REPORT

OVERVIEW OF THE NEW BEDFORD HARBOR PHYSICAL/CHEMICAL MODELING PROGRAM

Prepared for

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This document provides a concise summary of the New Bedford Harbor physical and chemical modeling program. The purpose of the document is to make the results contained in the full report more accessible and to provide an expanded discussion of the uncertainties in the model results. However, the reader is referred to the final modeling program report for a complete description of the model and results. The topics discussed include the physical characteristics of New Bedford Harbor system, a description of the numerical model, the calibration of the model, key model results, and uncertainties associated with the modeling effort. The document concludes with recommendations on how the model results should be used.

I. PHYSICAL SETTING

New Bedford Harbor, located on the north shore of Buzzards Bay, is a small urban estuary composed of the drowned, smooth-floored valley of the Acushnet River, trending north-northwest-south-southeast, and emptying into Buzzards Bay, with New Bedford on the west and Fairhaven on the east. It can be divided into two main basins; the outer Harbor and the inner Harbor. The outer Harbor extends south from the hurricane barrier to a line connecting Round Hill Point on the west and Wilbur Point on the east, that line being the boundary between the Harbor and Buzzards Bay. The outer Harbor is relatively shallow, with several natural 9-m channels and a dredged 9-m channel, connecting the inner Harbor with Buzzards Bay.

The inner Harbor, that part of the Acushnet River estuary north of the hurricane barrier to the Wood Street Bridge, is approximately 6.4 km long. Tidal flow in the inner Harbor is severely restricted by three structures: the Coggeshall Street Bridge; the Interstate 195 Bridge, about 100 m downstream of the Coggeshall Street Bridge; and the hurricane barrier. The Coggeshall Street Bridge has a maximum opening width of approximately 33.5 m and a depth of 5.8 m. The hurricane barrier constricts the entrance to the inner Harbor to a width of 45.7 m and a depth of 8.5 m. North of Popes Island, which is about two-thirds of the distance from the Wood Street Bridge to the hurricane barrier, the water depth decreases to 7 m and continues to decrease to 4.6 m near the Coggeshall Street Bridge. The estuary north of the Coggeshall Street Bridge is shallow and non-navigable.

The New Bedford area is characterized by frequent but short periods of heavy precipitation, distributed uniformly throughout the year and averaging about 114 cm annually. Winds at New Bedford

predominate from the northwest in winter and southwest in summer, with the highest average wind speeds in March and April, and the lowest averages in August, although the fastest gusts are usually recorded in August. Severe weather conditions at New Bedford can result from short-duration thunderstorms from May through August, coastal storms which generally occur from late fall into spring, and hurricanes in the summer and fall. October through April is generally regarded as the stormy season for Buzzards Bay, storm events occurring once or twice a month through that period. Freshwater inflow into the Harbor is small, the only major source being the Acushnet River. The mean annual discharge of the Acushnet River is estimated to be about 0.85 m^3/s, and average runoff is about 0.79 m^3/s.

Tides in New Bedford are semidiurnal, two high waters and two low waters occurring each lunar day. The Wood Street Bridge is the approximate upstream limit of tidal influence. Maximum flood/ebb currents occur approximately 3 h before high/low water. There is little tidal damping or phase shift between the lower and upper Harbor and Buzzards Bay. In the outer Harbor, currents are generally less than 0.50 m/s. In the inner Harbor, they vary considerably because of the constrictions. At the hurricane barrier, they have been estimated at about 1.2 m/s. At the Coggeshall Street Bridge, they were measured at about 1.8 m/s maximum ebb and 0.9 m/s maximum flood. North of the Coggeshall Street Bridge, current speeds average about 0.09 m/s, with a maximum of 0.26 m/s. Current speeds measured at two stations south of the Coggeshall Street Bridge over two tidal cycles averaged approximately 0.06 m/s, with a maximum of 0.18 m/s.

New Bedford Harbor is a weakly stratified, partially mixed estuary, with salinities varying from about 26 to 30 ppt, occasionally going to 12 ppt during heavy rains. At the Coggeshall Street Bridge, vertical salinity differences as great as 18 ppt have been reported although south of the bridge surface-to-bottom salinity differences seldom exceed 2 ppt. Water temperatures in the Harbor range from a winter low of about 0.5•C to a summer high of 19•C.

Wave heights in the outer Harbor seldom exceed 1 m because of the relatively shallow water, although it is estimated that storm-generated heights as great as 2 m could be reached by waves from the southwest. In the inner Harbor, the narrow width of the Harbor, its relatively shallow depths, and the constrictions at the hurricane barrier and the bridges greatly restrict wind fetch. In the deep channel just upstream of the Coggeshall Street Bridge, waves may reach a height of almost 1 m during a storm with wind speeds up to 48 km/h. In the shallower areas outside the main channel, wave heights decrease rapidly.

The surficial sediments of New Bedford Harbor are primarily silty material of glacial origin, with varying amounts of clay and sand. The silt and clay content of the shallow estuary landward of the Coggeshall Street Bridge varies from 10% to 80%, increasing in percentage seaward toward the bridge. Seaward of the bridge, in the deeper portions of the Harbor, the sediments are primarily silt and clay, except for sandy depositions around the constrictions of the bridges and the hurricane barrier, where the higher currents prevent the finer material from depositing.

Sediments seaward of the hurricane barrier are generally coarser than in the inner Harbor. The finer sediments are found along the deeper western margins of the Harbor. Along the shallow east shore, sand content varies from 50% to 90%.

Suspended sediment concentrations range from a general condition of less than 10 mg/L to approximately 40 mg/L during storm events. Suspended sediments are generally one and one-half to two times higher in bottom waters than in surface waters, and are highest approximately 1 h after the maximum flood velocity. Suspended sediments tend to be lowest during winter and highest during early spring through early summer. Resuspension of bottom sediment from storm waves appears to be the major source of seasonally suspended sediment.

Various field data were collected and used to establish initial and boundary conditions for the model, and to develop a conceptual description of circulation and contaminant transport in New Bedford Harbor. Data from National Ocean Survey charts, U.S. Army Corps of Engineers, and Tibbetts Engineering Company were used for initial depth conditions in the model. Surface sediment data from the literature were used to generate the grain-size database used in the model. Grain size contours were developed for the clay, silt, sand, and gravel fractions.

Information on the distribution of PCBs in bottom sediments, used as initial conditions, was obtained from the Battelle Ocean Sciences, Alliance, and GCA databases. Only the surface samples reported in the three databases, representing the upper 20 cm of a sediment core, or results from surface grab samples were used in generating the initial PCB bottom sediment conditions for the model.

The PCB data from the three databases were compiled in a single file, along with the data source, sample number, location, total PCB concentration, units for PCB concentrations, and numbers of samples summed to produce the total concentration for the surface sediment value (0 to 20 cm). The PCB data from the three databases were interpolated onto a 30 x 30 grid covering the inner and outer Harbor. A quadrant-search gridding algorithm was employed where, for each grid location, the algorithm used up to two data points from each of four quadrants centered about the grid location to calculate the

grid PCB value. At least one data point closer to the grid than 244 m was required to produce a PCB value for that grid. Any additional data points, up to a maximum of eight, within a 457-m radius were used to calculate the PCB value. The PCB value at each grid was estimated as the inverse distance-weighted average of the eight, or fewer, data points. A digital shoreline was incorporated, and a contour map of the surface sediment PCB concentrations was then prepared.

Conceptual Model of New Bedford Harbor

New Bedford Harbor is a weakly stratified, partially mixed estuary with very small freshwater inflows. The inner Harbor is small, shallow, and well protected from most wind events. With such estuaries, tides are normally the dominating process for water mass exchange and are the main mechanism for dispersion and mixing within the estuary. Density and wind-driven circulation is secondary to that of tides under most conditions. However, during storm events density and wind-driven currents can temporarily dominate the circulation in the Harbor. The resuspension and transport of PCB-contaminated bottom sediments should increase during storm conditions, which may represent the major PCB transport and redistribution episodes during a year. Storms with wind speeds in excess of 15 m/s occur once or twice per month, with durations of 1 to 2 days during October through April.

Dispersion and mixing within New Bedford Harbor is complicated. A dye dispersion study showed a net seaward transport of dissolved constituents released in the upper Harbor. The travel time between the northern portion of the site, just south of the Wood Street Bridge and the hurricane barrier was 2 days, and relatively steady-state conditions were reached in the estuary after 6 days. Large vertical, lateral, and longitudinal dye concentration gradients were observed, especially in the upper Harbor near the dye release point. Vertical stratification was observed, with the surface dye concentrations typically being 5 to 10 times higher than the bottom values in the upper Harbor. Stratification decreased in the down-estuary direction but was still prevalent in the lower Harbor. The data from the dye dispersion study suggest that the upper Harbor is not well mixed laterally, and that flow and eddy diffusion are highly three-dimensional processes.

The three severe physical constrictions in the Harbor, (the hurricane barrier and the Coggeshall Street and Interstate 195 Bridges), can influence dispersion and mixing within the estuary. These constrictions do not appear to affect the surface tide, since little tidal damping or phase shift between the upper and lower Harbors and Buzzards Bay occurs. The most obvious effects of the constrictions are their effects on the circulation within the Harbor. The constrictions will tend to cause secondary circulation cells, thereby short-circuiting the exchange of water between cells. Because there will be a greater degree of recirculation of water within the cells, the presence of secondary circulation cells in an estuary will generally increase the residence time of contaminants within the estuary.

The upper Harbor also has a central channel with adjacent subtidal flats on both sides. The volume transport of water and advection of dissolved and suspended contaminants in the upper Harbor therefore varies across the estuary with the stage of the tide. These flow features and the associated lateral dispersion are highly three-dimensional.

The migration of PCB contamination from the source area in the upper Harbor to adjacent environments (Buzzards Bay and the atmosphere) is conceptually modeled as follows:

> PCBs migrate from the highly contaminated bottom sediments into the overlying water column as a result of 1) desorption from fine-grained sediment particles and upward diffusion in interstitial (pore) water, 2) erosion and resuspension of sediment particles by boundary layer currents (steady and/or wind-wave generated) and 3) benthic organisms.
>
> Dissolved PCBs in the water column reabsorb to "clean" fine-grained sediment particles exported to the Harbor from Buzzards Bay and upland sources. The fate of these adsorbed PCBs then depends on subsequent advection or diffusion and deposition and resuspension of the scavenging particles. Particles which depart the Harbor with adsorbed PCB and do not return represent a net loss from the system. Particles that have a small concentration of adsorbed PCB can remain in the source area and sequester PCBs from the water column prevent evaporation and transport mechanisms from removing PCBs from the system for at least one adsorption/desorption cycle.
>
> Gains and losses of particle-bound PCBs from New Bedford Harbor represent a sediment transport problem involving erosion and deposition (particle settling) and advective and diffusive transport of suspended particles. The flow field and eddy diffusion regimes in time and space must be known to estimate instantaneous sediment transport reliably. In aggregate, they determine the rate at which the contaminated particles in the source area exchange with cleaner particles in Buzzards Bay.
>
> Transport and losses of dissolved PCB from the water column depend on the balance between the rates at which the chemical migrates diffusively from contaminated bottom sediments, advects to and from the system, and evaporates to the atmosphere. In New Bedford Harbor, the rate-limiting process appears to be mass transfer from the sediments, although vertical diffusivities in the water column may be important as well.

Conceptually, a comprehensive model must simulate all these diverse processes. Practically, the dominant ones are the most important to the present analysis and these are shown schematically in Figure 1. The transport processes are discussed in more detail below, in the context of the numerical simulations.

II. MODEL DESCRIPTION

The transport and fate of PCBs within New Bedford Harbor was modeled using a numerical, three-dimensional hydrodynamic model combined with a numerical sediment/contaminant transport submodel

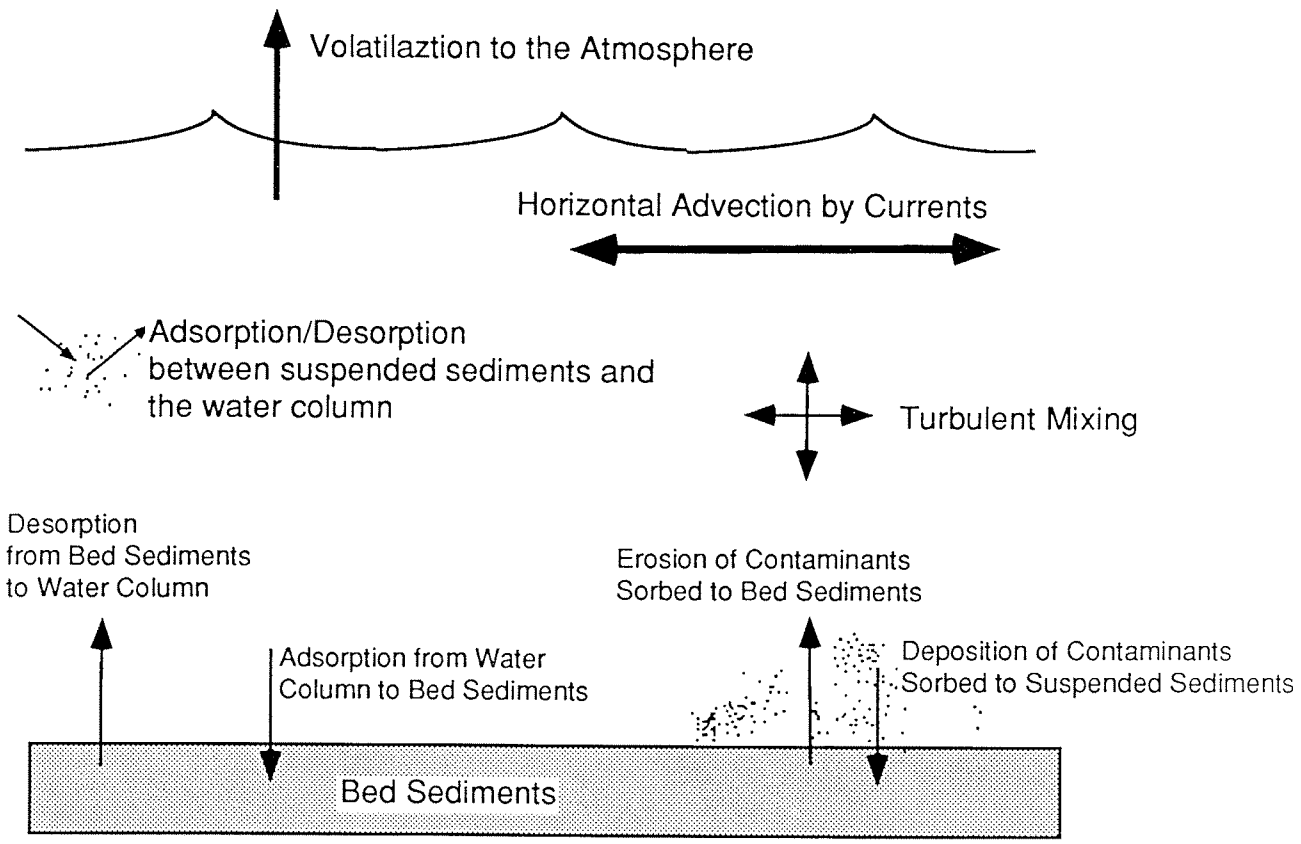


Figure 1. Contaminant Transport Mechanisms Represented in the Model

to account for sediment transport, contaminant transport, and sediment-contaminant interaction in both the water column and Harbor bed. Model simulation results were extrapolated in 2-year increments in order to attempt to estimate the fate of the PCBs in the Harbor system over long time periods out to 10-years. The long-term estimations were performed for various cases of remedial action alternatives, including the case of no remedial action to be taken. Continuous computer modeling of the combined hydrodynamics and transport models required unreasonable amounts of computer time, and the method to extend simulation results from shorter representative periods was developed to accommodate the ten-year period of interest. The method utilized a combination of transport-only submodel calculations, driven by previously computed hydrodynamics, and linear extrapolation of the submodel results.

For hydrodynamics calculations, New Bedford Harbor is assumed to be a slowly-varying, shallow-water flow system dominated by tidally-driven and wind-driven circulation. The numerical hydrodynamic model used for the simulations is based on the TEMPEST program developed previously at Battelle, modified to allow for free surface elevation changes and corresponding currents due to tides and other long-period wave phenomena, and to account for bottom friction enhanced by the action of surface wind-waves. This marine version of TEMPEST solves the equations for the conservation of fluid mass, momentum, thermal energy, and constituent transport (e.g. salt) in Cartesian coordinates using finite-difference techniques. The model hydrodynamics include Coriolis terms in the horizontal momentum equations to account for the effects caused by the rotation of the Earth. Water density variations, due to three-dimensional distributions of water temperatures and salinities, are also included in the model hydrodynamic equations. The fundamental assumptions underlying the TEMPEST equations include the assumption that the equations describe time-averaged quantities (i.e., Reynolds averaging is assumed); the assumption that fluid density variations are much smaller than the fluid density itself (Boussinesq approximation); and the assumption of turbulence closure to the hydrodynamic equations via constant eddy viscosities which are different in the horizontal and vertical dimensions. The time-varying free water-surface elevation is determined using the hydrostatic approximation, where the vertical component of the fluid momentum equations is assumed to be the hydrostatic equation.

A three-dimensional, nonuniform, rectangular grid was developed for the New Bedford Harbor computer modeling work, covering an area of approximately 9 x 12 km. The grid, shown in Figure 2, was comprised of 45 x 45 cells of various sizes in the horizontal plane at the MLW surface, and 6 flow computation levels in the vertical dimension of constant but unequal thickness. The rectangular grid was oriented 16.5 degrees counterclockwise from true north coordinates to best align the model grid with the major Harbor topographical features. Bathymetric (water depth) and shoreline features were mapped onto the grid using available data from charts and other more recent sources. The southern boundary of the model grid was defined to be a line running from near Round Hill Point on the west side of the

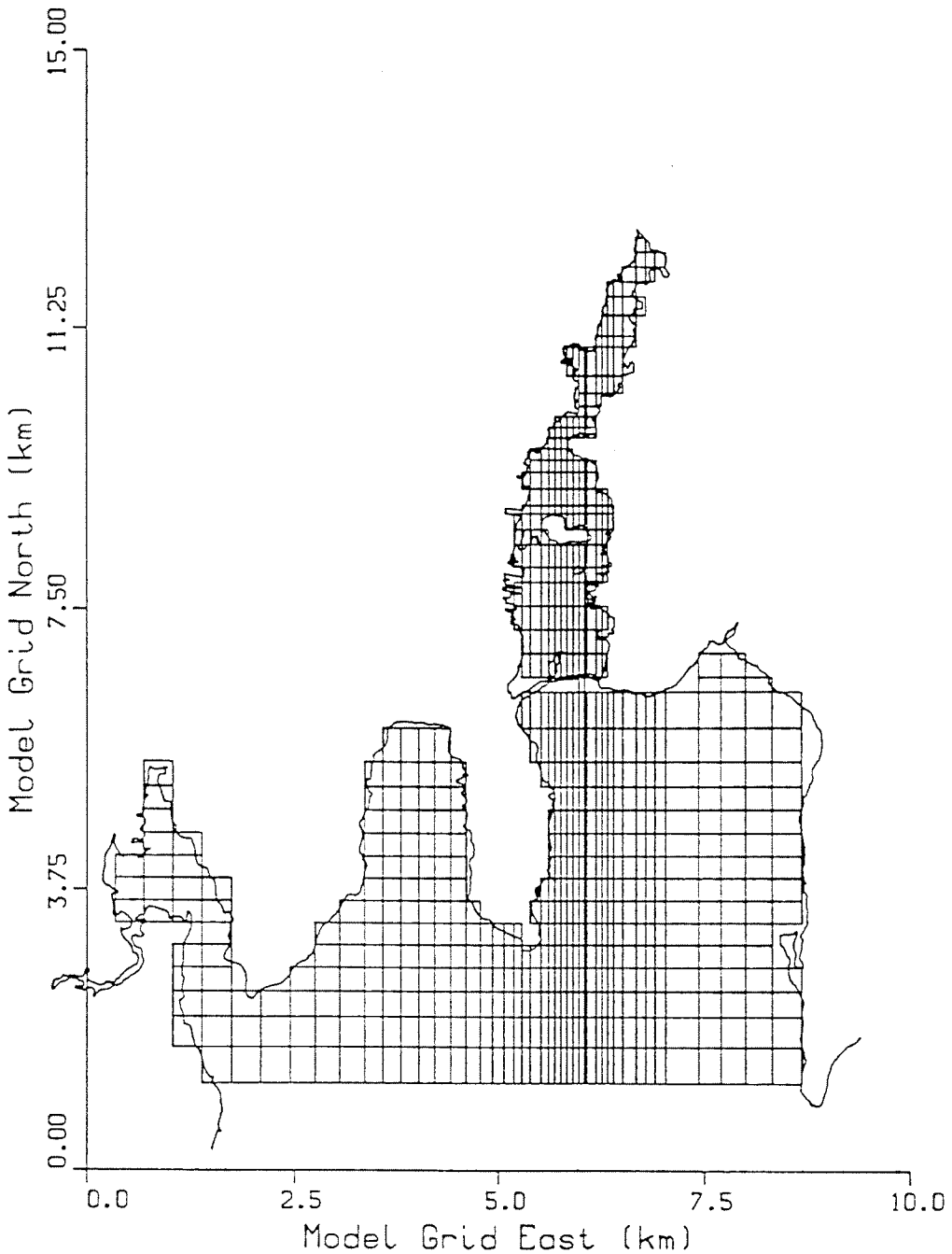


Figure 2. Plan View of the New Bedford Harbor Model Grid Surface Grid Layer

Harbor to near Wilbur Point on the east side. The northern boundary of the grid was defined to be the Wood Street Bridge crossing of the Acushnet River. Horizontal grid cell sizes in the model varied from 300 x 500 m for the largest to 33 x 100 m for the smallest cells. The horizontal grid sizing was selected to provide good resolution of relevant hydrodynamic processes (i.e., tidal and wind-driven circulations) and salient features in the Harbor, such as the hurricane barrier and Popes Island, while keeping the total number of grid cells within a computationally feasible range. The model grid cells in the vertical dimension consisted of constant thickness layers of 1.0, 0.9, 1.4, 1.8, 2.4, and 3.0 m, from near surface to near bottom. In addition to these 6 layers where flow parameters are computed, the model incorporates a surface layer and bottom layer which are used to set internal boundary conditions for the model's water surface and seabed.

Boundary conditions for the hydrodynamic model were established to correspond to the primary physical processes of importance to the model dynamics. At the water surface, wind shear stress was imposed uniformly over the entire surface layer by utilizing a standard wind-friction drag force relationship, proportional to the square of the wind speed and a drag coefficient which was linearly dependent on wind speed. The wind force was assumed to act on the elemental cell volumes of the surface layer. The uniform wind stress was computed at each time step of model simulation runs using time series data sets of observed wind speeds and directions as measured at the hurricane barrier in the Harbor. The surface layer of the model is also adjusted at each time step to account for changes in elevation due to tides. At the seabed, the governing boundary condition was formulated by estimating the frictional resistance force to the near-bottom water flow, utilizing a standard quadratic relationship to the flow velocity components, computed at each time step and for each bottom grid cell.

The model boundary conditions at the open, vertical plane separating the outer Harbor from Buzzards Bay waters were carefully formulated so that the changing surface elevation due to the tide in Buzzards Bay just outside the Harbor are incorporated along the open boundary. Waves shorter than the tide are allowed to pass out of the Harbor without reflection, while no waves besides the tide are considered to propagate into the Harbor from the Bay. The surface elevation along the open boundary is comprised of the tidal height variation plus an additive component required from the conservation of fluid mass (i.e., the continuity equation) for flow directed out of the Harbor system. Thus, the water surface level elevation along the open boundary is not permitted to drop below the elevation imposed by the external Bay tide, but can be computed to be above the purely tidal elevation when flow is computed to be directed out of the Harbor model domain. Flow directed into the model domain is driven entirely by the externally imposed tidal stage in the adjacent Bay. The open boundary conditions for temperatures and salinities were imposed during flowage into the Harbor model domain, using representative values derived from the field hydrographic survey work. The model did not incorporate freshwater inflow from

the Acushnet River because its low volumetric flow rate is normally insignificant to the modeled hydrodynamics. Since the Wood Street Bridge crossing is the approximate limit of upstream tidal influence, the model boundary was taken as a closed boundary at this northern terminus of the Harbor model domain.

Initial conditions imposed at the beginning of each hydrodynamic model simulation consisted of "cold start" conditions of initially motionless water and a uniform surface elevation throughout the model domain. An initial model spin-up period of at least one semi-diurnal tidal cycle (12.4 hr) was used in all model simulation runs. During test cases, less than one-half of a semi-diurnal tidal cycle was necessary (typically 4 hr) for model spin-up and generation of fully developed flow conditions in the model domain.

The hydrodynamic model was calibrated using field data from two 24-hr periods. Tidal height data measured near to the Harbor/Bay boundary were used to force the model, along with wind time series data measured in the Harbor at the hurricane barrier. The model was run in a diagnostic mode using an initial density field determined from field survey data. After performing several sensitivity simulations, the coefficient values showing the most reasonable agreement with available field measurements of current speeds and directions and surface height elevations were adopted for use in the Harbor model simulations: 0.001 m^2/s for vertical eddy viscosity, 1.0 m^2/s for horizontal eddy viscosity, and 0.0026 for the bottom friction coefficient (this does not include the wave-enhanced bottom friction during storm simulation).

The sediment/contaminant transport submodel used for New Bedford Harbor model simulations is based on the FLESCOT program developed previously at Battelle. Incorporating governing conservation equations for sediment mass, dissolved contaminant mass, and sediment-sorbed contaminant mass, the FLESCOT constituent transport routines account for sediment transport, contaminant transport, and sediment/contaminant interactions in the water column and at the seabed. Fundamental assumptions underlying the FLESCOT transport routines are that dissolved contaminants are neutrally buoyant, suspended sediments have no effects on the hydrodynamics, and that sediment adsorption/desorption of the contaminant is governed by processes which are linear functions of the concentration gradients. The conservation equations are coupled to each other to account for interchanges between dissolved and sorbed-contaminant constituents. The FLESCOT submodel used for the New Bedford Harbor modeling allowed for inclusion of both cohesive (two size fractions) and noncohesive (one size fraction) sediments in the simulation of sediment transport processes. The migration of each sediment fraction through transport, deposition, and erosion processes is solved separately for each size fraction. The sediment transport formulation includes mechanisms for 1) advection and dispersion of sediments, 2) particle

settling velocities and cohesiveness, 3) deposition on the seabed, 4) erosion from the seabed, 5) sediment contributions from point or distributed sources, including open boundaries. Changes in bed elevations caused by deposition/ erosion are computed for each model time step and each seabed grid cell, and the partitioning among the three size fractions for both cohesive and noncohesive sediments is tracked for all water column and seabed grid cells.

Seabed sediment deposition/erosion rates in the submodel utilize different formulations for cohesive and non-cohesive constituents, based on appropriate empirical criteria from accepted literature sources. The erosion or deposition rate of noncohesive sediments (sand) is determined by using DuBoy's equation to compute the transport capacity of the flow. For cohesive sediments (silt and clay), the formulas developed by Partheniades and Krone are used to compute erosion and deposition rates. These formulations use bottom shear stresses computed from the hydrodynamic model current velocities at the seabed compared to critical shear stress values specified for the different sediment types and size fractions, along with empirically determined parameters to determine erosion rates at each seabed cell. The submodel bottom boundary condition for sediment erosion during storm conditions included a modification to the computed shear stress at the seabed to account for enhancement of the bottom stress caused by the activity of surface wind-waves.

The governing equation for the three-dimensional transport and fate of the dissolved (PCB) contaminant within the submodel included mechanisms for 1) advection and dispersion of the dissolved contaminant, 2) adsorption of the dissolved contaminant in the near-bottom water by sediments in the seabed, or desorption of the contaminant from seabed sediments into the near-bottom water, 3) volatilization of dissolved contaminant from the surface layer into the atmosphere, and 4) contaminant contributions from point or distributed sources, including open boundaries.

The migration and fate for contaminants attached to sediments are solved separately for those adsorbed by each sediment size fraction of cohesive and non-cohesive sediments. The submodel equations for transport of particulate contaminant carried by each type of sediment and size fraction includes mechanisms for 1) advection and dispersion of particulate contaminant, 2) adsorption of dissolved contaminant by suspended sediments in the water column or desorption from suspended sediments into the water column, 3) deposition of suspended contaminated particulates from the near-bottom water onto the seabed or erosion of contaminated seabed particulates into suspension, and 4) contaminated particulate contributions from point or distributed sources, including open boundaries. Figure 1 illustrates the various processes accounted for in the submodel simulations.

Contaminant mass transfer between the seabed and water column thus occurs in the model through the deposition and erosion of sediment-sorbed contaminant and through direct desorption and adsorption. The direct adsorption/desorption of contaminant between the water column and seabed is specified via a bed-water column partition coefficient and rate constant for each constituent sediment type. Similarly, the partitioning of contaminant in the water column between dissolved and sorbed form is specified through an equilibrium partitioning coefficient and an associated rate constant for each sediment type. Volatilization of contaminant through the surface layer to the atmosphere is treated as a first-order rate process, specified with a rate constant based on an average of several reported values. An average literature value was used because no site specific information was available to assign the volatilization rate coefficient. The submodel did not account for the diffusion of contaminant in the pore waters of the seabed sediments.

The sediment calibration parameters for the submodel include mean grain size for noncohesive size fractions, critical shear stresses for each type and size fraction of the seabed sediments, and erodibility coefficients for cohesive sediments. The primary calibration parameters for PCB contaminant are the bed partitioning coefficients which control the adsorption/desorption mass transfers between the bed sediments and water column and between sorbed-sediment suspended constituents and the water column.

Boundary conditions for the dispersion of sediments and diffusion of contaminant through the lateral and longitudinal boundaries were set at zero, preventing diffusion/dispersion through both open and solid boundary walls in the submodel. Consequently, dissolved contaminant or suspended sediments could only be advected by the currents through the open boundary separating the Harbor model domain from Buzzards Bay.

Initial conditions for bed sediments (sand, silt, and clay fractions) and total PCB sorbed to the bed sediments were assigned by averaging field survey data onto the model grid. To obtain sufficient detail to assign bed conditions throughout the model domain, several sets of bed sediment data for grain size distributions and PCB concentrations taken at different times had to be utilized. Data to determine the open boundary conditions between Harbor and Bay for suspended sediments and total PCBs were quite limited. The open boundary conditions, applied only when the currents are flowing into the model domain (primarily during flood tide stages), were set uniformly across the open boundary at 6.0 mg/l and 4.8 ng/l for suspended sediment and total PCB concentrations, respectively. During the modeling of storm conditions, these values were increased by a factor of three to approximate the effects of more intensive sediment resuspension in the Bay near to the model boundary. The assumed boundary values were within the range of field survey data collected in the outer Harbor and adjacent Bay. Model tests

showed that resultant PCB concentrations computed for inner Harbor locations were not very sensitive to the specified open boundary concentrations.

III. MODEL CALIBRATION

The sediment and contaminant transport submodel was calibrated by adjustment of model parameters and comparing the resultant model concentrations of suspended sediments and PCBs with water column data from the Harbor field surveys. Additionally, the computed net fluxes of sediments and PCBs beneath the Coggeshall St. Bridge were compared with previous estimates obtained via measurements. The comparison of computed model values with water column field survey data showed reasonable agreement. The computed net fluxes were in the same direction as the estimates derived from measured data, but the modeled flux magnitudes were lower.

A rigorous validation of the model simulated PCB transport and fate was not possible because the necessary field data were not available. Ideally, a minimum of three independent sets of synoptic data are needed for a rigorous calibration and validation. One set to use as initial conditions, another set to calibrate the model, and a final set to validate the model. In the New Bedford Harbor case these data sets should be separated by a period of years because of the desire to estimate long-term trends in the PCB distribution throughout the system. All the available data were used to assign initial conditions and calibrate the model. Lacking a synoptic data set to use for validation, the long-term model results were compared observed trends in the flux data for sediments and PCBs.

A simulation was conducted to test the combined hydrodynamic model and decoupled sediment/contaminant transport submodel in comparison to data obtained from a previous field study of continuous dye release over 14-days, discharged into the surface water of the upper estuary near the northern model boundary. Since the hydrodynamic model simulation did not correspond to the actual tide and wind conditions during the field study, a detailed, quantitative comparison could not be made, but it permitted qualitative assessment of the model capability to estimate dispersive processes for the inner Harbor. Turbulent diffusivities for the tracer was assumed to be identical to the eddy viscosities determined for the model. Initial conditions for the tracer were set to zero throughout the model domain, and the open boundary condition between the outer Harbor and Buzzards Bay was maintained at zero dye concentration throughout the test simulation. The hydrodynamic model was run for a 24-hr period, and these results were repetitively used with the decoupled sediment/contaminant transport submodel over the 14-day simulation. Tracer was released at a constant rate of 29 mg/s over an initial 8-day period, and the release was then stopped, as in the field study. Model simulation was then continued for an additional 6-day period. The field study showed that measurable dye concentrations initially reached

the hurricane barrier in the lower Harbor 2 days after the start of dye release, and a steady state was attained after 6 days. The model test simulation resulted in tracer arriving at the hurricane barrier 4 days after the start of dye release, and a steady state was approached after 14 days. In addition, the field study showed that dye concentrations decreased rapidly, reaching a value of approximately 0.1 ppb throughout the Harbor system 6 days following cessation of the dye release, whereas the model simulation suggested that 15 days were required. This test comparison is discussed in detail within the main body of the report (Section 5.5.3).

The time required for the sediment and contaminant transport solutions to reach a quasi- steady state was approximately 10 days. Thus, calibration simulations for the sediments and PCBs were computed in a decoupled, transport-only mode, with the hydrodynamic model and transport submodel run separately. The constituent transport calculations were performed using previously computed and stored velocity fields and surface elevations from the hydrodynamic model simulations. The hydrodynamic model was run for two cases, each 24 hr in duration, to generate the velocity and surface elevation time series for the decoupled Harbor simulations: a general case with northerly winds ranging from 2 to 10 m/s, and a storm case with southerly winds of 1 to 15 m/s. Both simulated cases were forced by a semi-diurnal tide having an amplitude corresponding to the mean semi-diurnal tidal amplitude for New Bedford Harbor (0.55 m). Sediment and PCB transports were then simulated for a 95-day period by repeating the hydrodynamics computed for the two cases in five sequential stages: 1) 31 days of the general case, 2) 1 day of the storm case, 3) 31 days of the general case, 4) 1 day of the storm case, and 5) 31 days of the general case. The final water column and bed concentrations for sediments and contaminant determined from each simulation stage served as the initial conditions for the subsequent stage. Each 95-day simulation required approximately 5 hours of running time on a Cray X-MP supercomputer.

Since computer costs to generate long-term simulations were prohibitive, 10-year projections were estimated via the following procedure. For each 95-day simulation, the rate of mass change for sediments and contaminant in each bed cell was determined from the difference between the ends of stage 3 and stage 5, divided by the elapsed time (32 days). Using this calculated rate of change, the mass of sediments and contaminant in each bed cell was extrapolated 2 years forward in time. The extrapolated values were then used to define new initial bed conditions, and a 95-day simulation was again performed. Specified model parameters such as partitioning and rate coefficients, and the open boundary conditions were not varied from year to year. This procedure was repeated until the extrapolations for the tenth year were obtained. Thus, extrapolated estimates of Harbor concentrations were obtained for years 0, 2, 4, 6, 8, and 10. Year 0 corresponds to the end of the first 95-day simulation.

IV. NO ACTION AND REMEDIAL ACTION RESULTS

Estimates of the water column and bed sediment concentration of PCBs for a no action and six remedial action scenarios were obtained by running 10-year projections using the procedure described above. The information required to model each remedial action scenario was specified by the REM III team. This information included the definition of the shoreline, bathymetry, and concentration of PCBs sorbed to bed sediments after remediation. Confined disposal facilities (CDFs) were incorporated into the model shoreline as solid cells in the model grid for the scenarios that specified the use of CDFs. Potential PCB releases during the implementation of the remedial actions were not modeled.

The general characteristics of the scenarios were as follows:

No-Action scenario. This scenario is the continuation of the 95-day calibration simulation (referred to as year 0 of no action). The long-term modeling procedure was used to compute results for years 2, 4, 6, 8, and 10.

Hot-Spot scenario. The grid cells encompassing the PCB hot-spot area were remediated to a residual sediment PCB concentration of 10 ppm.

Upper-Estuary scenario. The area between Coggeshall and Wood Street Bridges was remediated to a residual sediment PCB concentration ranging from 1 to 10 ppm (the exact value depended on the location). This scenario included CDFs along the shoreline north of the Coggeshall Street Bridge. No remediation was assumed for the Lower and Outer Harbor areas. The hydrodynamics were recalculated using the altered shoreline.

Lower-Harbor scenario. This scenario specified the cleanup of the region between the Hurricane Barrier and the Wood Street Bridge to a residual PCB concentration ranging from 1 to 10 ppm. This scenario included CDFs both north and south of the Coggeshall Street Bridge. No remediation was assumed for the Outer Harbor area. The hydrodynamics were recalculated using the altered shoreline.

500-ppm scenario. All locations between the Hurricane Barrier and Wood Street Bridge with a PCB concentration of 500 ppm or greater were remediated to a residual sediment PCB concentration ranging from 1 to 250 ppm. No remediation was assumed for the Outer Harbor area. This scenario used the Lower-Harbor hydrodynamics.

50-ppm scenario. All locations between the Hurricane Barrier and Wood Street Bridge with a PCB concentration of 50 ppm or greater were remediated to a residual sediment PCB concentration ranging from 1 to 10 ppm. No remediation was assumed for the Outer Harbor area. This scenario used the Lower-Harbor hydrodynamics.

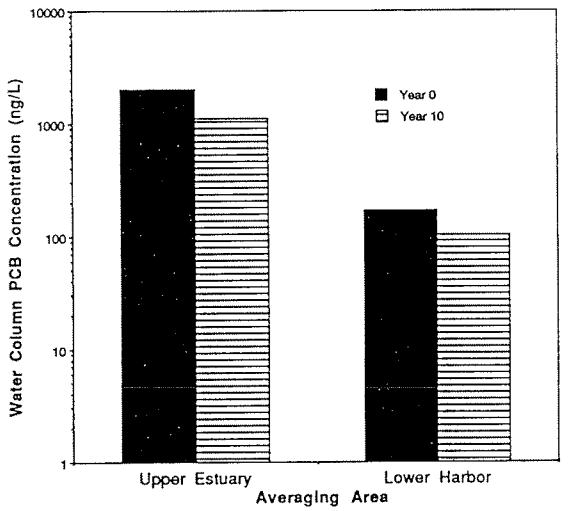
1-ppm scenario. The initial bed-sediment PCB concentration over the entire model domain (which includes the areas outside the Hurricane Barrier) was set to 1 ppm. This scenario used the Lower-Harbor hydrodynamics.

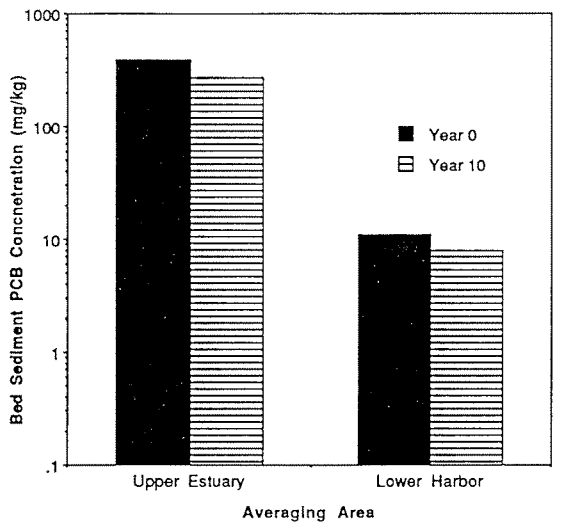
All simulations used the same open-boundary conditions and model parameters. For example, the water column and bed sediment partitioning coefficient (K_d) values were not changed from scenario to scenario.

The net flux and area averaged model results for each scenario at years 0 and 10 are shown in Figures 3 through 8. The flux is defined as the mass of PCBs or sediment that move through a given measurement plane over a given time period. Because of flow reversals between ebb and flood tide the flux direction is not constant. A negative net flux indicates flow toward Buzzards Bay. The results of the No-Action and Remedial Action scenarios are summarized by comparing the net flux of PCBs (Figure 10), area averaged water column PCB concentration (Figure 11), and area averaged bed sediment PCB concentration (Figure 12) at the end of the 10-year projections. The Hot-Spot and 500-ppm scenarios produce comparable results because of the similarity of the initial bed sediment PCB concentrations used in these cases. Furthermore, the results of these two scenarios are not markedly different from the No Action scenario. The results of the remaining scenarios (i.e., Upper-Estuary, Lower-Harbor, 50-ppm, and 1-ppm) show much reduced fluxes through the Coggeshall Street Bridge and the Hurricane Barrier as well as lower water column and bed sediment PCB concentrations as compared to the No-Action scenario. Because only the 1-ppm scenario applied a remediation to the Outer Harbor region, all other Remedial Action and No-Action scenarios yield similar concentrations in the outer Harbor region. It is significant the model suggest that the principal effects of a remedial action will be localized; for example, removal of the Hot Spot will not lead to dramatically reduced water column and bed sediment concentrations in the Lower Harbor and/or Outer Harbor areas.

V. UNCERTAINTY IN THE SIMULATION RESULTS

Any methodology that seeks to estimate the future behavior of an environmental system is fraught with many uncertainties and limitations. This is true of the modeling approach used in this study. The 10-year projections are based on simulation results which are affected by uncertainties from several sources. The governing equations used in the numerical model use parameterizations of many physical processes that are poorly understood. For example, the parameterizations used for sediment transport and sediment-contaminant interactions are idealizations of extremely complex physical phenomena. The model also requires the specification of many parameter values for which no site-specific values are available, for example, the volatilization rate for PCBs. Uncertainties are present in the field measurements of bed sediment PCB concentrations used to initialize the model. Conditions for suspended sediment and PCB concentrations at the model open boundary are also uncertain. The synthetic hydrodynamics and linear extrapolation procedure used to carry out the 10-year projections also introduce uncertainty into the model results. Finally, all calculations are carried out on a discrete





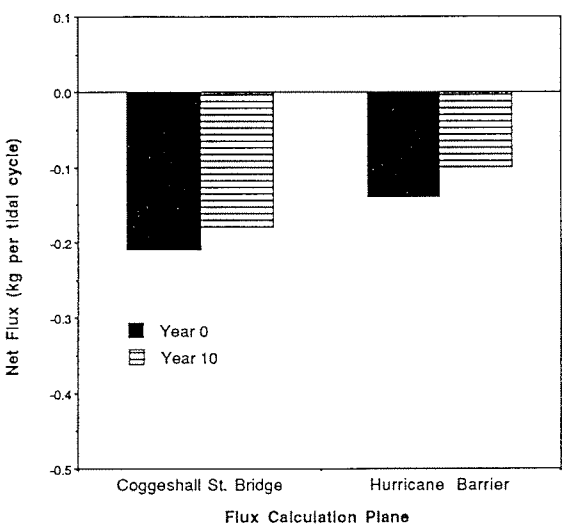


Figure 3. Results for No-Action Scenario

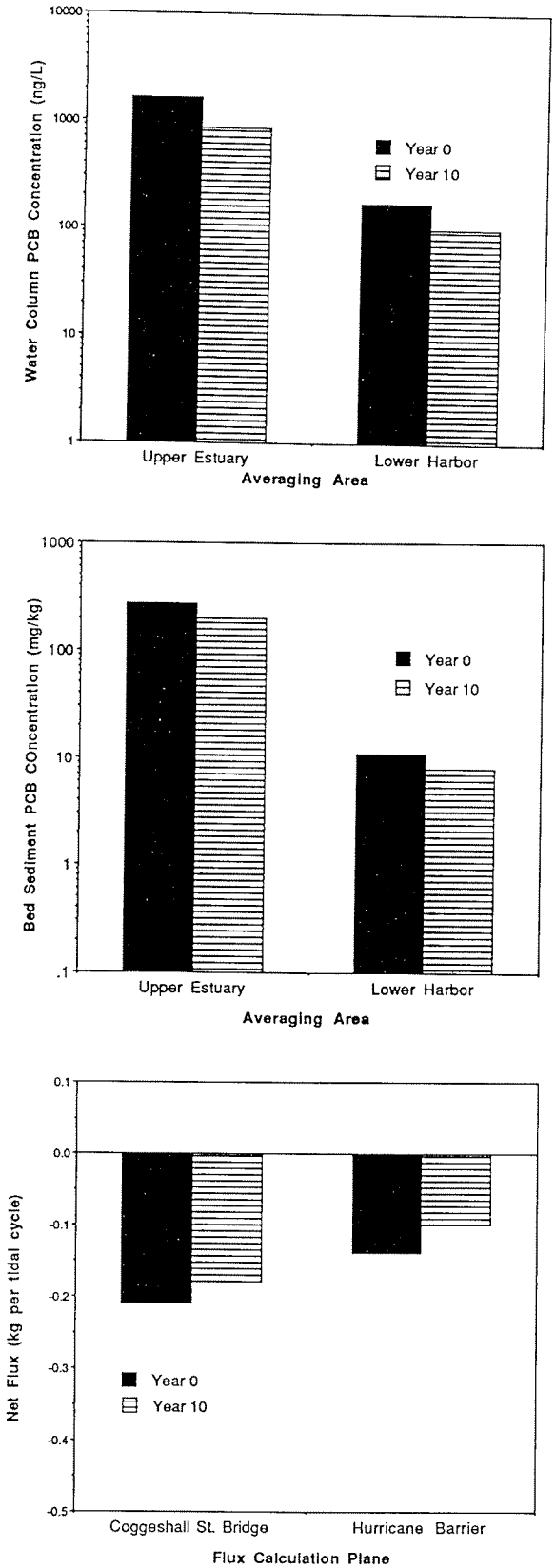
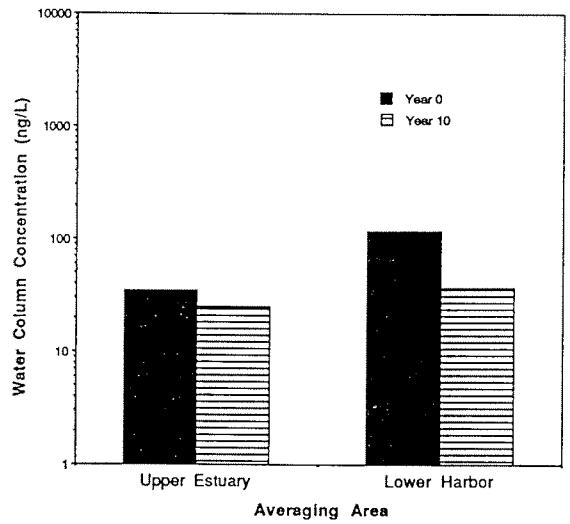
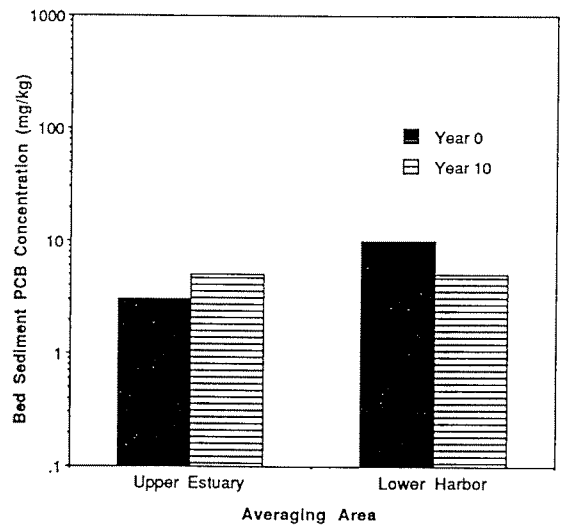


Figure 4. Results for Hot-Spot Scenario





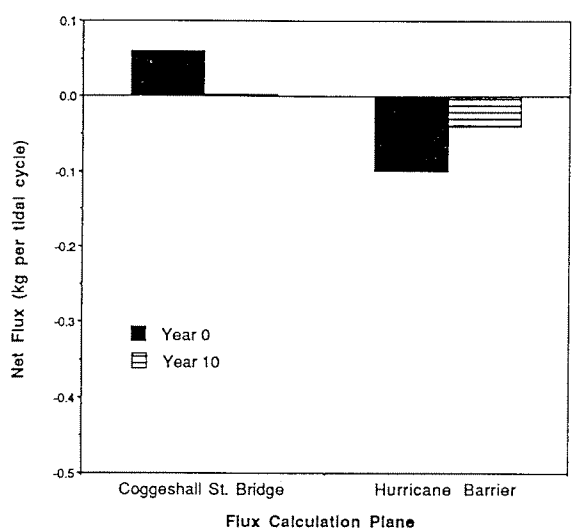
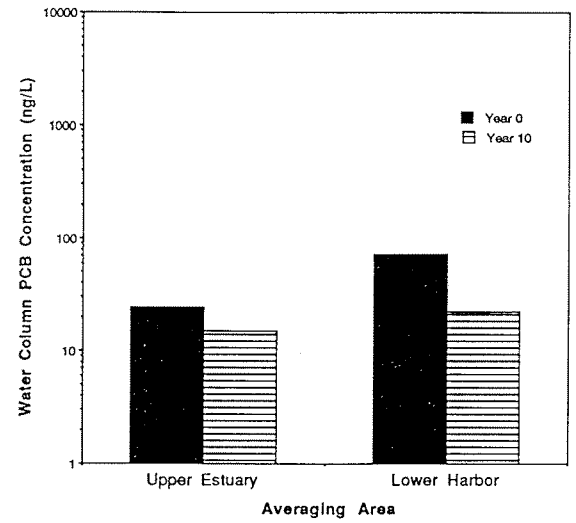
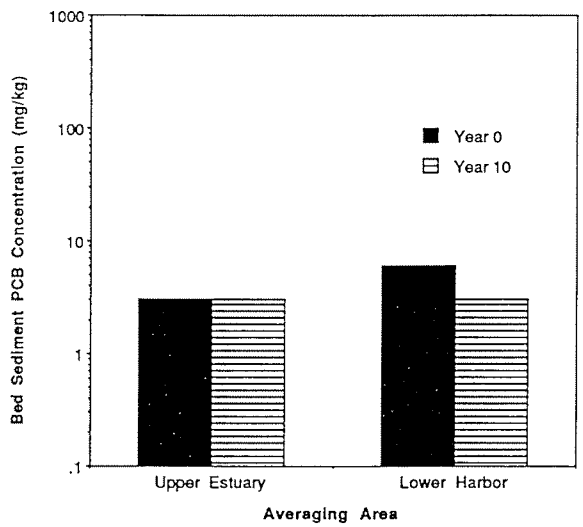


Figure 5. Results for Upper-Estuary Scenario





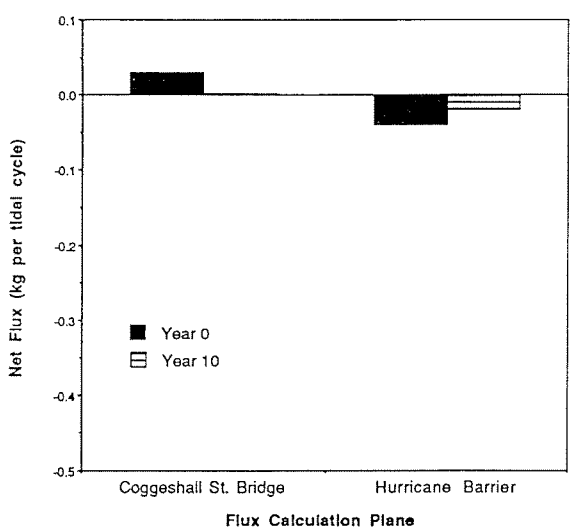
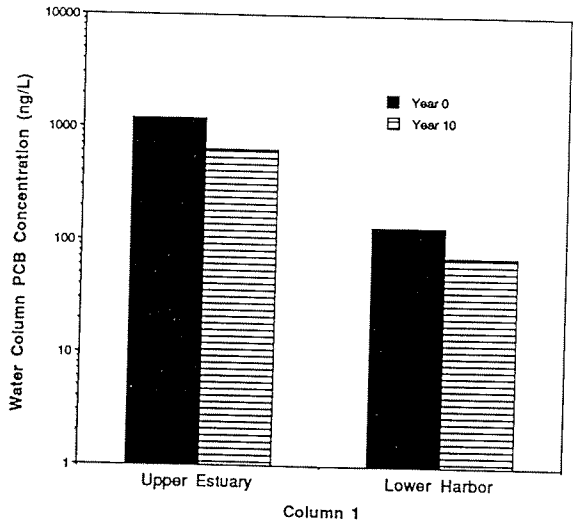
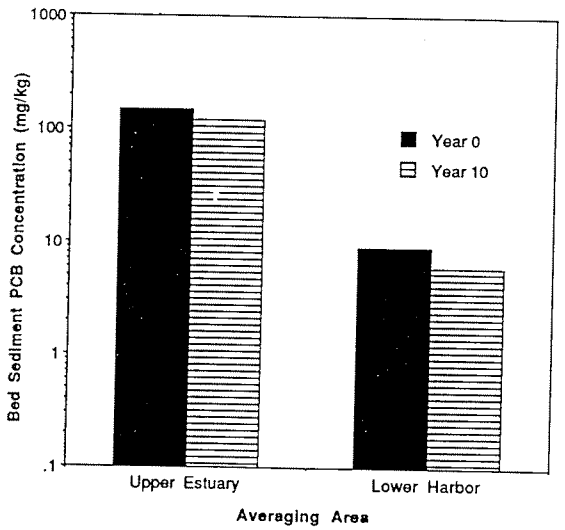


Figure 6. Results for Lower-Harbor Scenario





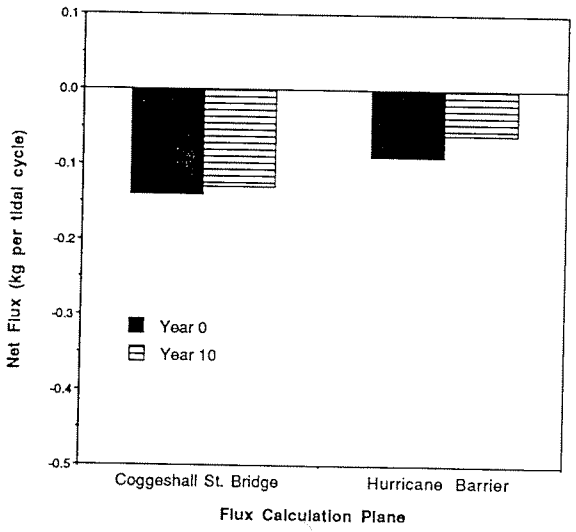


Figure 7. Results for 500-ppm Scenario

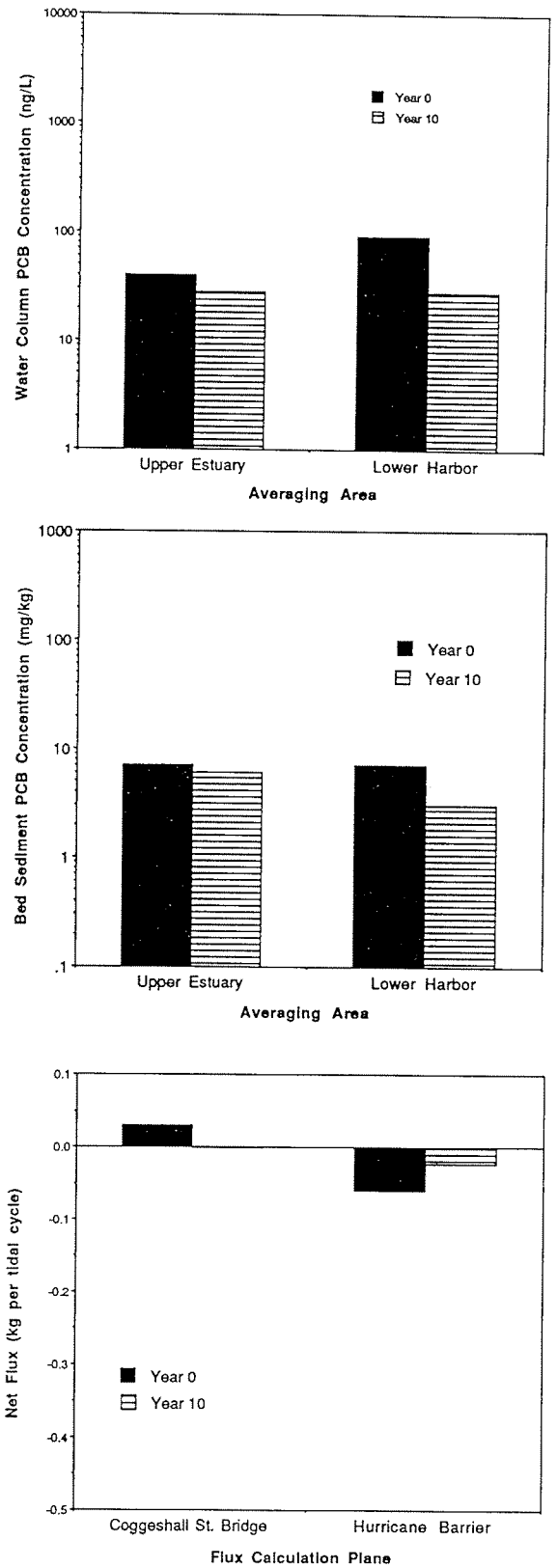
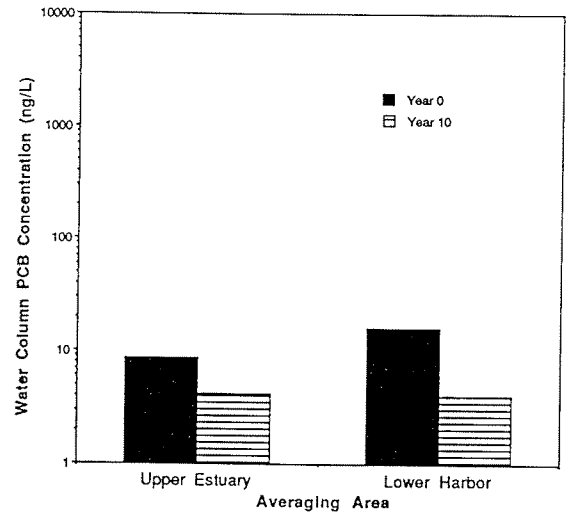
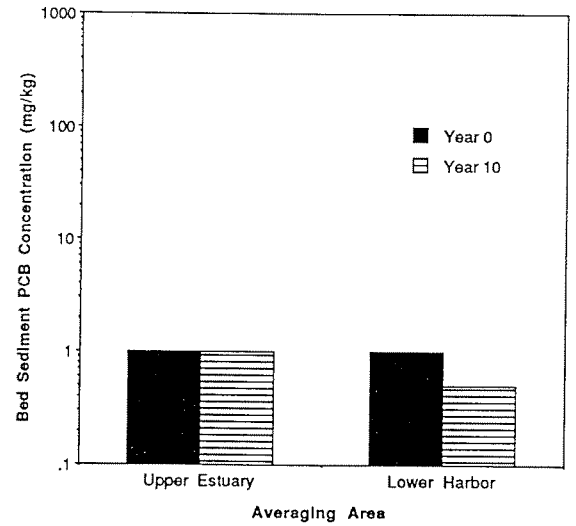


Figure 8. Results for 50-ppm Scenario





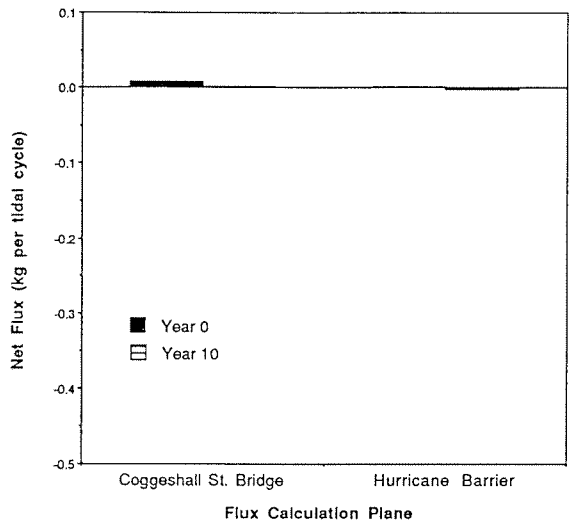


Figure 9. Results for 1-ppm Scenario

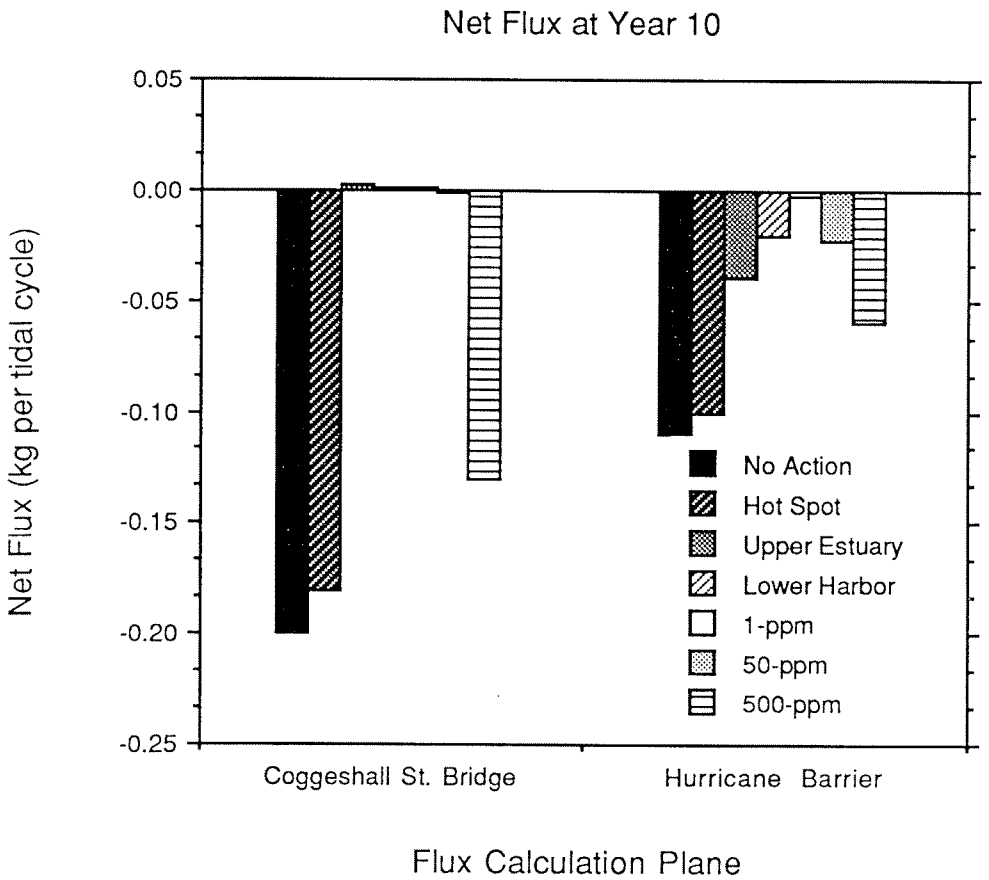


Figure 10. Comparison of the Computed Net Flux at Year 10

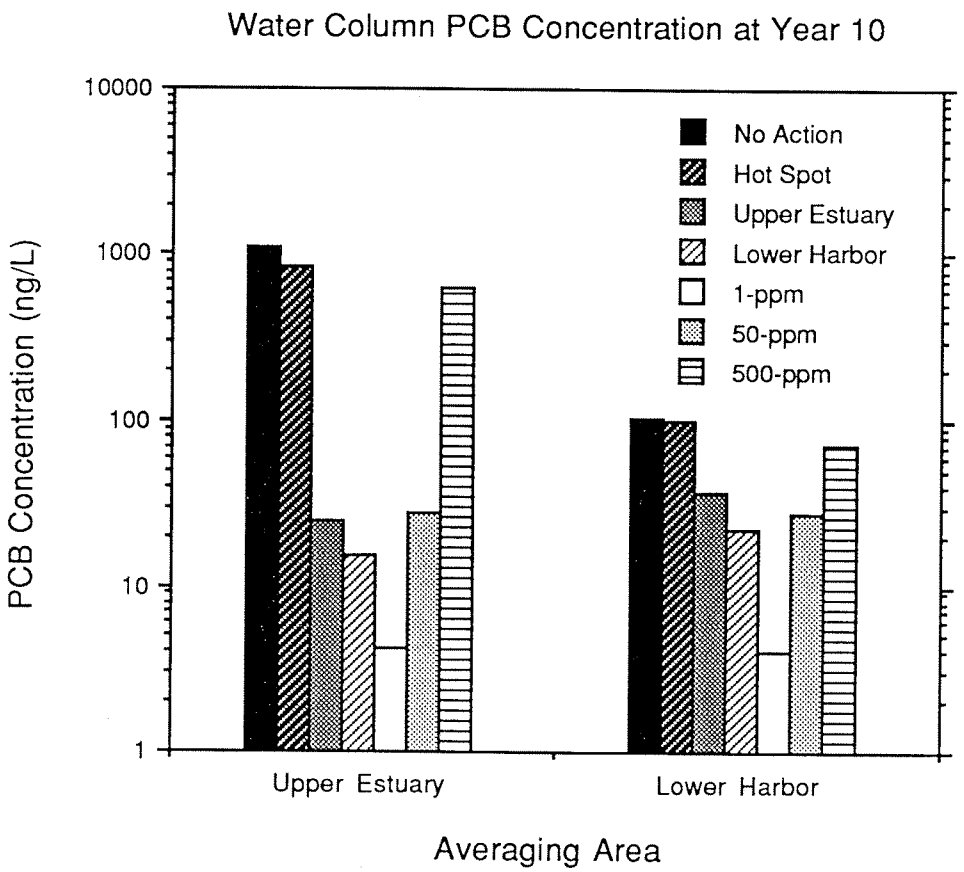


Figure 11. Comparison of the Area Averaged Water-Column PCB Concentration at Year 10

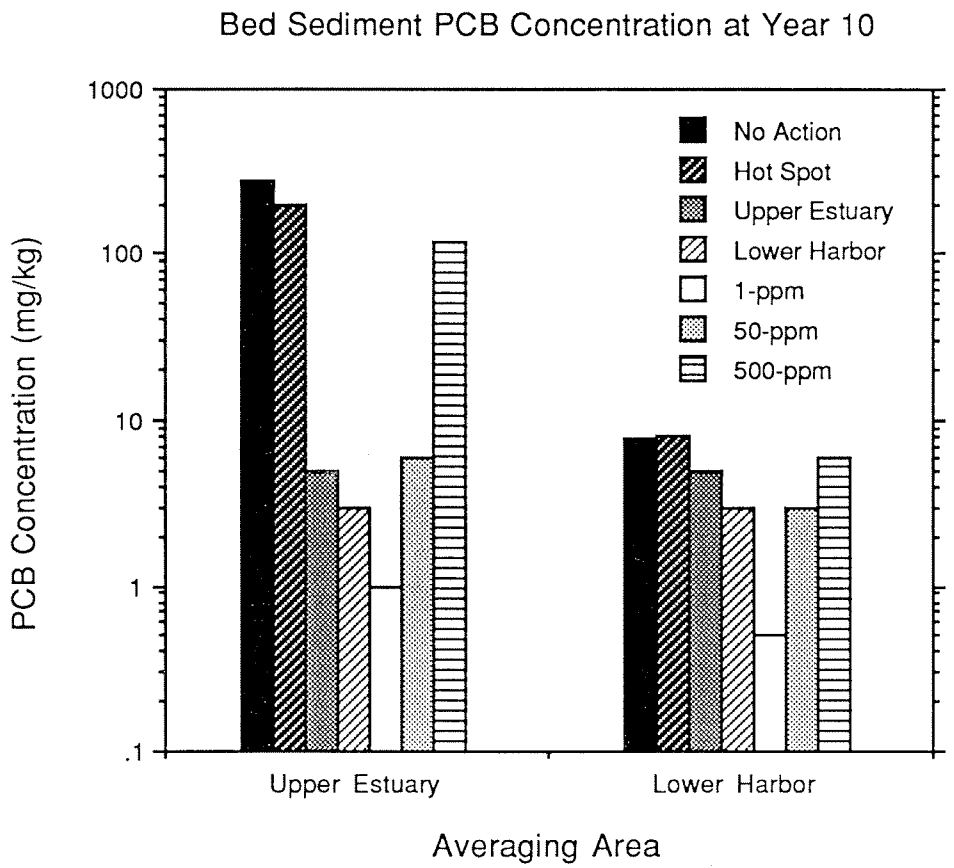


Figure 12. Comparison of the Area Averaged Bed-Sediment PCB Concentration at Year 10

grid which approximates the actual shoreline and bathymetry. Despite the difficulties and uncertainties associated with selecting parameter values and initial bed sediment conditions, use of a model (simple or complex) requires the assignment of a discrete parameter or initial concentration value. Using specified input the model produces a discrete result; those unfamiliar with the process of modeling environmental systems should not assume that a discrete result necessarily implies a precise result.

It is difficult to obtain an exact measure of the uncertainty present in the results without running a large number of sensitivity simulations. This was not done in this study because of the high computational cost of running the model. Some sensitivity tests were done and are summarized in the main report. These tests included varying the PCB partitioning coefficient, initial bed sediment PCB concentrations, and the assigned PCB concentration at the model open boundary. The results for the calibration simulation provide a gross measure of the model uncertainty. The calibration results are generally within ±50% of the measured water column PCB concentrations. It is suggested that this level of uncertainty be applied to the computed concentration estimates.

It is recommended that the model results be used in a qualitative manner to assist in determining the factors that influence the effectiveness of one scenario versus another. The results should be viewed qualitatively so as to minimize the effect of uncertainties introduced by qualitative model parameters or operating procedures on the selection of a best alternative. The following example illustrates why the model results should be used carefully and in a qualitative manner. As the model computed sediment transport seeks equilibrium, the model shows a net export at the end of year 0 of sediments from inside the model through the open boundary to Buzzards Bay. At the end of year 10 this is reversed, the model shows a net import of sediments from Buzzards Bay through the open boundary into the model. This reversal of sediment flux at the open boundary does not reflect any known physical process and is an artifice of the modeling process which is caused by uncertainties in the initial bed sediment size distribution. Without further sensitivity simulations the precise effect of the sediment flux reversal cannot be determined. This artifice of the modeling procedure is present in each of the No Action and Remedial Action simulations. It should be noted that the model shows a net importation of sediments into the lower Harbor and upper estuary in year 0 and year 10. This latter model result is in agreement with the observed physical processes occurring in the Harbor. Thus, the sediment flux reversal should mainly effect model results for the outer Harbor area.

The initial concentration of PCBs in the bed sediments is uncertain and directly effects the model results. Because no single set of synoptic measurements with adequate spatial extent were available to assign the initial bed sediment conditions, several sets of data taken at different times had to be used to develop the initial conditions. Therefore, the initial conditions at the start of year 0 do not directly correspond to a

single point in time, but represent a composite bed condition over several years in the early to mid-1980s. The data collected in the outer Harbor area may have been biased toward known and likely areas of PCB contamination such as the City of New Bedford sewage treatment plant outfall. Because of this potential bias, the initial concentration conditions used in the outer Harbor are probably too high on the average. The main effect of this and the sediment transport issue discussed above is that the model shows a large decrease in PCB concentration in the outer Harbor that would not occur if the initial concentrations were lower. Over estimating the amount of PCBs in the outer Harbor bed sediments may cause a lower net flux of PCBs through the Hurricane Barrier and thereby the lower the rate at which the PCB concentration decreases in the lower Harbor area.

The model represents the bed by a single 4 cm thick layer. The surficial PCB concentration measured from field surveys was used to assign the initial model PCB concentration. Thus, the initial bed PCB concentration in the No-Action simulation may over or underestimate the actual concentration of PCBs in the upper 4 cm of the bed sediments. The use of a 4 cm thick layer also means that the overall mass of PCBs represented in the model bed sediments is lower than what is actually present in New Bedford Harbor. Underestimating the overall inventory may cause the model to show larger decreases in bed PCB concentration in the No-Action case than might occur if a larger initial inventory were used. In the remedial action simulations it was assumed that the contamination located at depth would be removed from the system leaving a new 4 cm thick layer with a specified residual PCB concentration.

Parameter uncertainty also affects the model results. The key parameters are the water column and bed PCB partition coefficients and the PCB volatilization rate. The sensitivity of the results to variations in the partition coefficients was shown in the calibration simulations. The PCB volatilization rate coefficient was held constant at a mean value taken from several previous investigations reported in the literature. The volatilization rate was not varied because of the lack of site specific information on its magnitude in New Bedford Harbor and also to reduce the overall number of adjustable parameters in the model.

The model results are also subject to uncertainties introduced by the synthetic 95-day hydrodynamics and linear extrapolation procedure. The use of an average tide range and one storm per month to represent conditions at the site is an idealization. Linearly extrapolating the model results over a series of 2-year periods to generate a 10-year projection is based on assuming linear behavior of the system. The lack of synoptic data collected over a several year period makes it impossible to verify this assumption. Some small increases in bed PCB mass in the lower Harbor in the remedial action cases as compared to the no action case are most likely caused by the extrapolation procedure.

The precise effect of the aforementioned uncertainties on the model results is not known because a rigorous validation of the model was not possible. Because the purpose of the model is to make long-term projections synoptic data collected over a several year period would be required to validate the model. Lacking the necessary long-term data, the effect of uncertainties on the 10-year projections can only be completely understood through extensive and costly sensitivity simulations.

VI. RECOMMENDATIONS

The main recommendation is that the model results be used in a qualitative manner, to determine the significance of the different factors that may influence the effectiveness of the different remedial alternatives. The absolute value of any model calculated concentration should be considered, at a minimum, to be accurate to ±50%. There are two primary reasons why the model results should not be taken as absolute predictions. First, a rigorous validation of the model was not possible because synoptic field data collected over a several year period were lacking. Second, inherent in the simulation results are the effects of uncertainties in the assumptions and physics included in the numerical model, model parameters, extrapolation procedure, and field data used to assign boundary and initial conditions.

Despite the limitations in its use, the model provides a consistent framework for assessing the relative performance of a given remedial action. The general trends estimated by the model are in reasonable agreement with the limited data available. The model results clearly show that there is a greater reduction over time in the water column and bed sediment PCB concentration from the remedial actions under consideration than would occur by doing nothing. The model results also suggest the principal effects of a remedial action will be localized; removal of the PCB hot spot in the Upper Estuary may not lead to significant reductions in water column and bed sediment PCB concentrations in the Lower Harbor. Given the uncertainties present in the simulations, the results can be placed in three groups. The 1-ppm scenario clearly yields the greatest reduction in PCB concentration. The Upper-Estuary, Lower-Harbor, and 50-ppm scenarios form a second group of alternatives. Finally, the Hot-Spot and 500-ppm scenarios are not significantly different from the No-Action case.