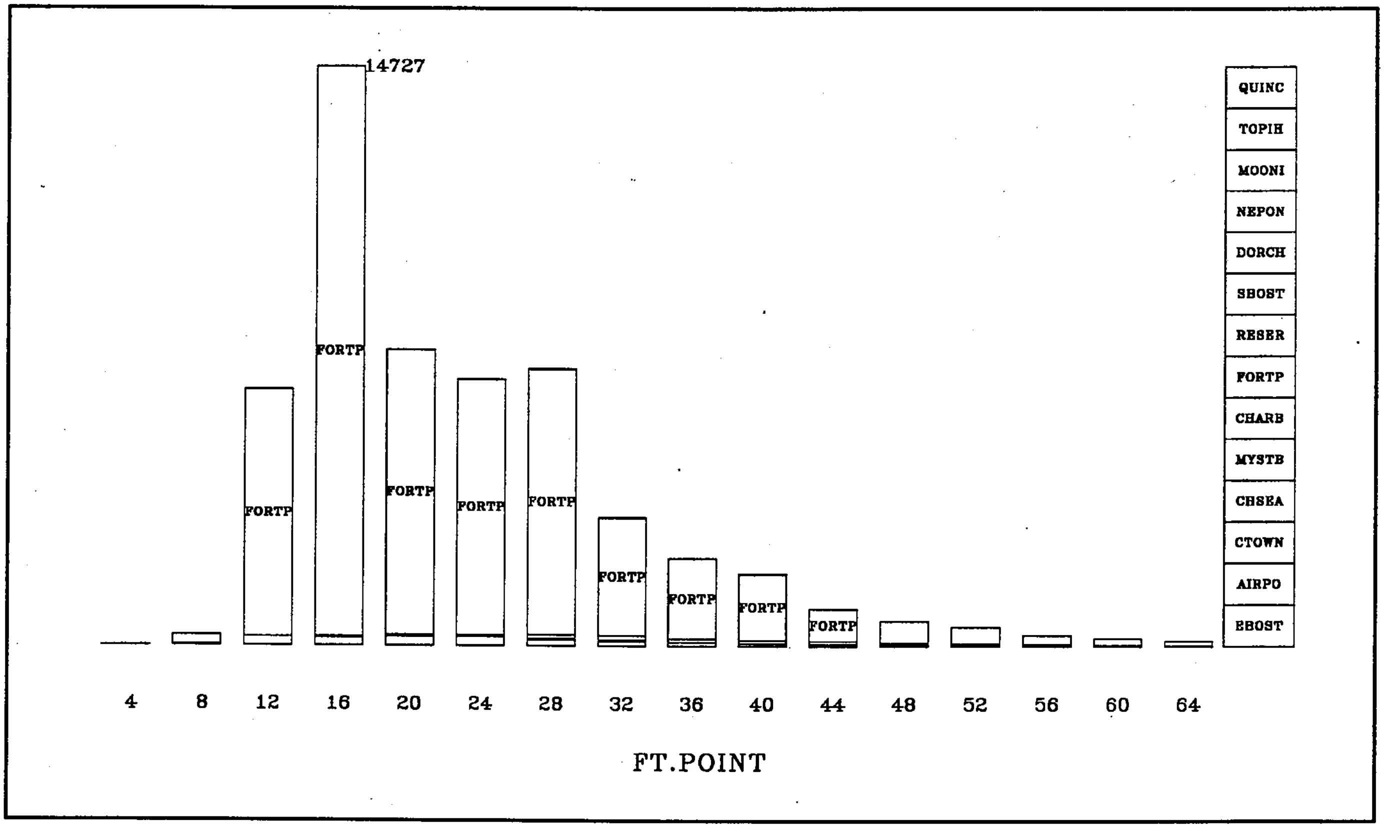


Figure 9. Relative impact of 14 aggregate sources on fecal coliform concentrations as a function of time step for one-year storm under future no-action conditions
a) Fort Point Channel mouth

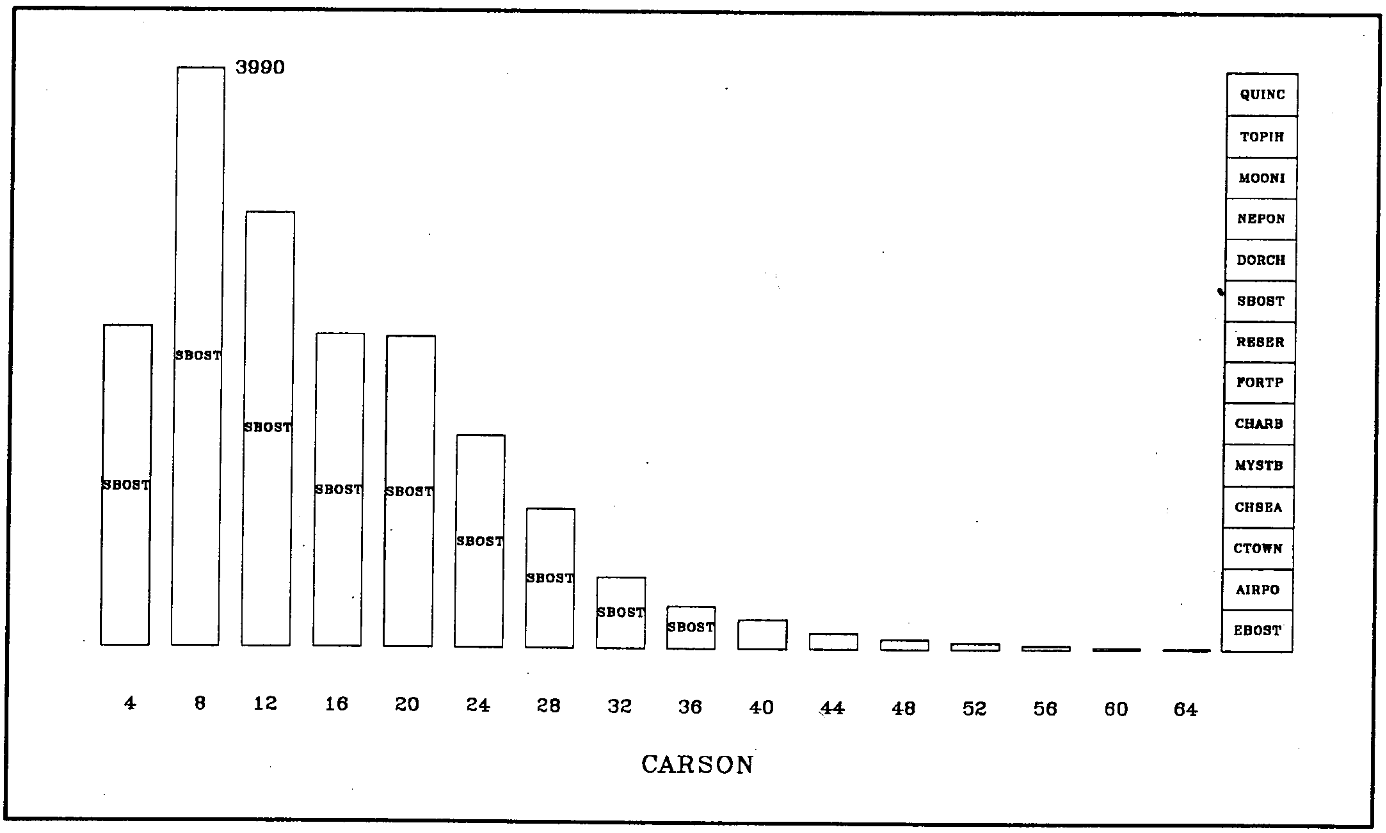


Figure 18d. Carson Beach

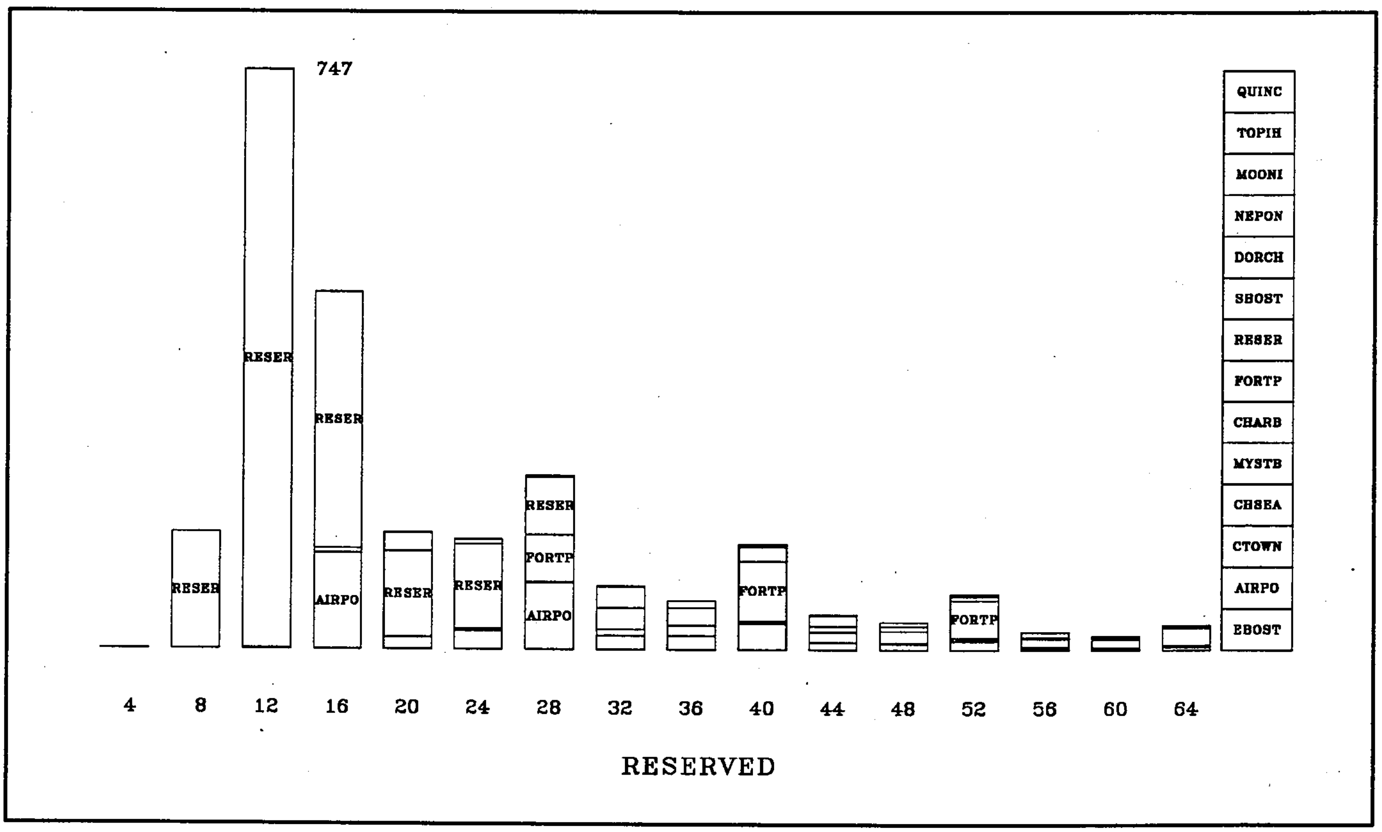


Figure 9b. Reserved Channel mouth

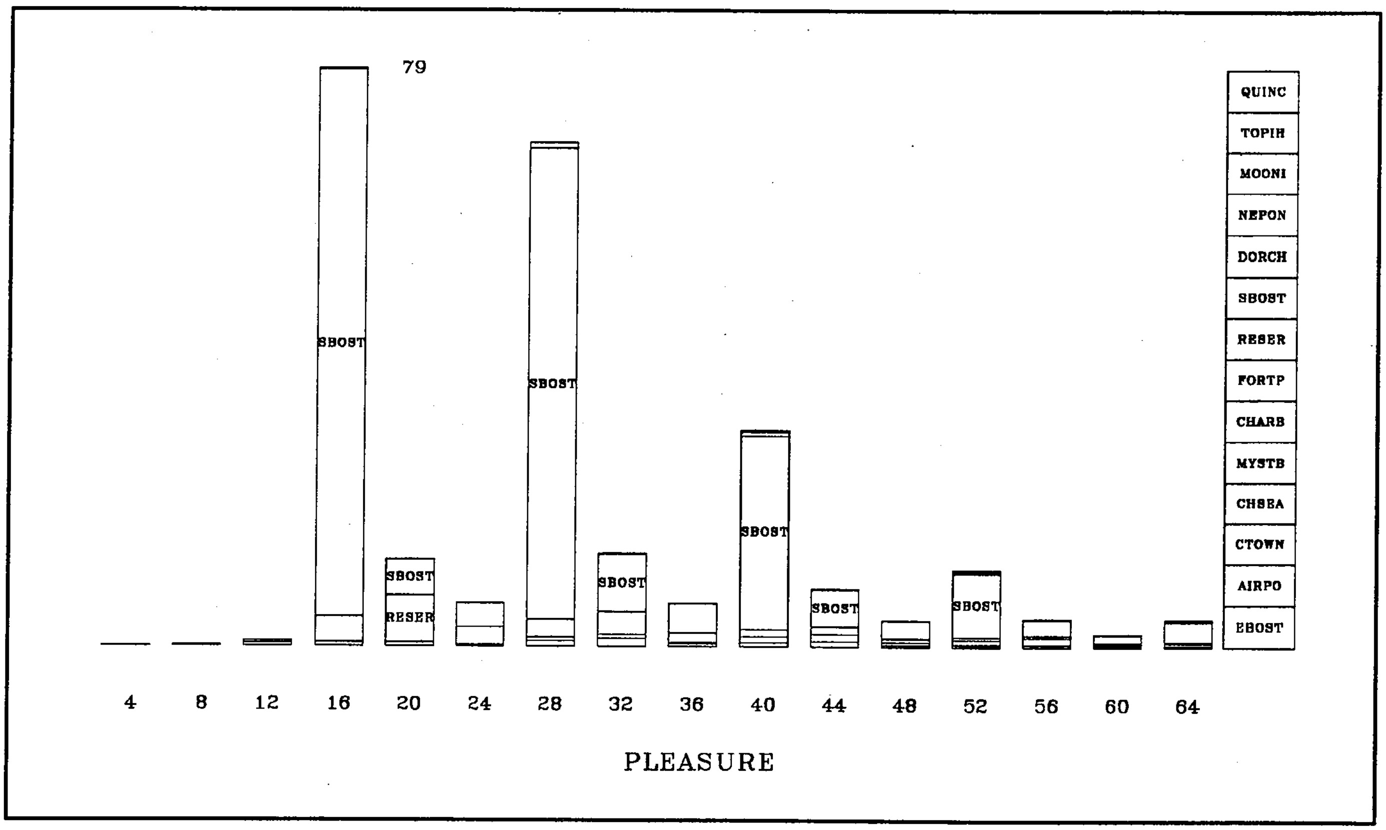


Figure 18c. Pleasure Bay

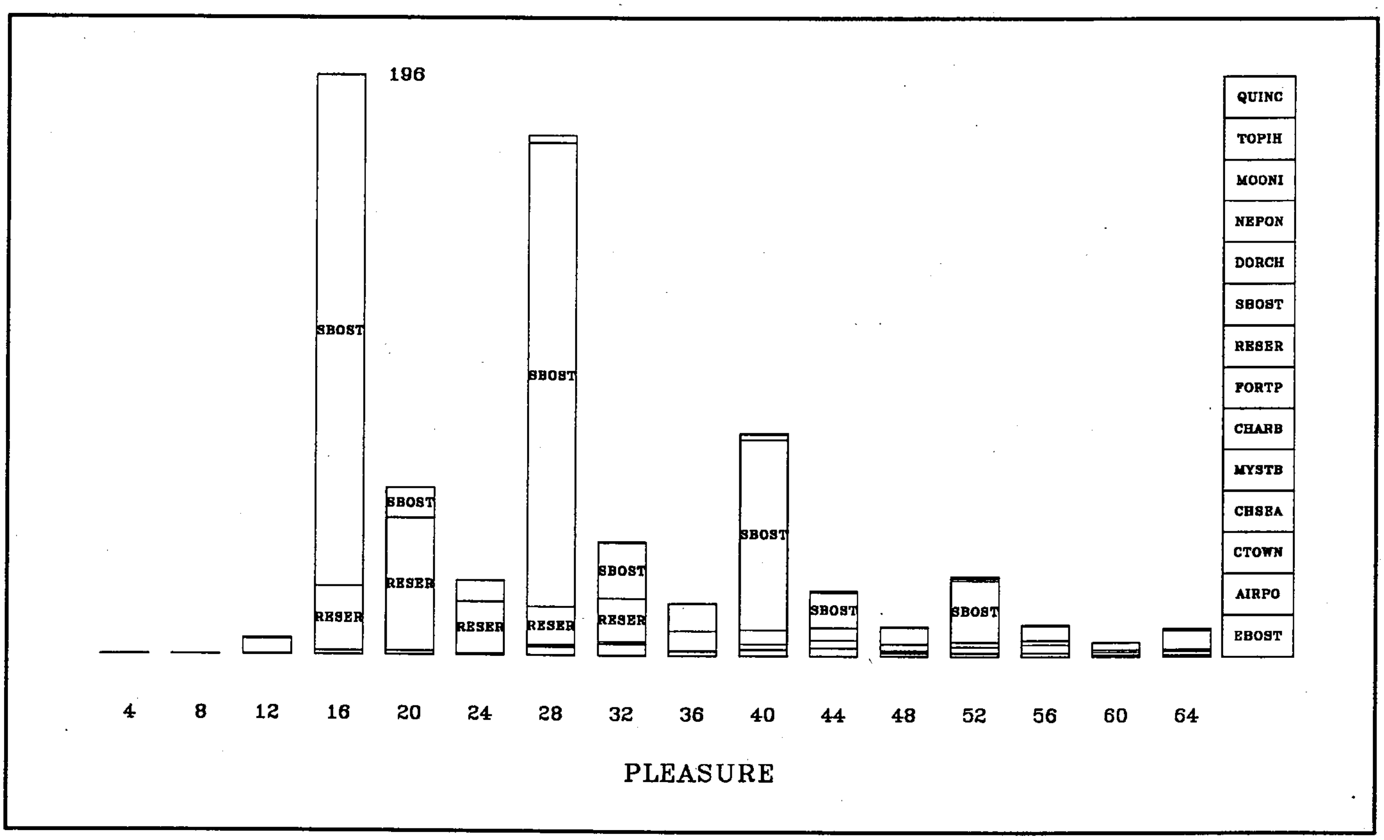


Figure 9c. Pleasure Bay

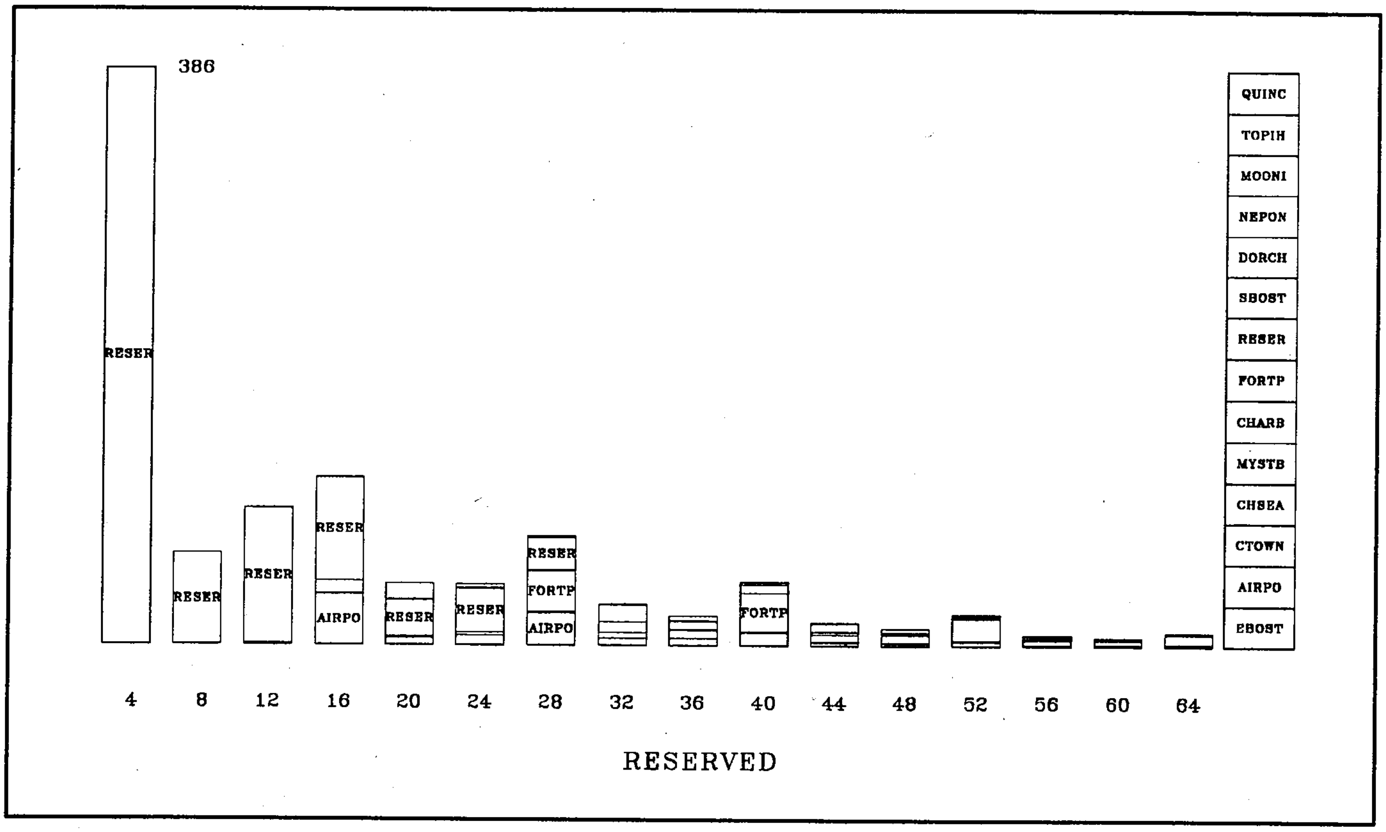


Figure 18b. Reserved Channel mouth

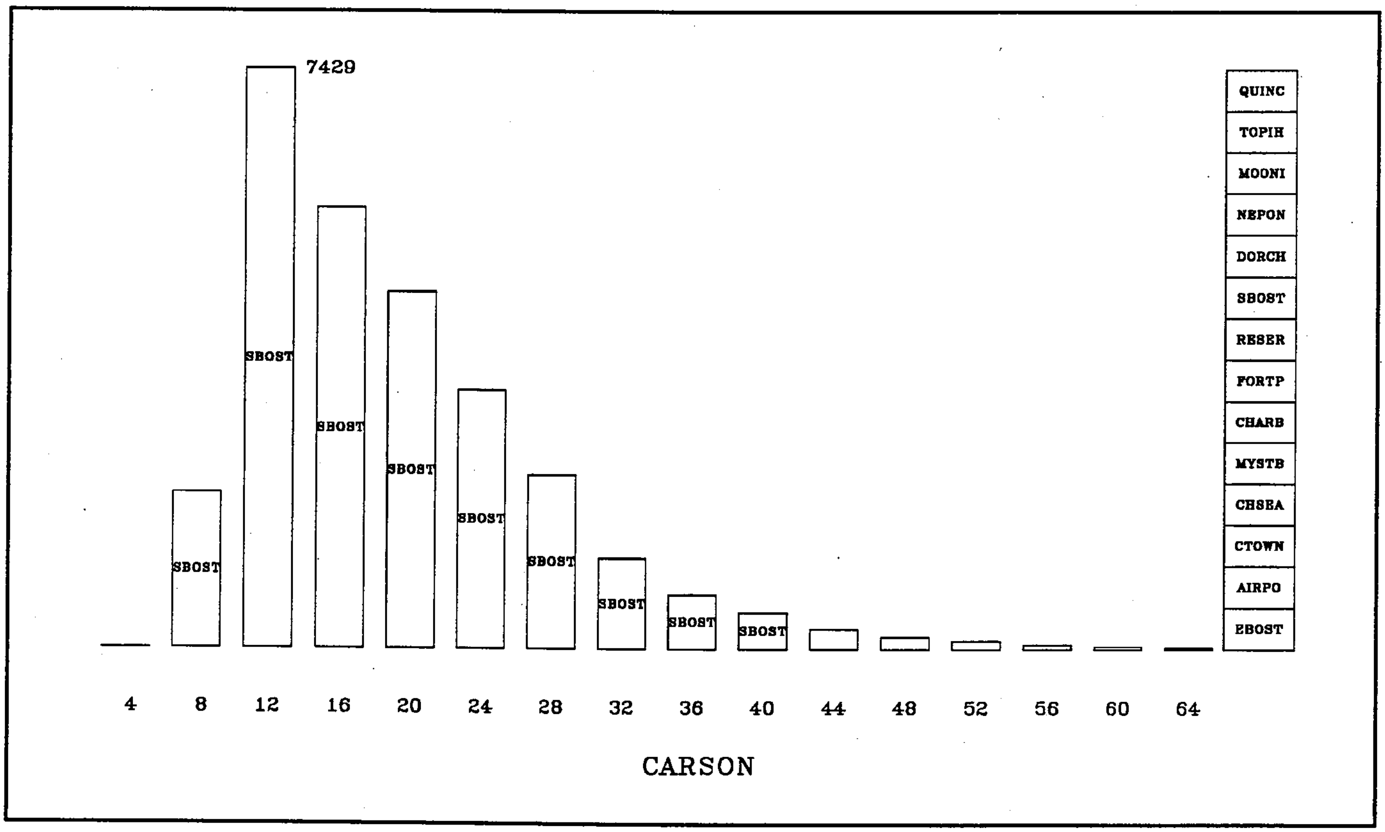


Figure 9d. Carson Beach

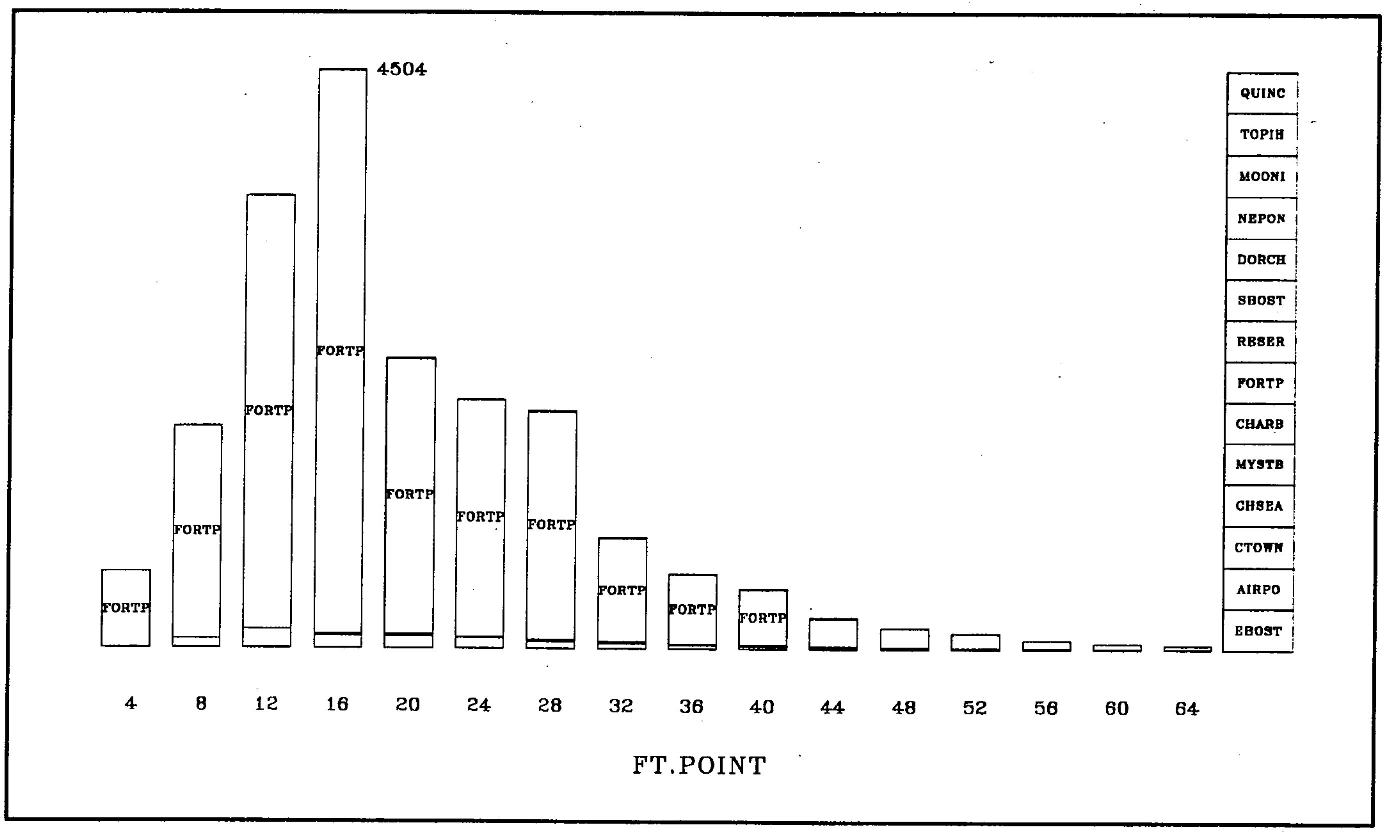


Figure 18. Relative impact of 14 aggregate sources on fecal coliform concentrations as a function of time step for 3-month storm under future no-action conditions.

a) Fort Point Channel mouth

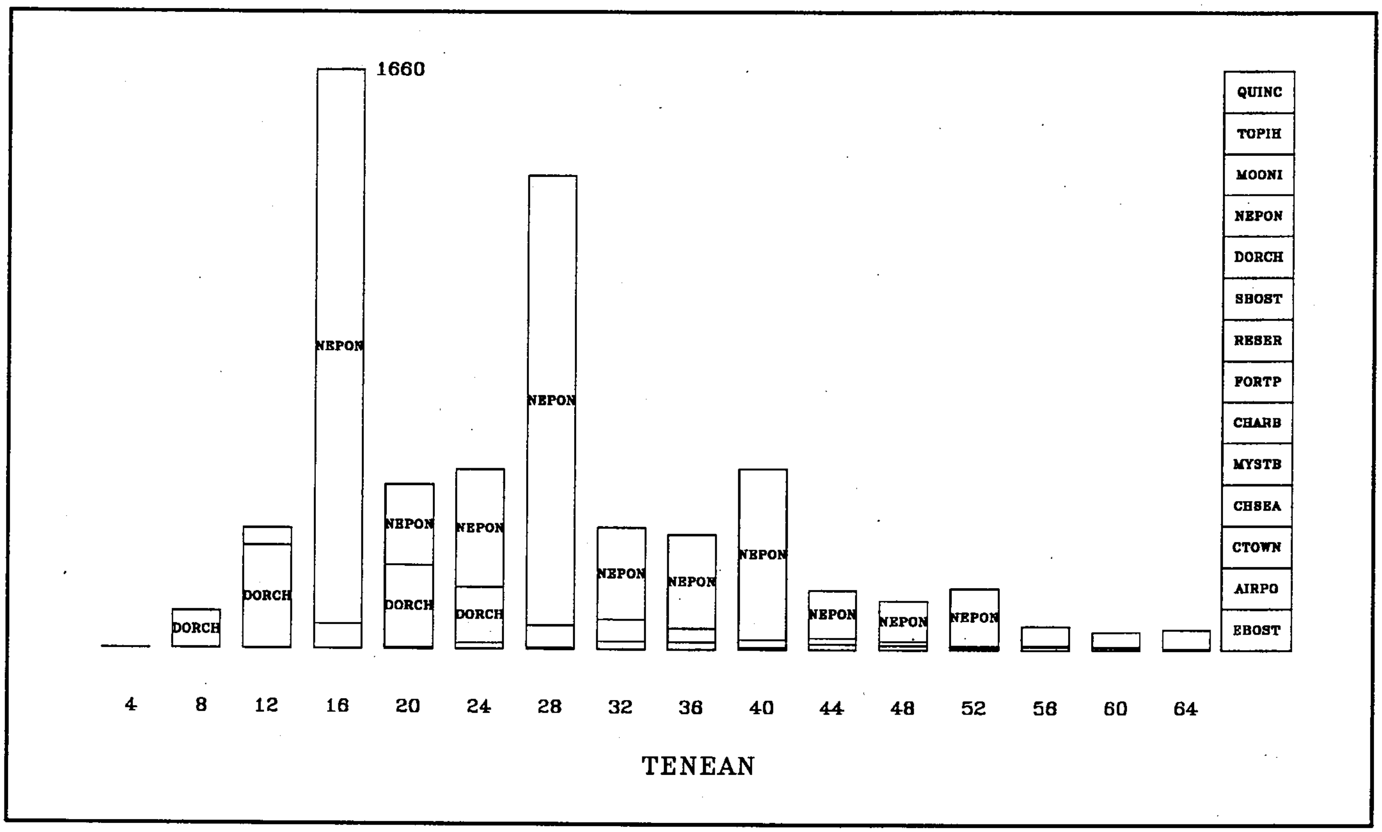


Figure 9e. Tenean Beach

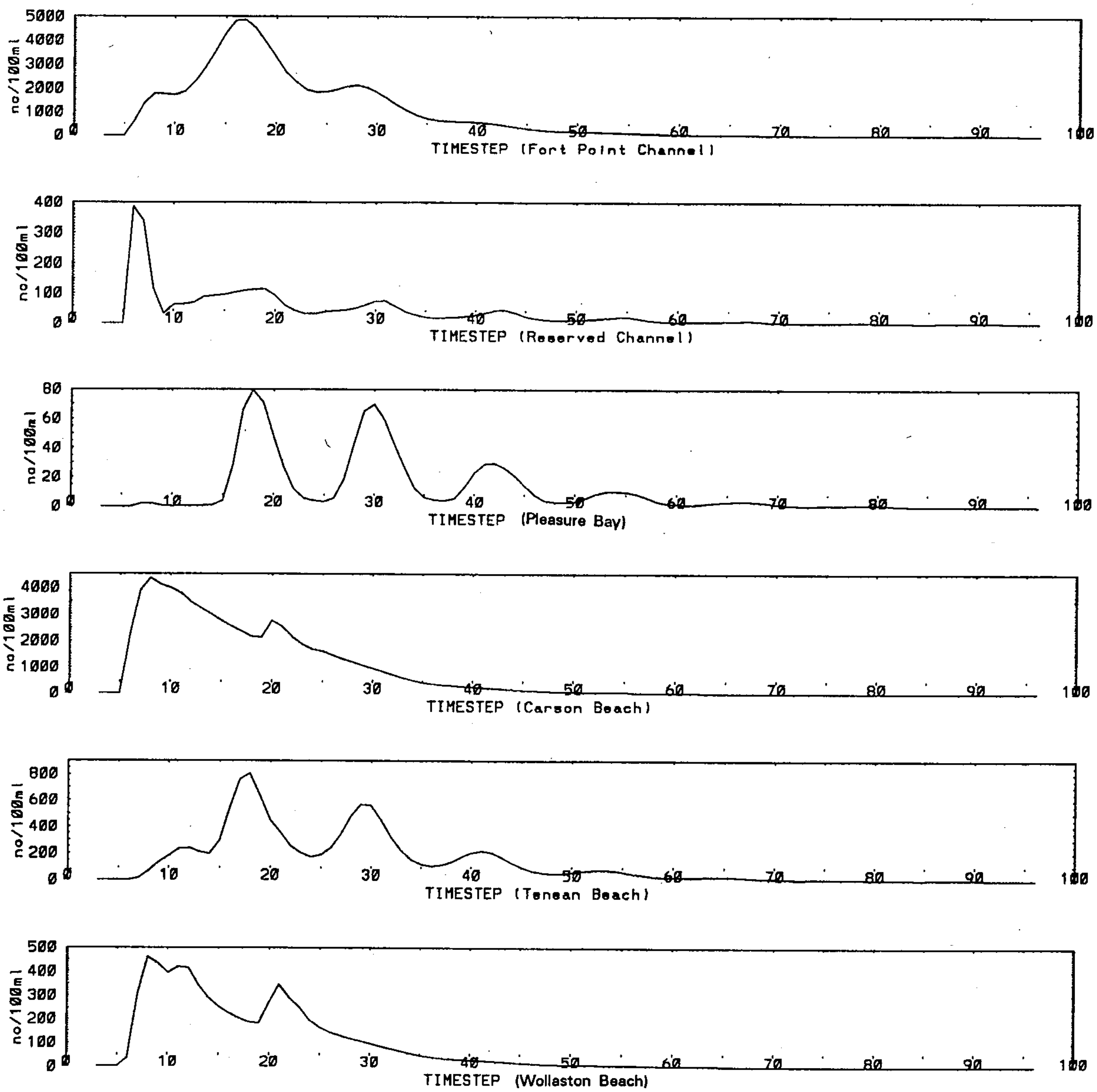


Figure 17. Simulated fecal coliform concentration versus time at six locations following 3-month storm under future no-action conditions. Time step equals 1.04 hours.

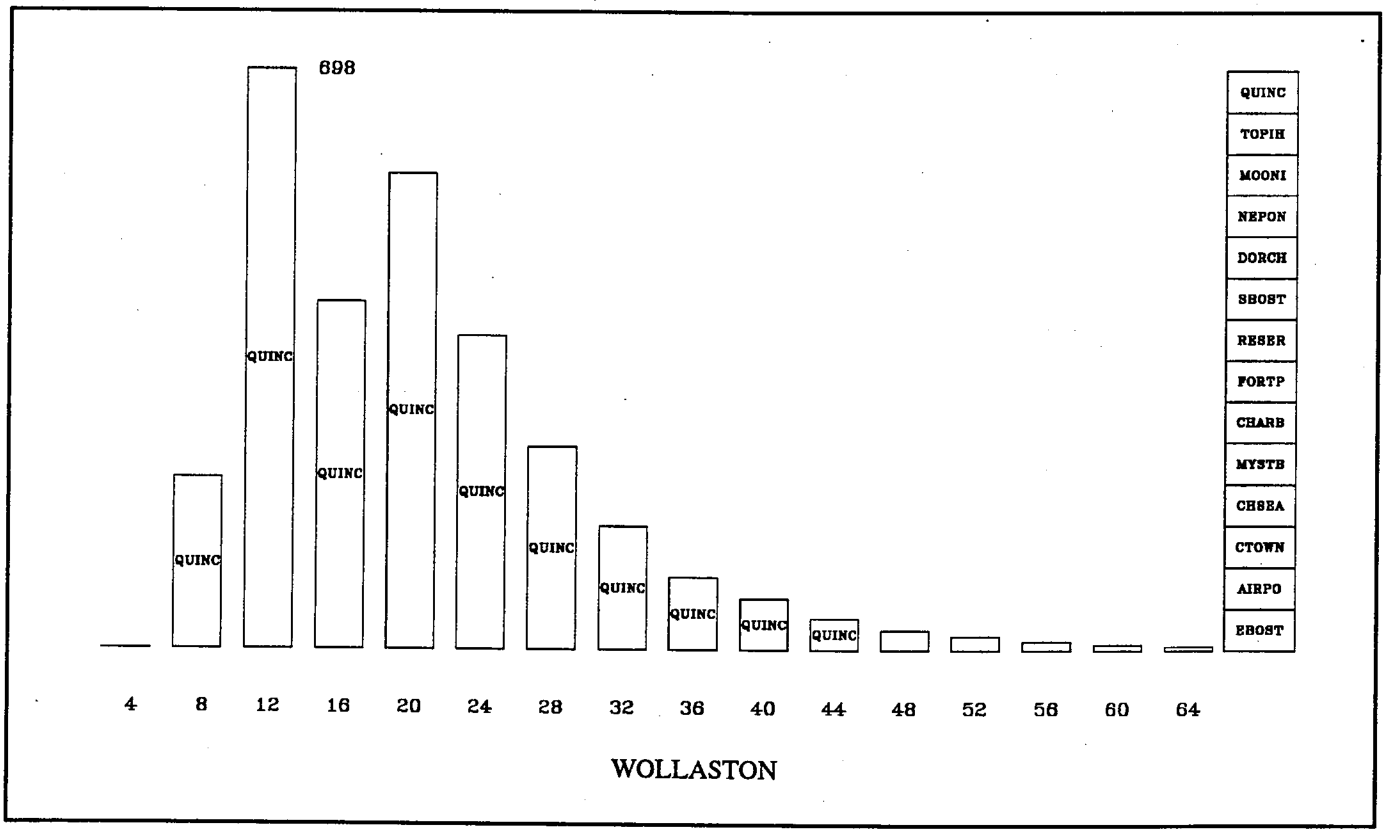


Figure 9f. Wollaston Beach

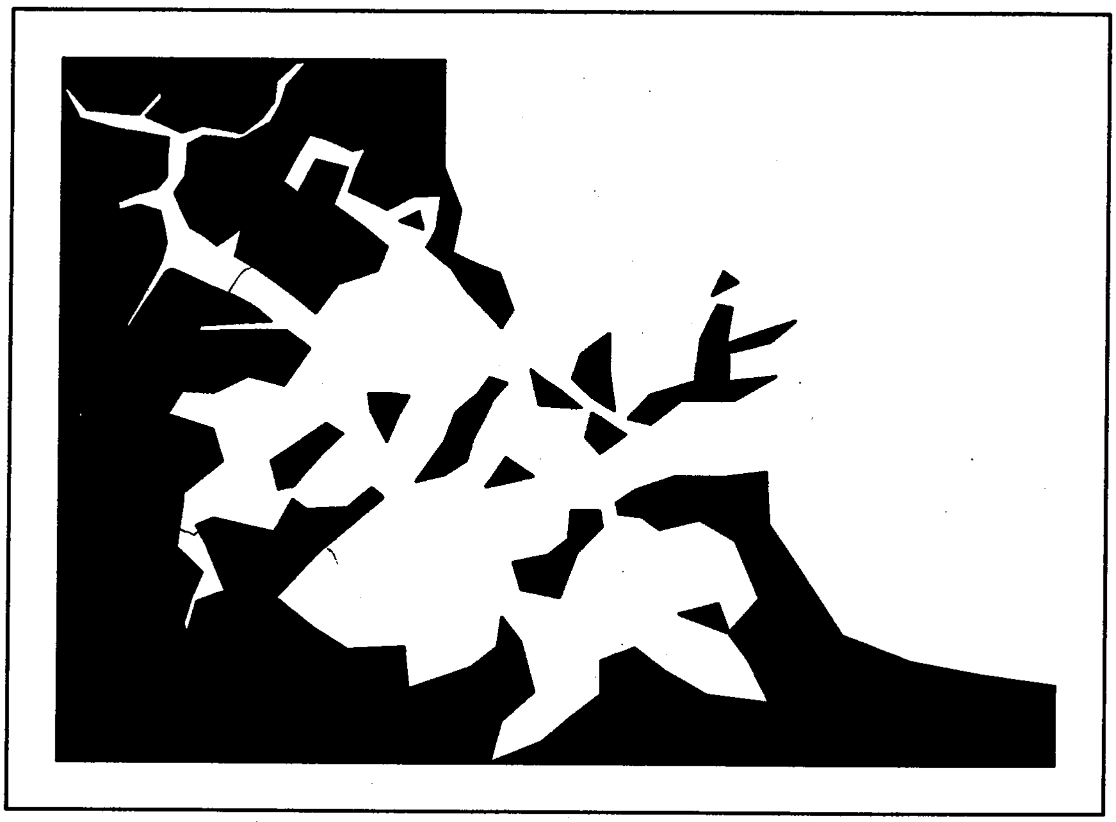


Figure 16d. Four days after storm

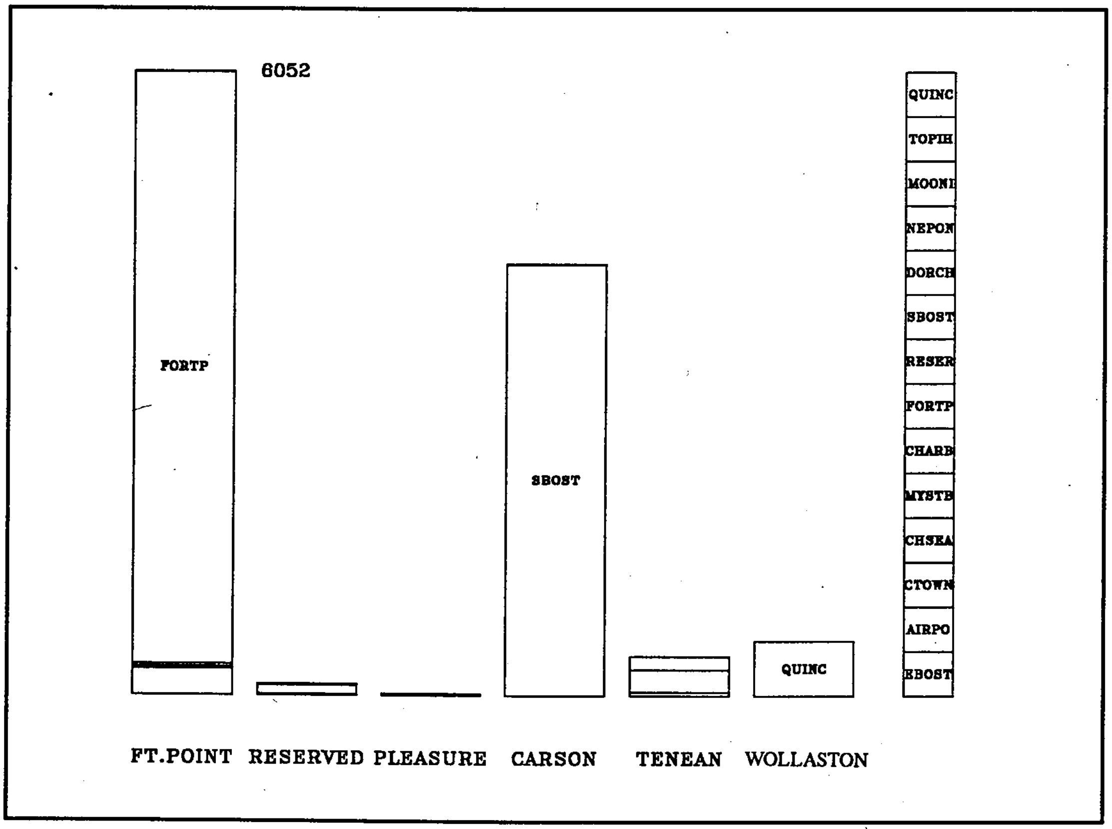


Figure 10. Summary of source impact at six locations following one-year storm under future no action conditions.
a) One day after storm

Figure 16c. Three days after storm

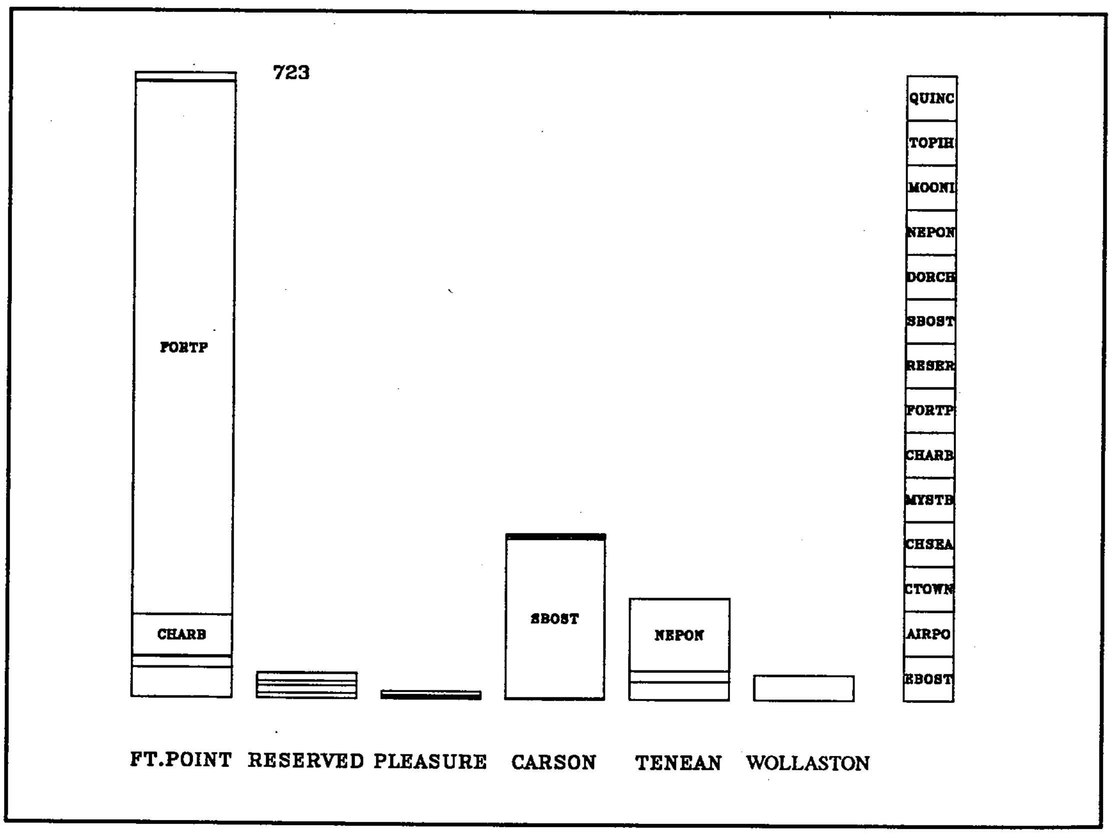


Figure 10b. Two days after storm

Figure 16b. Two days after storm

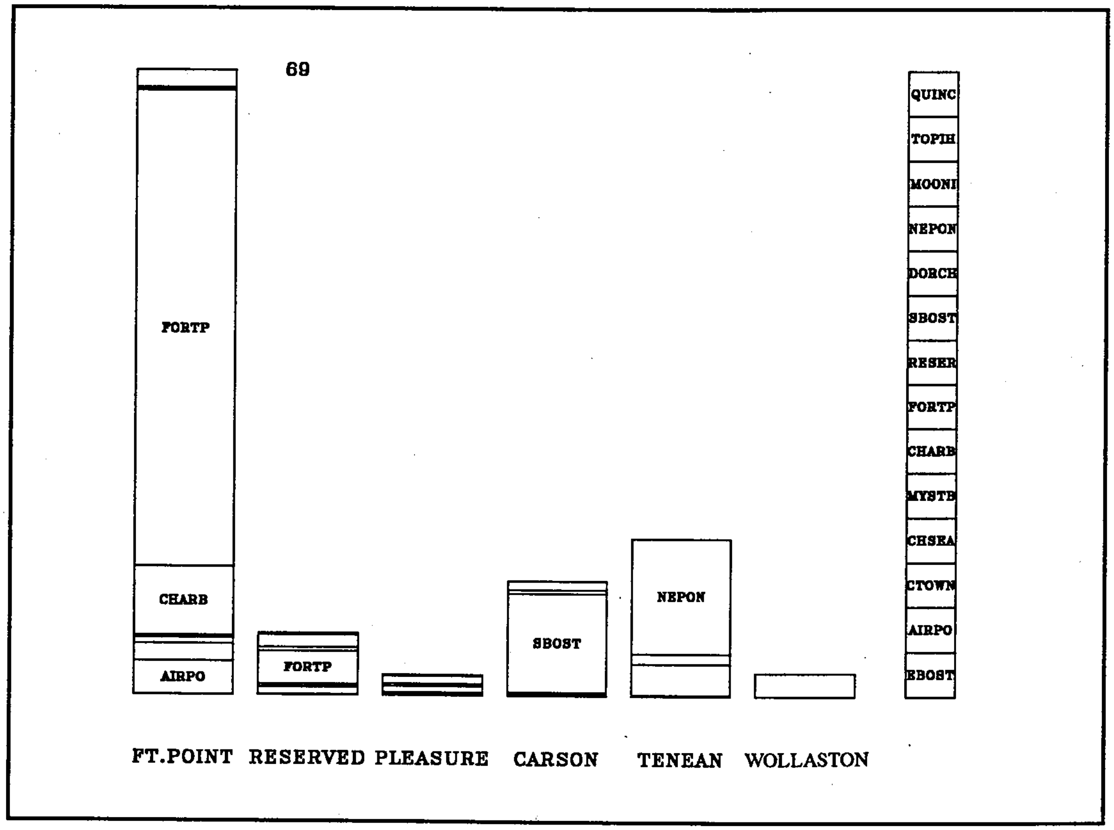


Figure 10c. Three days after storm

Figure 16a. Simulated depth-average fecal coliform concentration following 3-month storm under future no-action conditions. Contour intervals from offshore to inshore represent 1, 14, 200, and 1000 counts 100 ml.

a) one day after storm

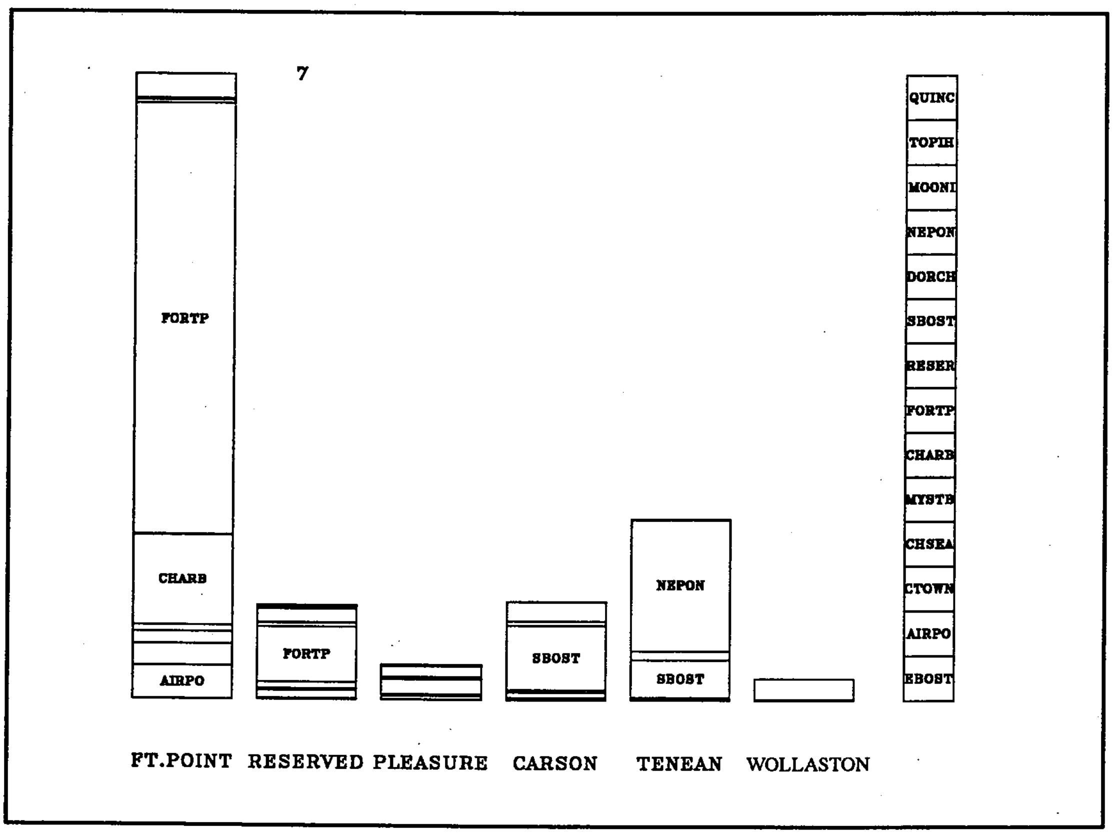


Figure 10d. Four days after storm

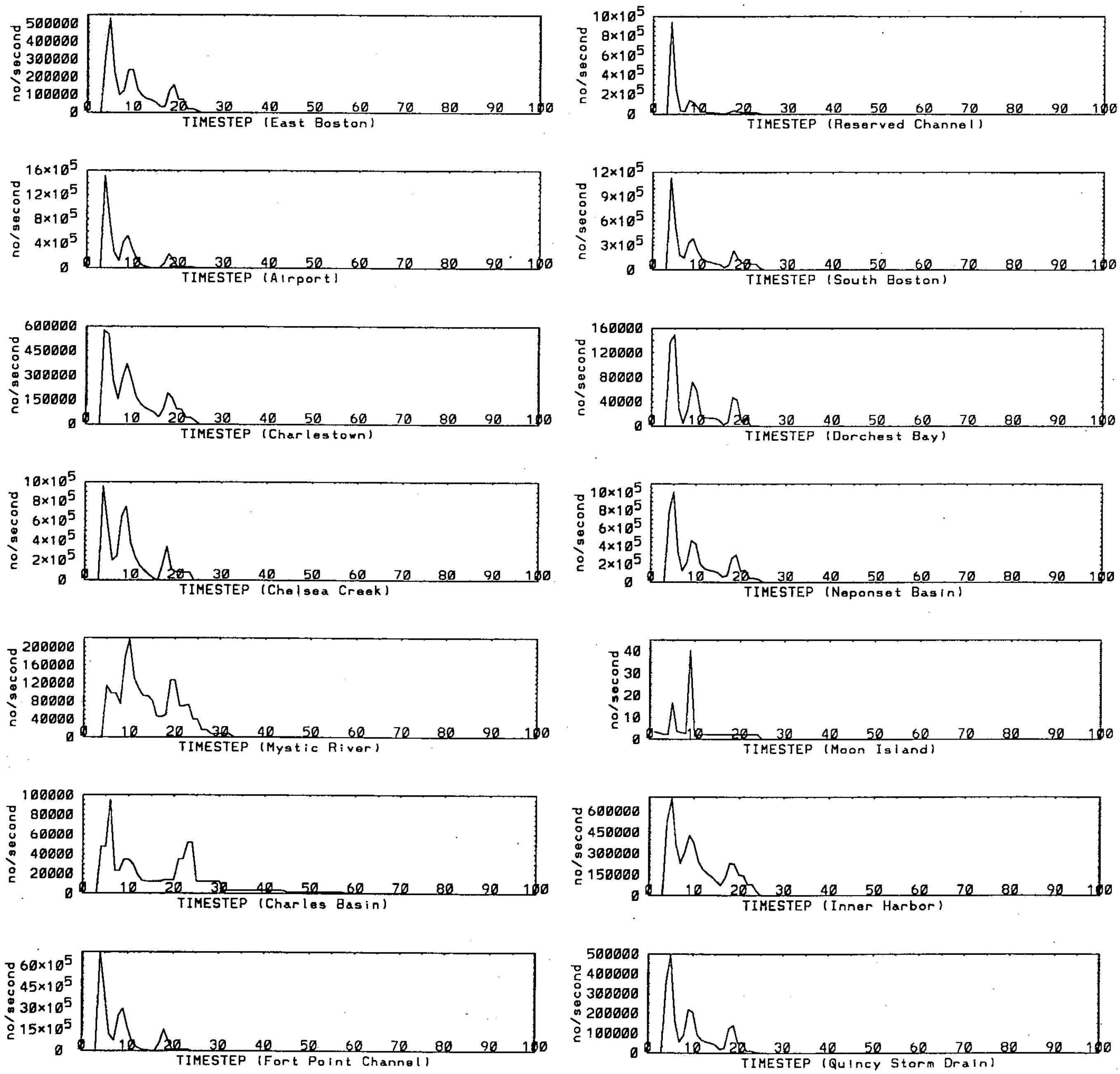


Figure 15. Time series of loading for each aggregate source (3-month storm; future no-action condition). Note that loadings have been divided by 10^4 in order to yield simulated concentrations in no/100 ml rather than no/m^3

Figure 11. Simulated depth-average fecal coliform concentrations following one-year storm using 1990 loading estimates. Coliform intervals from offshore to inshore represent 1, 14, 200, and 1000 counts/100 ml.
a) One day after storm

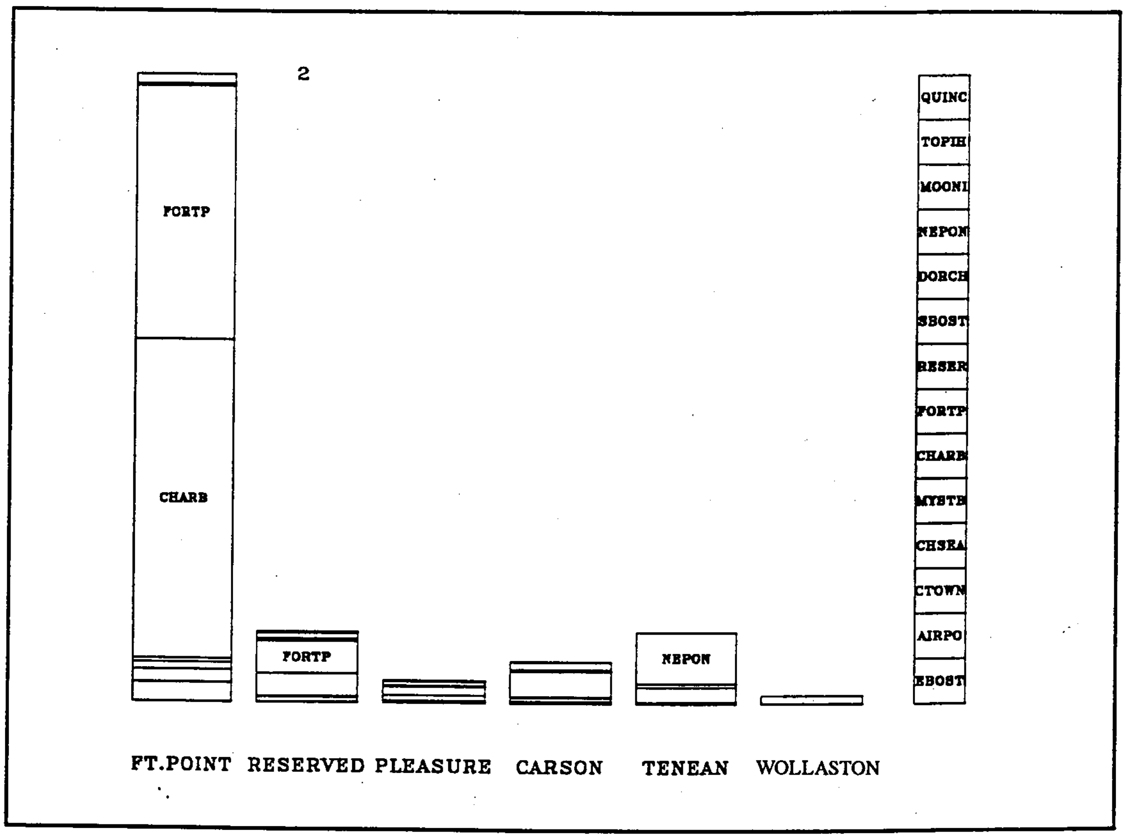


Figure 14d. Four days after storm

Figure 11b. Two days after storm

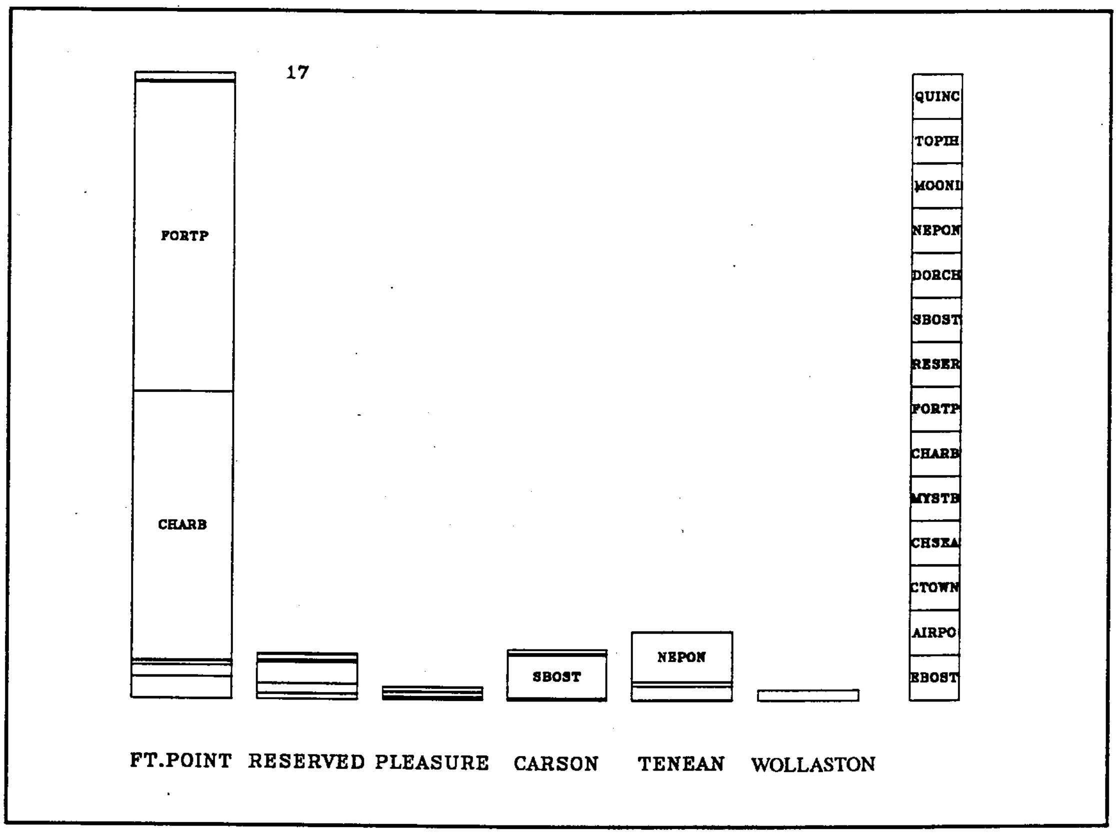


Figure 14c. Three days after storm

Figure 11c. Three days after storm

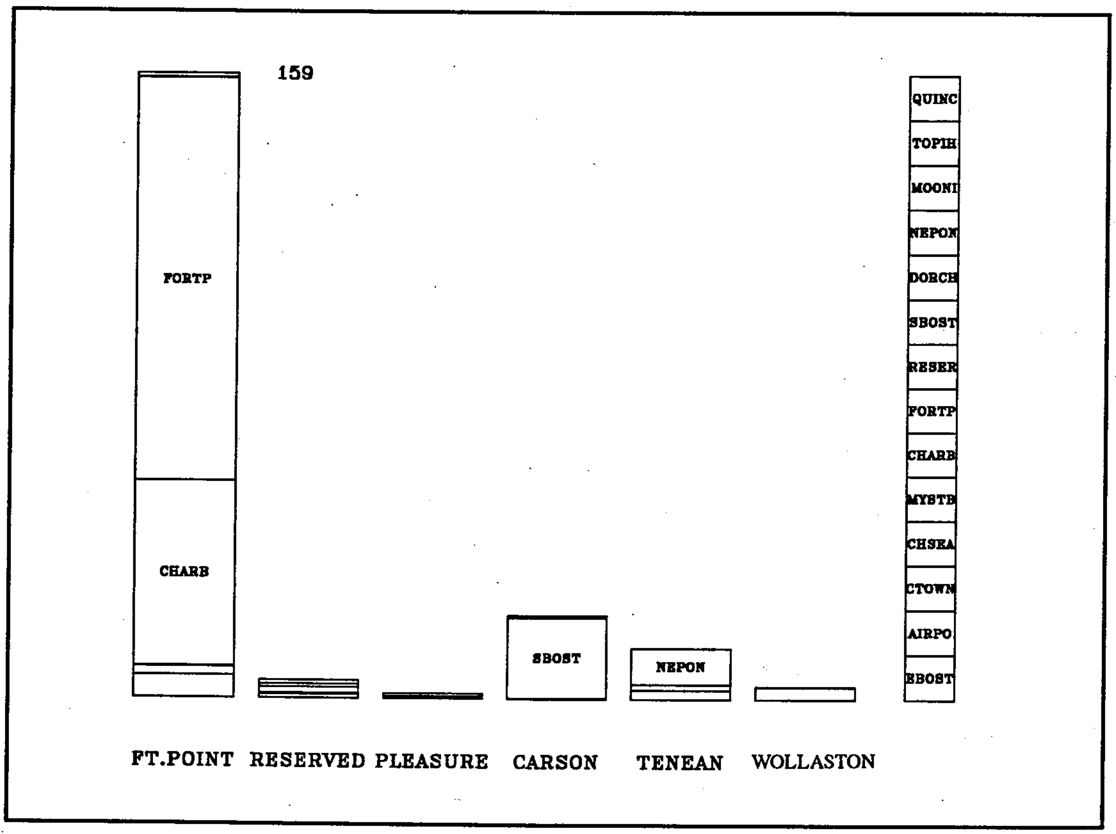


Figure 14b. Two days after storm

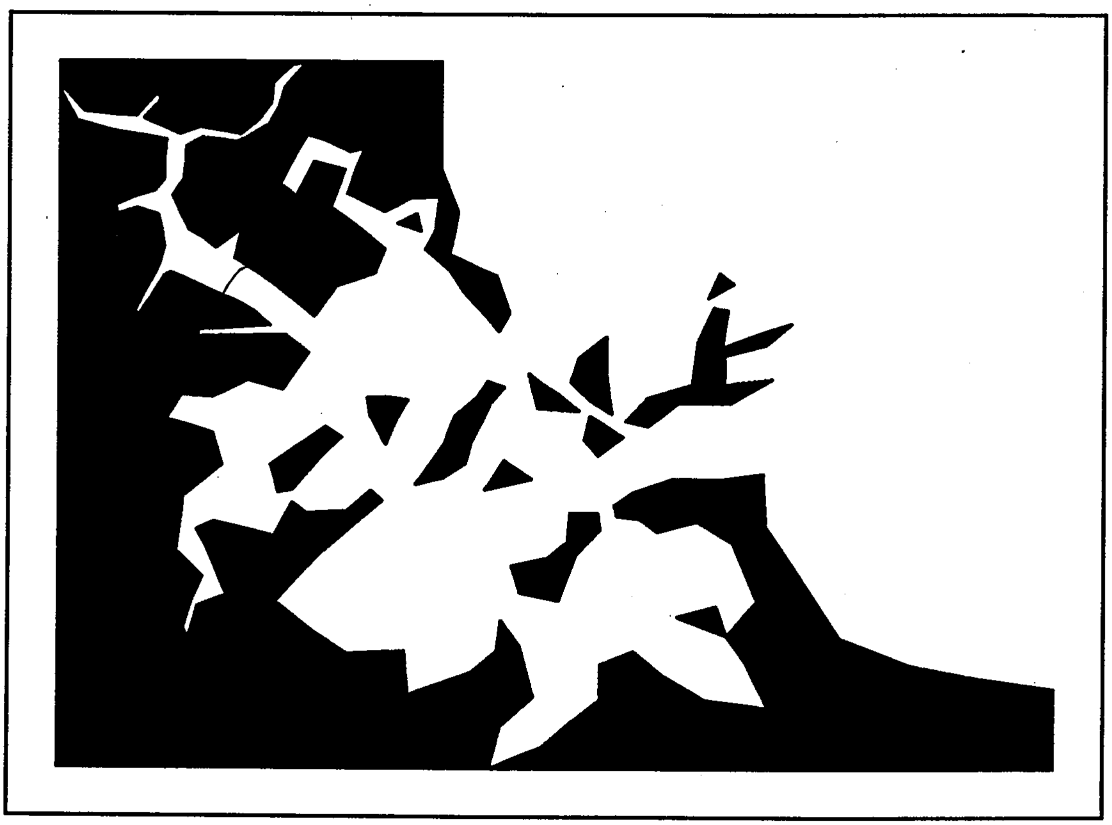


Figure 11d. Four days after storm

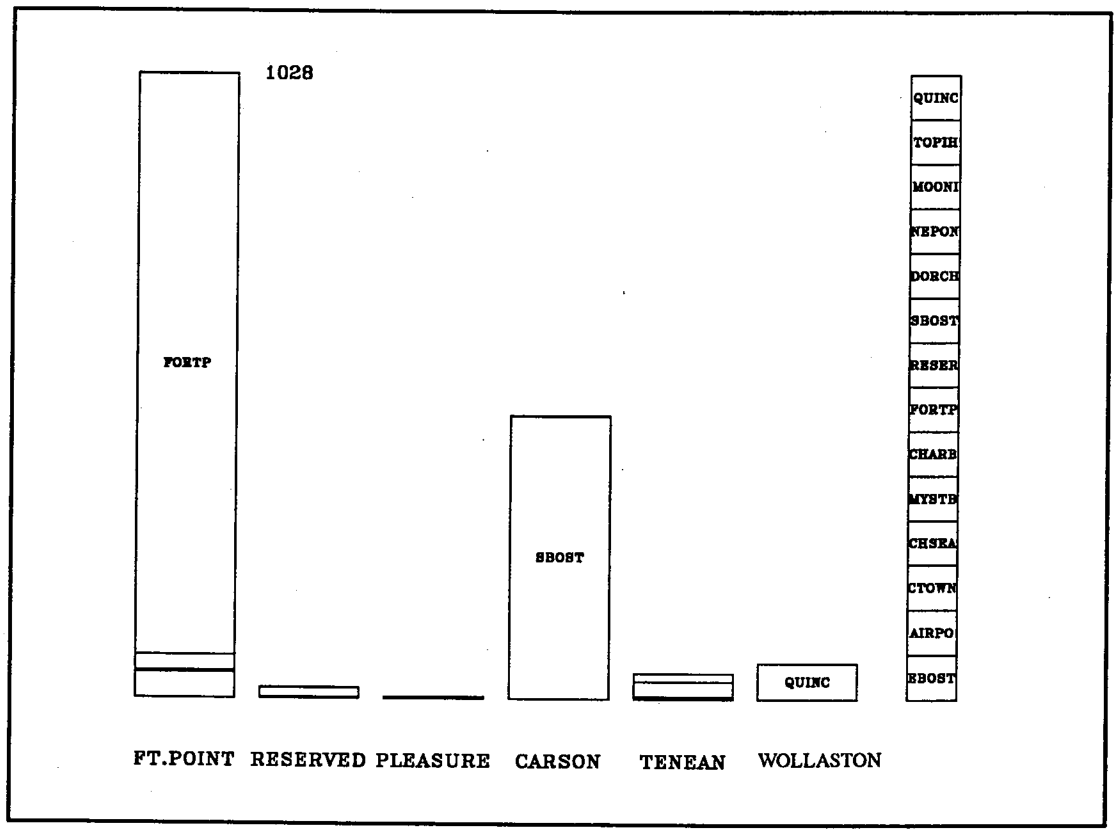


Figure 14. Summary of source impact at six locations following one-year storm assuming 1990 loading estimates
a) One day after storm

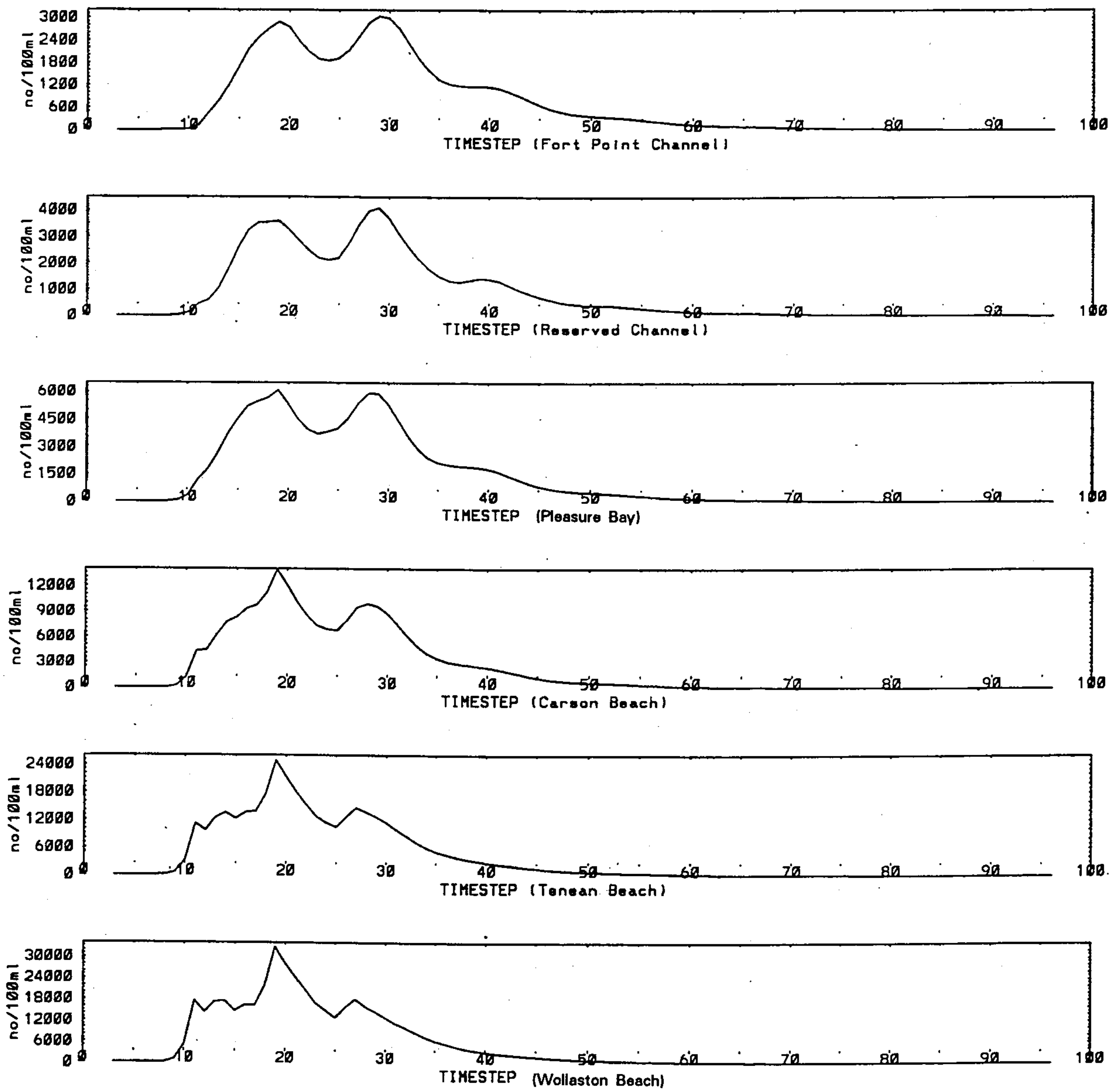


Figure 12. Simulated fecal coliform concentrations versus time at six locations following one-year storm assuming 1990 loading estimates. Time step equals 1.04 hours.

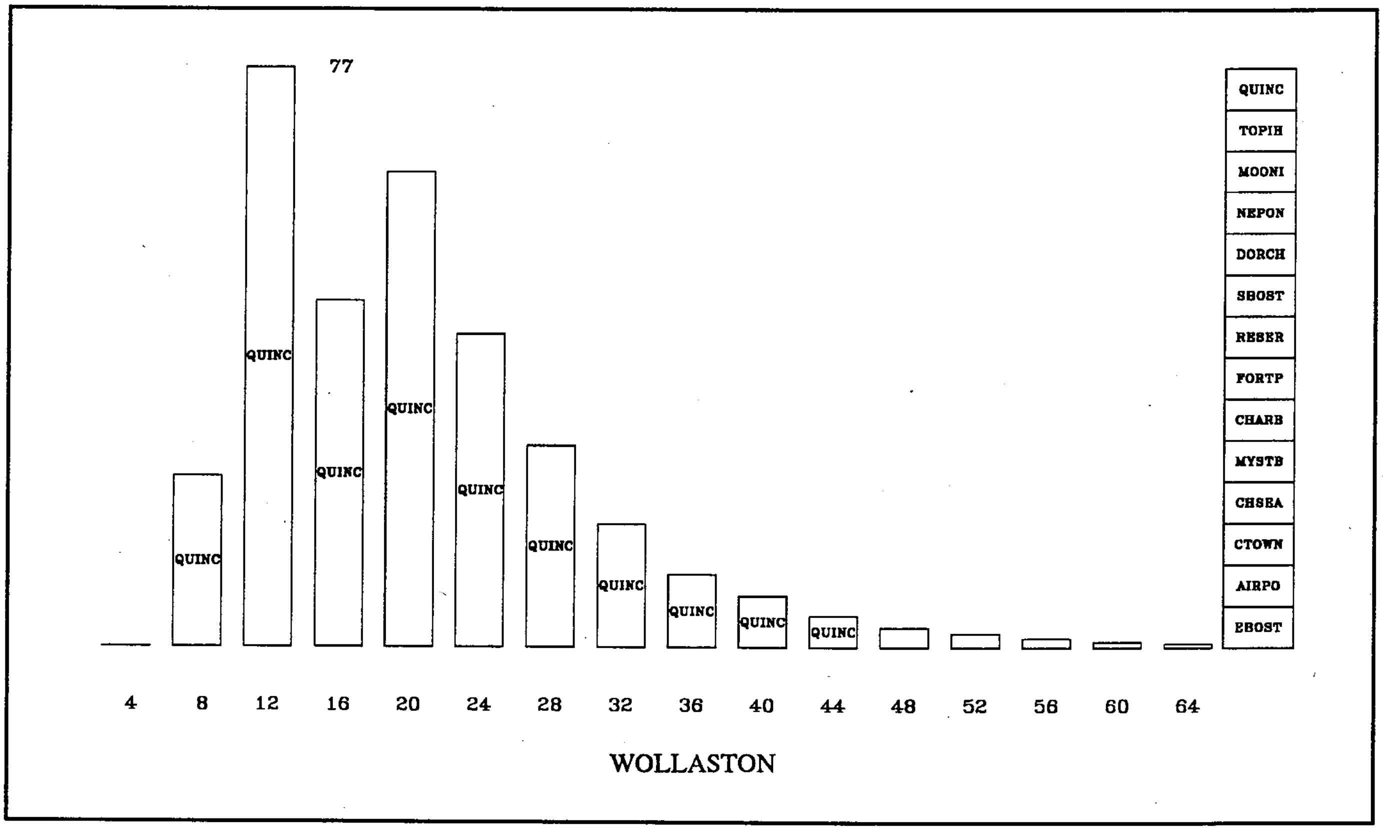


Figure 13f. Wollaston Beach

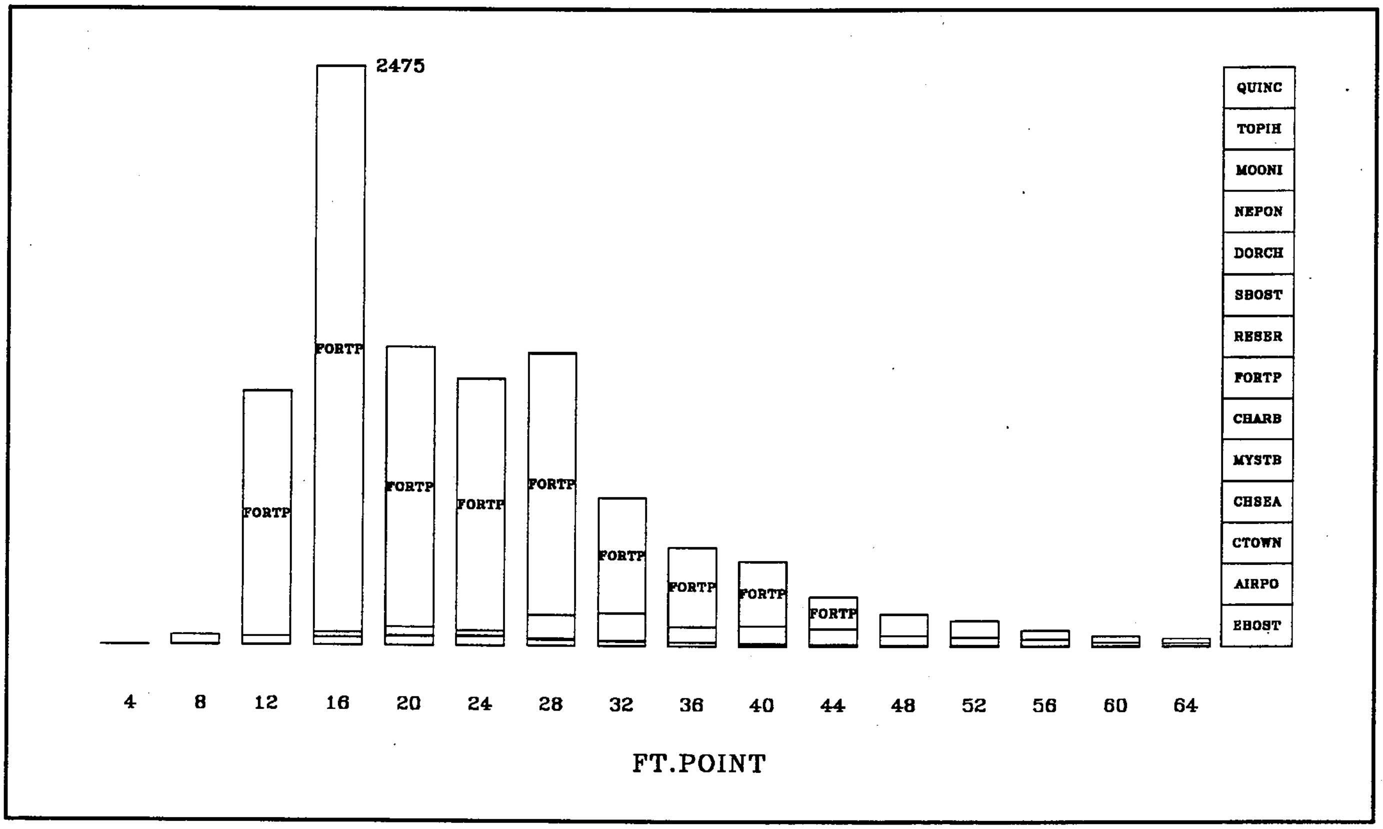


Figure 13. Relative impact of 14 aggregate sources on fecal coliform concentrations as a function of time step for one-year storm assuming 1990 loading estimates.
a) Fort Point Channel mouth

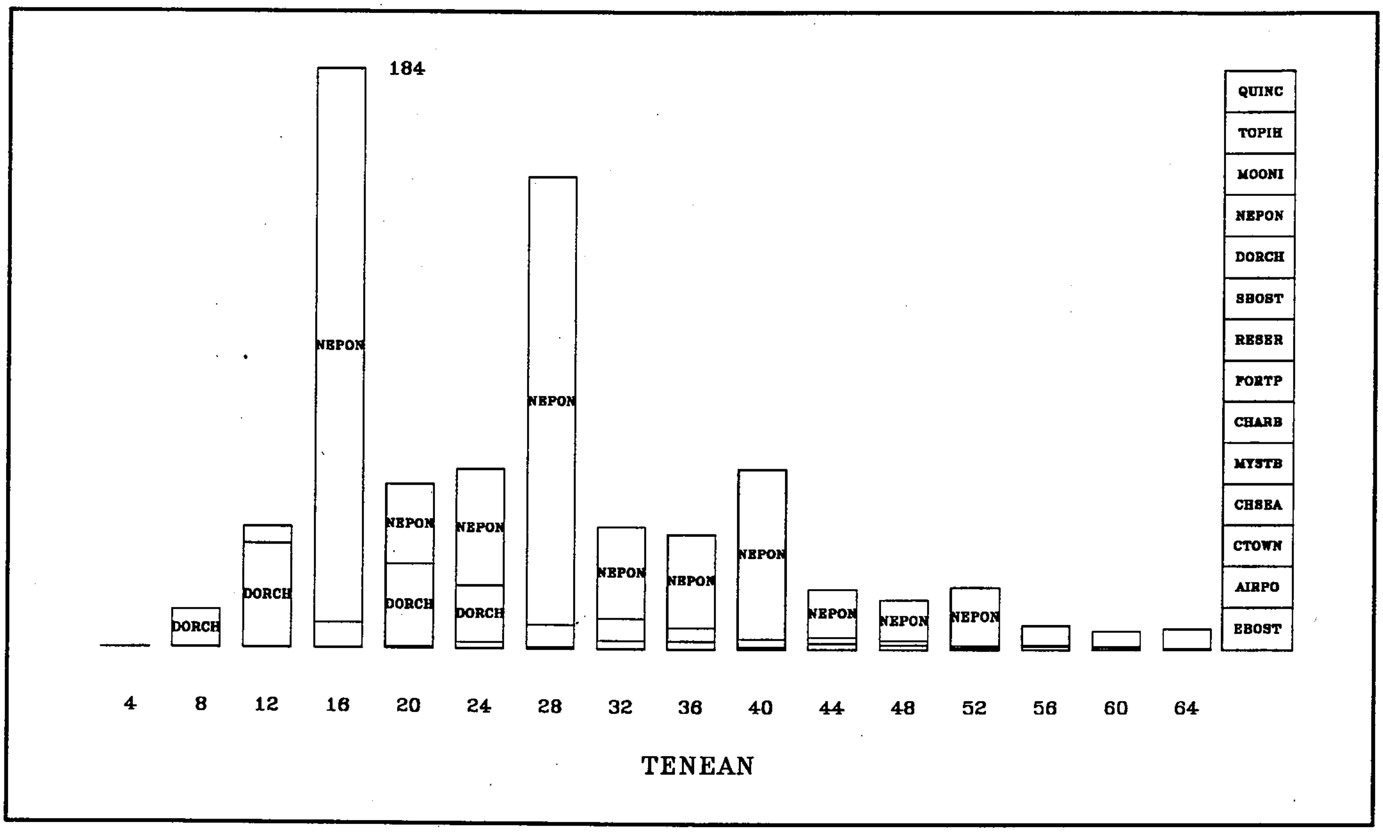


Figure 13e. Tenean Beach

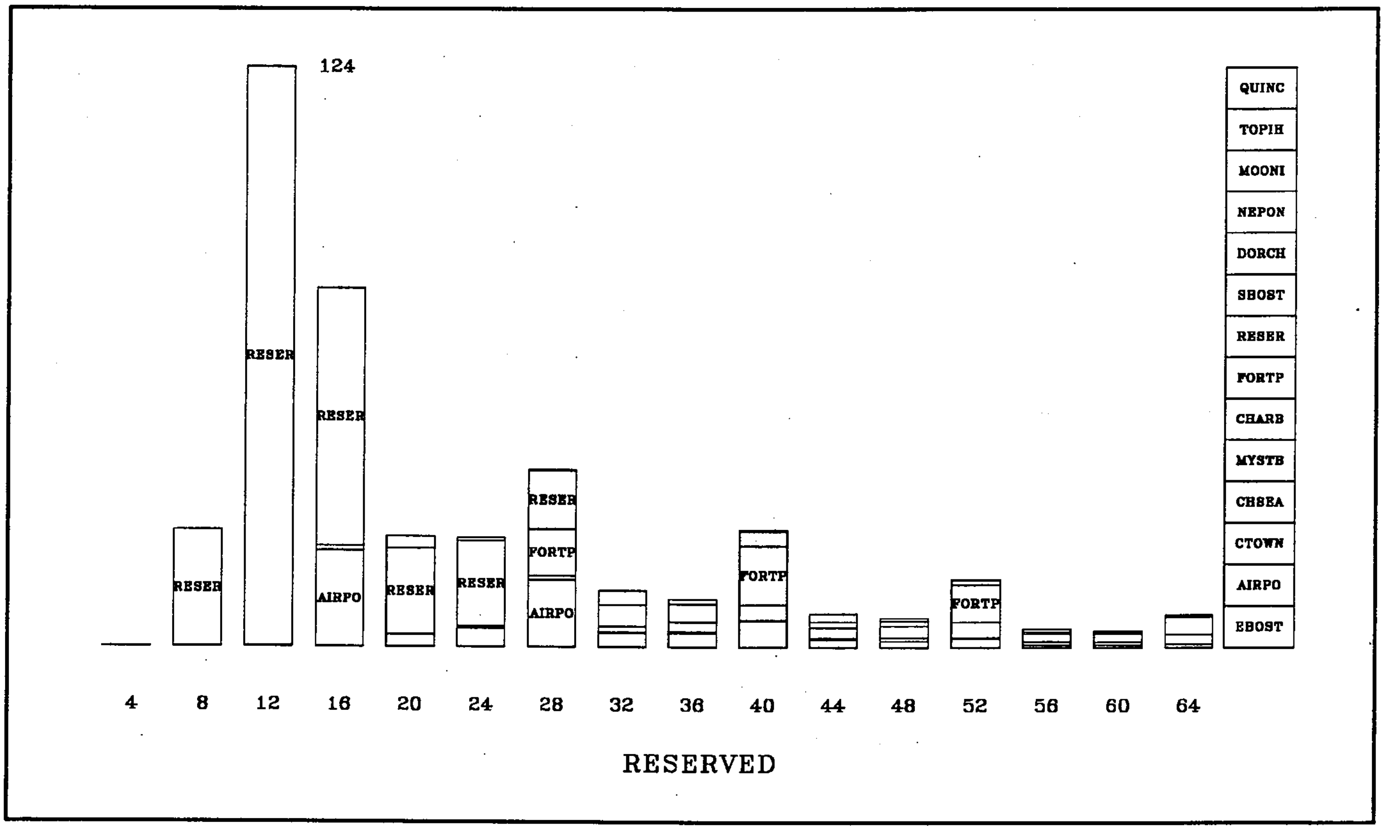


Figure 13b. Reserved Channel mouth

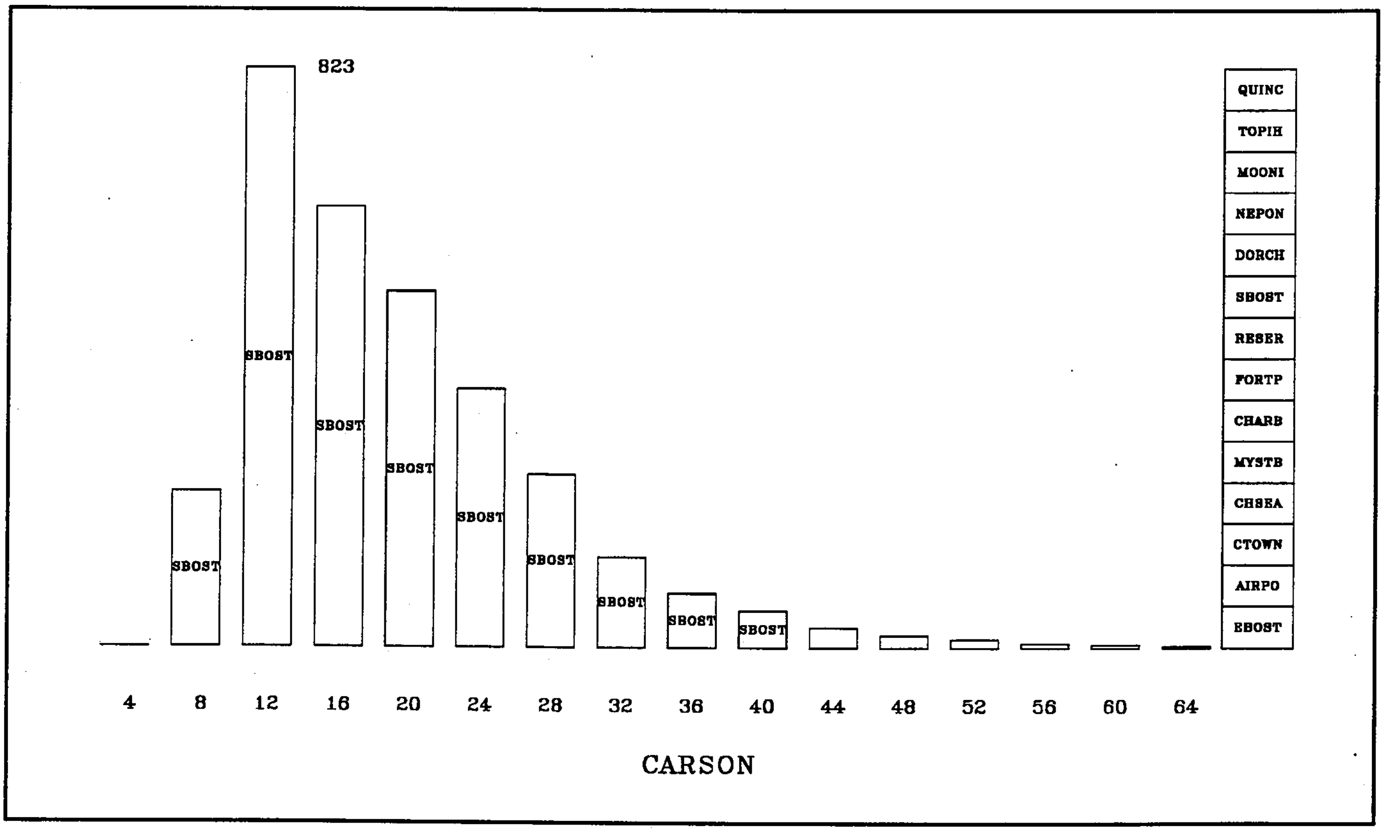


Figure 13d. Carson Beach

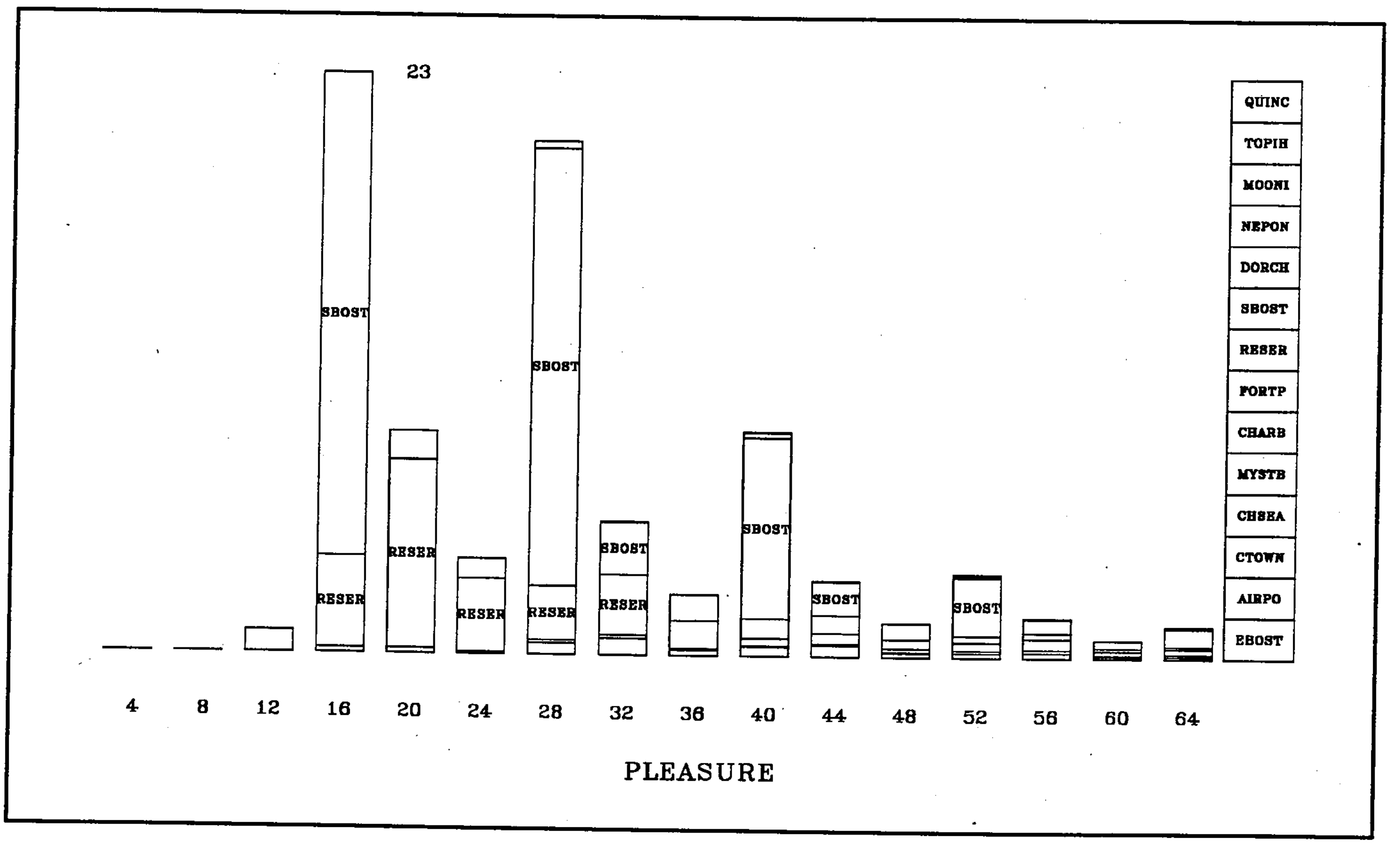


Figure 13c. Pleasure Bay