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# Preliminary Dredged Material Transport Modeling
# in New Bedford Harbor

**ASA Report  01 –100**                                             **Draft Final**

December 2001

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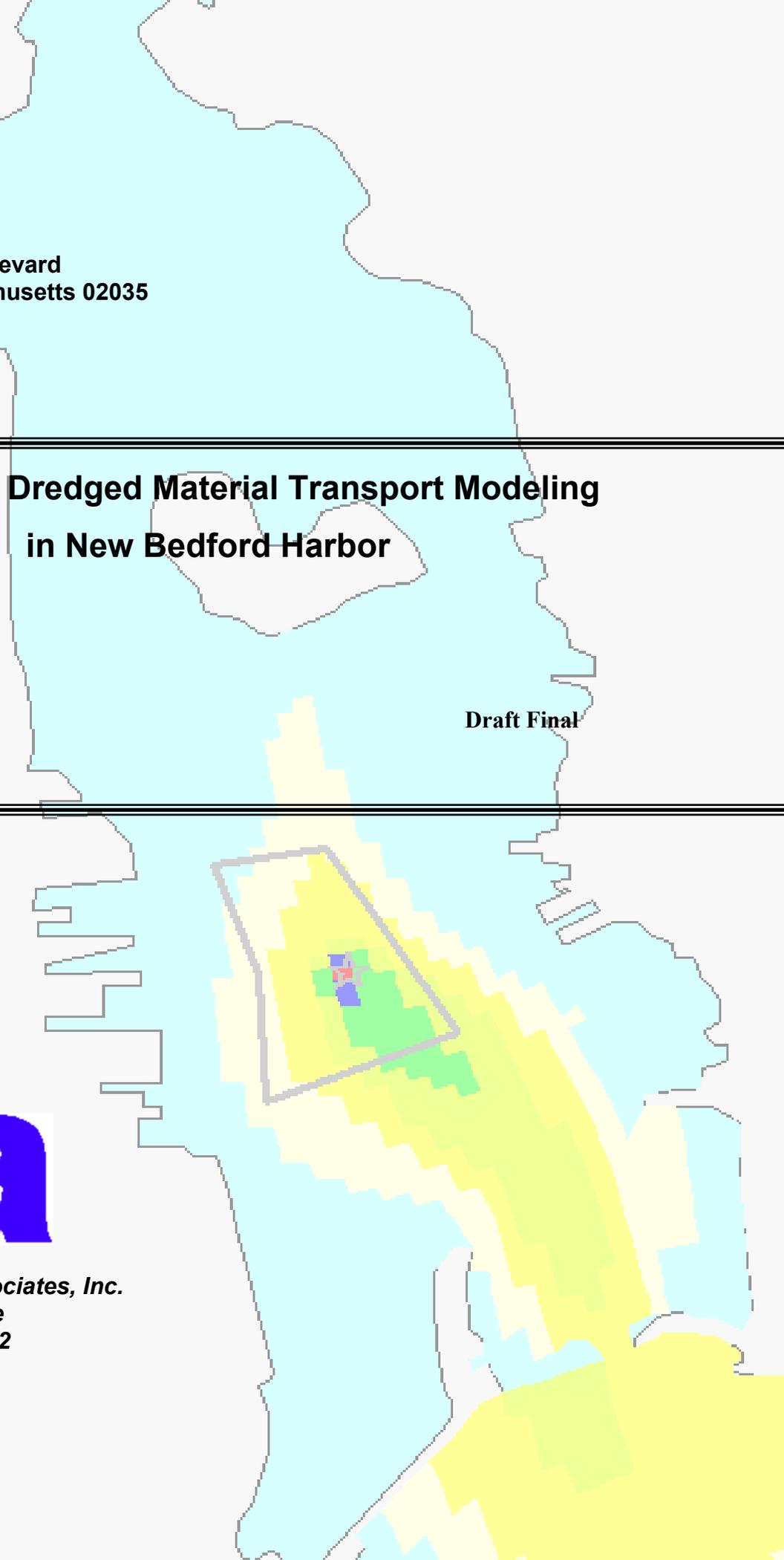*70 Dean Knauss Drive*
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# Executive Summary

A series of preliminary pollutant transport and fate simulations have been performed to estimate the water quality impacts in the water column from the proposed disposal operations for the Inner New Bedford Harbor, as part of the dredged material management project. ASA's WQMAP was used to estimate the water column concentrations of pollutants of interest: various metals (mercury, lead, cadmium, arsenic, chromium, copper, nickel, zinc), polychlorinated biphenyls (PCBs), and total petroleum hydrocarbons (TPH). The model simulated the fate and transport of the disposal materials at the two proposed sites: north of Popes Island (PI-CAD) and the federal navigation channel Inner site (LH-CAD). Two different release scenarios were set up and run. The instantaneous release simulated acute conditions and the continuous release simulated chronic conditions.

None of the constituents were found to exceed the USEPA water quality criteria under the tested scenarios with one exception. The concentration of copper at the time of instantaneous release was 20 (LH-CAD site) to 33 times (PI-CAD site) greater than the acute criteria. However, the concentrations decreased with time and quickly fell below the limit. With a continuous release, the pollutant levels increased with time. None of the constituents reached the chronic water quality limit, except copper. At the 29th simulation day, the copper concentration was almost four times the limit at the PI-CAD site release. The pollutant level at the same day was predicted to be 3 to 5 times smaller for the LH-CAD site release than the other site release.

The size and strength of modeled pollutant plume varied depending on the release location. The same amount of released material at the LH-CAD site resulted in smaller concentrations in the water column than at the other site. The reason was that larger currents existed at the channel Inner site than at the other site. The pollutant plume also varied with time. For an instantaneous release, the plume decreased in size and strength. The location of the maximum concentration changed in space. On the other hand, for a continuous release the size and intensity of the plume gradually increased. The plume varied at time scales of semi-diurnal tides. The maximum concentration was always observed at the release site.

The fate and transport of the pollutant component simulated in this work is based on a hypothetical loading of 3000 yd$^3$ of dredged material per day. It should be noted that once an actual loading is determined, the simulation results should be scaled by this load to obtain more accurate estimate of pollutant concentrations.

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# 1. Introduction

Massachusetts Coastal Zone Management (MCZM) has developed a proposed dredged material management plan in New Bedford Harbor. The plan is designed to dredge the federal navigation channel in the inner and outer Harbor and to dispose the material at two designated CAD (Contained Aquatic Disposal) sites in the Harbor. The work described here, modeling of the transport and fate of the disposal material in the Harbor, is part of the project. The goal of the work is to estimate the water quality impacts in the Harbor due to the disposal operations, using the ASA's WQMAP (Water Quality Mapping and Analysis Program).

The proposed dredging plan encompasses four areas in the inner Harbor and one area in the outer Harbor. The areas are north (FI-A, FI-B) and southeast of Fish Island (LH-A, LH-B, LH-C, LH-D), east of Crow Island (CI-A), and the federal channel outer Harbor (OH-A, OH-B, OH-C). Most of the material in the dredging area is silt with more than 90% in the top 0.6 m (2 ft) of the bottom and decreasing with depth. The dredging plan spans over 5 years, but the amount of dredged material is un-determined as yet. The dredged material will be disposed at two proposed CAD sites (Figure 1): north of Popes Island and the federal navigation channel at the lower Harbor. These sites cover areas of 0.57 km$^2$ (141 ac) and 0.31 km$^2$ (77 ac), respectively.

The inner New Bedford Harbor is morphologically simple and semi-enclosed by the Hurricane Barrier. The hydrodynamics in the area are accordingly straightforward, compared to the area, for instance, adjacent to the open ocean that can substantially be influenced by coastal dynamics. However, there is some variation in the dynamics due to non-local forcing. The currents in the Harbor are dominated by semi-diurnal tides, and the magnitude is on the order of 10 cm/s (0.2 kt). A small tributary to the system is the Acushnet River. The annual average of freshwater discharge from the River is on the order of 0.54 m$^3$/s (19.1 ft$^3$/s) (Abdelrhman and Dettmann, 1995).

To a first approximation, pollutant material is a passive tracer that is simply moved by the ambient currents. Therefore a hydrodynamic simulation is prerequisite to the transport and fate modeling of contaminants. For the hydrodynamic and transport modeling, the WQMAP (Water Quality Mapping and Analysis Program) package that was developed at ASA (ASA, 1999) was used. This program package has a several models including BFHYDRO (Boundary Fitted Hydrodynamic Model) for hydrodynamic modeling and BFMASS (Boundary Fitted Pollutant Mass Transport Model) for mass transport modeling. These two models use a boundary conforming grid (BFGRID: Boundary Fitted Grid Generation, one of the WQMAP modules).

For the pollutant mass transport simulations, BFMASS model requires information on the material source strength and the settling velocity. The pollutant is assumed in a dissolved form and therefore it has zero fall velocity. The source strength is defined as the amount of pollutant entering into the system in a given time. The amount of the disposal material

Figure 1. Proposed disposal site in the inner New Bedford Harbor. The northern site is designated PI-CAD and the southern site is denoted LH-CAD.

for this work is not yet known or the elutriate concentration is not available. We assume the loading amount 3000 yd³, and developed a method to estimate the elutriate concentration from available bulk-chemistry sediment measurements. This report

summarizes the water column concentration levels from the model application as a result of disposal operations. The focus is on the results from the WQMAP system that predicts pollutant concentration levels over time in the water column from the disposed material. The constituents examined are total polychlorinated biphenyls (PCBs), total (extractable) petroleum hydrocarbons (TPH or EPH), and metals (mercury, lead, cadmium, arsenic, chromium, copper, nickel and zinc). These components were chosen because they were found in New Bedford Harbor sediments.

The modeling performed and reported here is designed to screen for potential water quality problems during disposal operations. The predicted water column concentrations estimated from pollutant levels in the dredged sediments were compared to water quality criteria.

## 2. Model Description

### 2.1 WQMAP Description

WQMAP is a PC-based system that integrates geographic information (coastlines, land use, watersheds, etc.) and models (analytical and numerical, hydrodynamic, pollutant transport, etc.) to provide the user with a tool to analyze (with a graphical user interface) many alternatives to determine the optimum solution to a particular problem. It has been applied, with different models, as appropriate, to Total Maximum Daily Load (TMDL) analysis of Greenwich Bay, RI; to wastewater treatment facility effluent impacts to Cohasset Harbor, MA; to fecal coliform impacts from combined sewer overflows to the Providence River and upper Narragansett Bay, RI; to flushing estimates for alternative development configurations for Enighed Pond located on St. John, USVI; to circulation and flushing estimates for Nantucket Harbor, MA; and to dredging and disposal operations in Boston, MA and Providence, RI; among other applications.

The geographic information component of WQMAP holds user-specified layers of data appropriate for the task. Such layers might include shorelines, land use, pollutant point source locations, sampling locations, shellfishing closure areas, habitat maps, etc. Each data layer can be easily input, either directly into WQMAP with a mouse and screen forms or through import from existing geographic information systems such as ArcInfo. Data can be exported as well. Each layer can be displayed separately or in any combination. Graphics can be generated and sent directly to a printer (color or black and white) or stored for later use in a computer driven slide show.

The modeling component of WQMAP is uniquely versatile with its ability to link one or more of a suite of models of varying complexity into the system. These range from simple analytic calculations of flushing time in a single basin to full three dimensional, time dependent, boundary fitted numerical models of hydrodynamics and water quality. For the New Bedford project we used a boundary fitted, two-dimensional hydrodynamic model to generate tidal elevations and velocities. A constituent transport calculation used

the hydrodynamic model output and estimates of sediment pollutant load to estimate resulting water column concentrations.

## 2.2 Hydrodynamic Model (BFHYDRO)

The hydrodynamic model included in WQMAP solves the two- or three-dimensional, conservation of water mass, momentum, salt and energy equations on a spherical, non-orthogonal, boundary conforming grid system and is applicable for estuarine and coastal areas (Muin, 1993; Muin and Spaulding, 1996, 1997a,b).

The velocities are represented in their contra-variant form. A sigma stretching system is used to map the free surface and bottom to resolve bathymetric variations. The model employs a split mode solution methodology (Madala and Piaseck, 1977). In the exterior (vertically averaged) mode the Helmholtz equation, given in terms of the sea surface elevation, is solved by a semi-implicit algorithm to ease the time step restrictions normally imposed by gravity wave propagation. In the interior (vertical structure) mode the flow is predicted by an explicit finite difference method, except that the vertical diffusion term is treated implicitly. The time step generally remains the same for both exterior and interior modes. Computations are performed on a space staggered grid system in the horizontal and a non-staggered system in the vertical. Time is discretized using a three level scheme. Muin and Spaulding (1996, 1997a) provide a detailed description of the governing equations, numerical solution methodology, and in-depth testing against analytic solutions for two and three dimensional flow problems. Additional applications are given in Swanson and Mendelsohn (1993, 1996) and Mendelsohn et al. (1995).

## 2.3 Pollutant Transport Model (BFMASS)

There are three separate models within the WQMAP pollutant transport model system. The first is a single constituent transport model, which includes first order reaction terms. This model is suitable for a single constituent contaminant that is conservative, settles, decays, or grows. This model can be used to predict the temporally and spatially varying concentrations associated with transport of equilibrated sediment contaminants (e.g. hydrocarbons and metals). The second is a multi-constituent transport and fate model with a reaction matrix that can be specified by the user. This model can be used to custom design a multi-component water quality model system (e.g. dissolved oxygen and biochemical oxygen demand). The third is a multi-constituent eutrophication model (e.g. nitrogen, phosphorous, dissolved oxygen) which incorporates EPA WASP5 kinetic rate equations (Ambrose et al., 1994). The user can set the parameters of the rate equations via the user interface or select default values. The suite of models allows the system to be used for a wide range of pollutant transport and fate studies, extending from simple single parameter systems to complex multi-constituent problems with interacting components.

In each model the two- or three-dimensional advective diffusion equation is solved on a boundary conforming grid for each constituent of interest. The model employs the same grid system and obtains the face-centered, contra-variant velocity vector components from the hydrodynamic model. This procedure eliminates the need for aggregation or spatial interpolation of the flows from the hydrodynamic model and assures mass conservation. The transport model is solved using a simple explicit finite difference technique on the boundary conforming grid (ASA, 1997). The vertical diffusion, however, is represented implicitly to ease the time step restriction caused by the normally small vertical length scale that characterizes many coastal applications. The horizontal diffusion term is solved by a centered-in-space, explicit technique. The solution to the advective diffusion equation has been validated by comparison to one- and two-dimensional analytic solutions for a constant plane and line source loads in a uniform flow field and for a constant step function at the upstream boundary. The model has also been tested for salinity intrusion in a channel (Muin, 1993).

## 3. Modeling

The modeling domain is primarily the inner New Bedford Harbor. It includes the outer New Bedford Harbor, however, in order to include the influence of dynamics in Buzzards Bat and New England coastal waters. The deepest area in the Inner Harbor is along the federal navigation channel (about 10 m [32.8 ft]). The currents and surface elevation are primarily governed by semi-diurnal tides. Tidal range is approximately 1.2 m (3.9 ft). The freshwater discharge from Acushnet River is relatively low, with an annual average of 0.54 $m^3$/s (19.1 $ft^3$/s) (Abdelrhman and Dettmann, 1995).

Figure 2 shows the model grid conforming the coastline, generated using BFGRID. The upper Acushnet River and other contraction locations use at least two cells, in order to resolve the physical dynamics. The grid is composed of 39,072 cells and the mean depth is about 6.5 m (21.3 ft).

### 3.1 BFHYDRO Modeling

The hydrodynamic model predicts the currents and surface elevation. For this study, a two-dimensional model was used to obtain the depth-averaged currents. The model requires information on tidal forcing at the open boundary and the river flow. For this simulation, a composite tide with mean amplitudes and phases of dominant tidal constituents at the area was used (Figure 2). The river flow used for the modeling is the annual mean flow of the Acushnet River and other tributaries for a total average of 1 $m^3$/s (35.32 $ft^3$).

A summary of BFHYDRO input parameters is listed in Table 1.

Table 1. Model input parameters.

| Parameter | Value |
|---|---|
| Run Time | Semi-diurnal tidal cycle, 12.42 hours |
| Time Step | 10 min |
| Quadratic Bottom Drag Coefficient | 0.03 |
| Horizontal Diffusivity | 1 m$^2$/s (9 ft$^2$/s) |
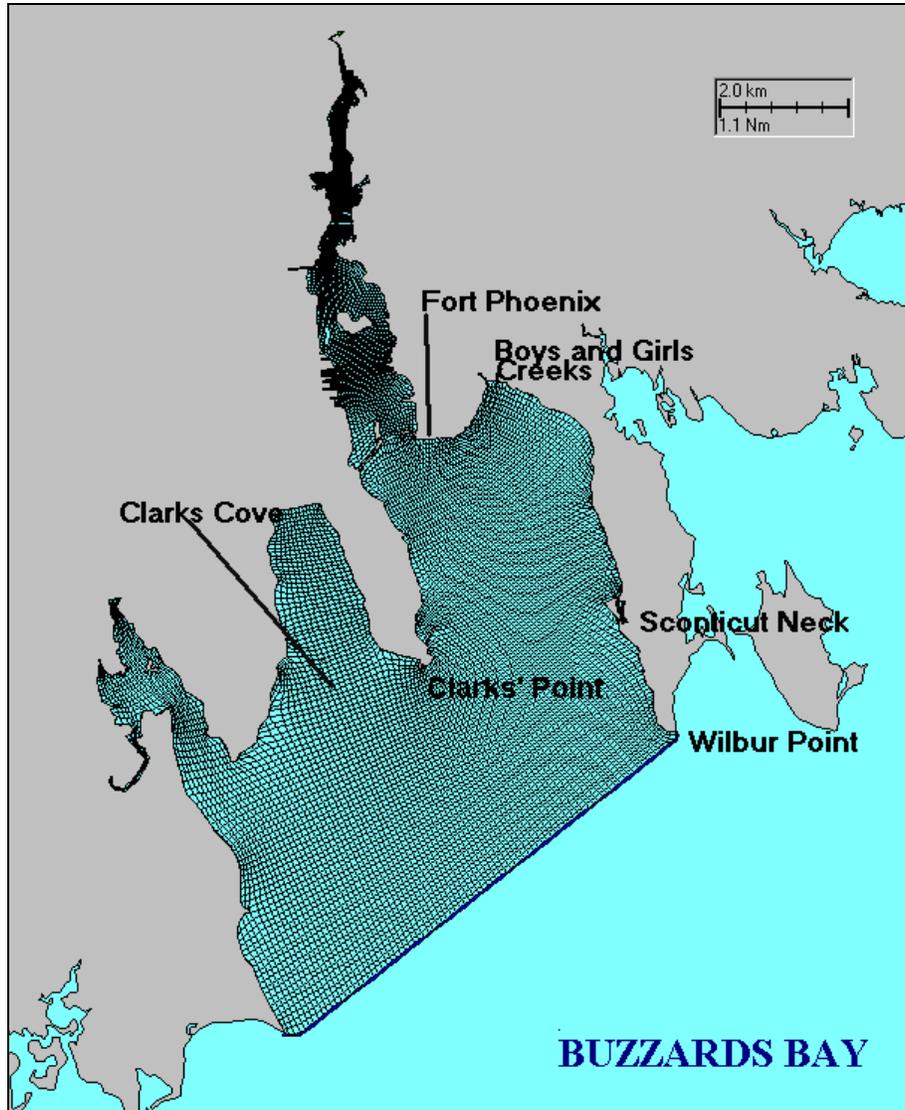


Figure 2. The New Bedford Harbor model domain and grid.

**Tidal Elevation in New Bedford Harbor**
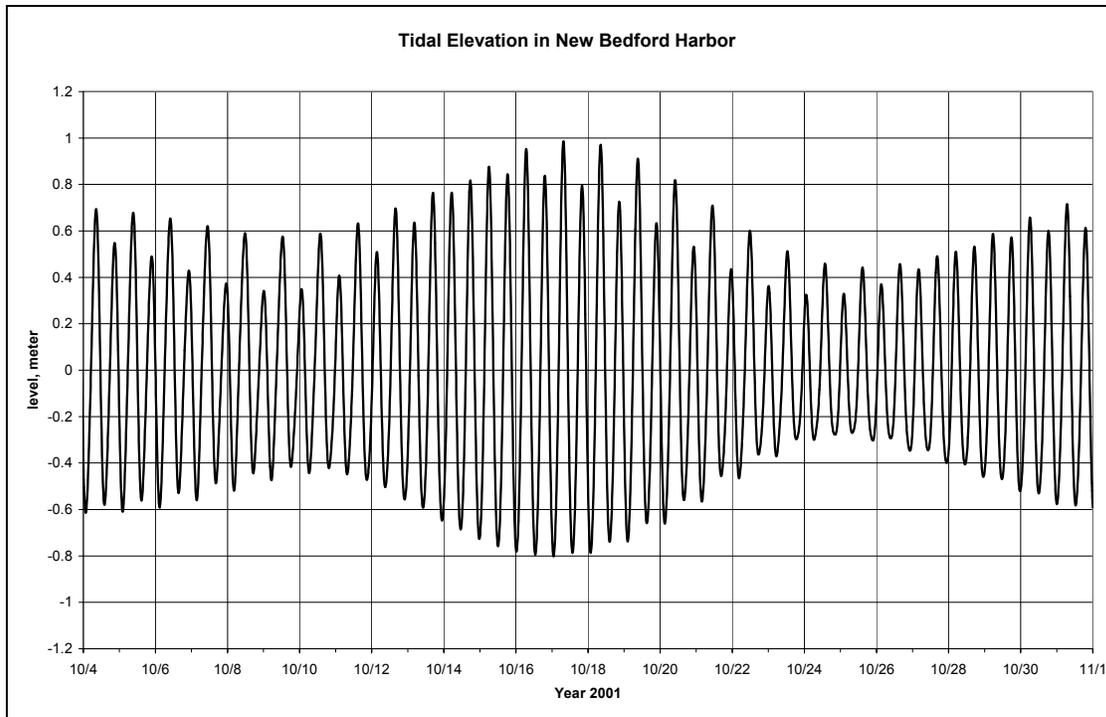
Figure 3. Tidal elevation in New Bedford Harbor.

Each hydrodynamic scenario is set up according to the strength of tides. Figure 3 shows a time series of the composite tide at Clark′s point for a period from 23 October to 1 November 2001. Mean tidal amplitude is about 0.6 m (2.0 ft), with varying to 0.85 m (2.8 ft) and 0.3 m (0.9 ft) for spring and neap tide, respectively. BFHYDRO simulations indicate that the largest current modeled in the Harbor is always found at the waterway between the Hurricane Barriers, especially during ebbs and floods. For instance, during the mean tidal condition the speed is about 0.25 m/s (0.5 kt). Figure 4 shows a snap shot of the speed field at the ebb tide under the Spring tidal condition. In general, the currents in the inner Harbor are on the order of (5 cm/s [0.1 kt]), with relatively large speeds along the federal navigation channel. The predicted speed for neap and spring tidal conditions is about 50% and 140% of the speed at mean tide, respectively.

## 3.2 BFMASS Modeling

The pollutant transport model computes the concentrations of a pollutant on the same grid as the hydrodynamic model. The BFMASS model requires information on the material source strength, and the settling velocity, if any.

The settling velocity acts as a mechanism to remove suspended sediment from the water column. It varies with the type (cohesive or non-cohesive) of material and particle size. For this preliminary screening, the pollutant of interest is assumed in a dissolved form only with zero fall velocity.

The source strength is the amount of pollutant entering the system on a rate basis. Types of the source strength specification for the BFMASS modeling are: an instantaneous
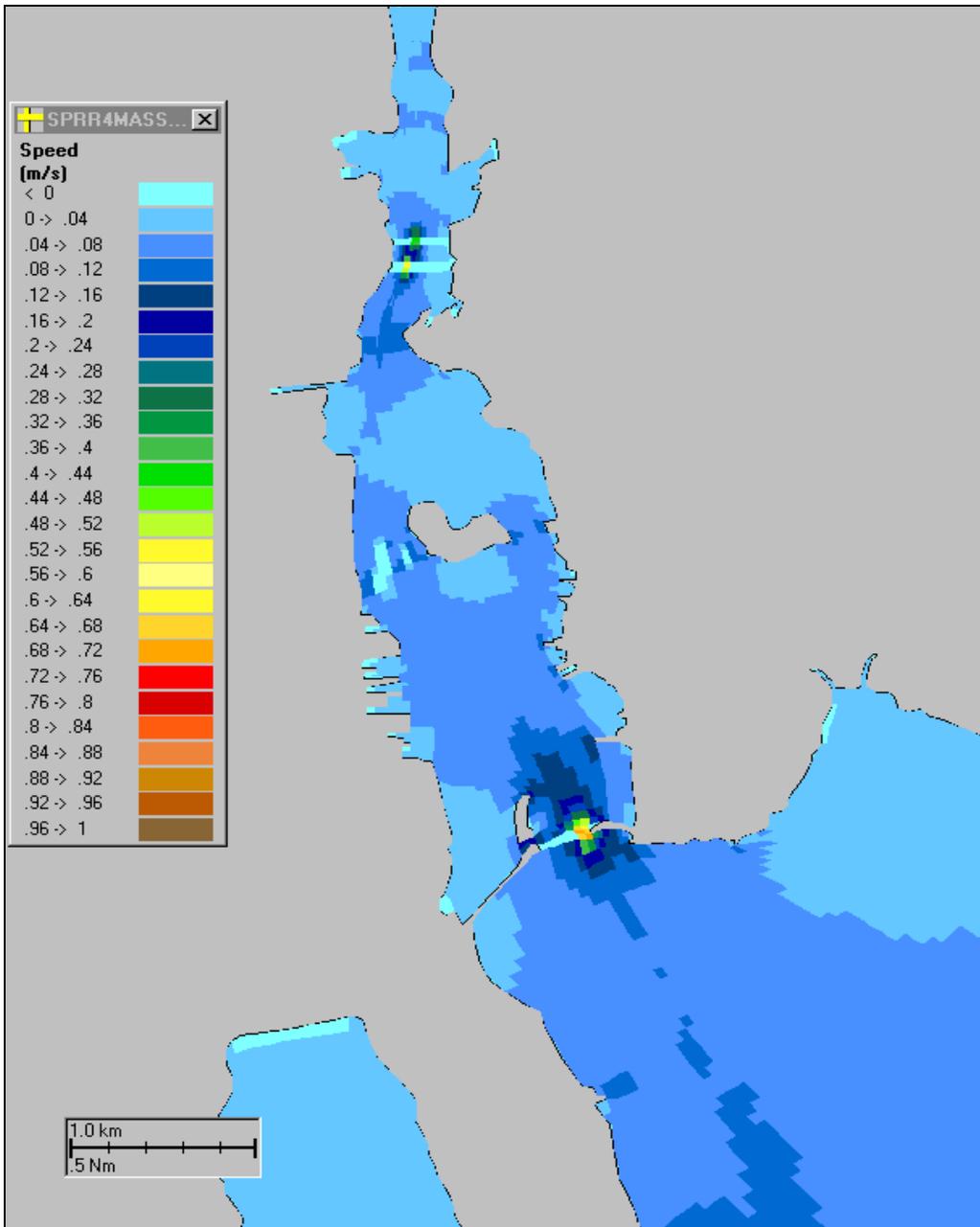
Figure 4. The modeled speed field at the ebb tide during spring tidal condition.

release to the water column, a constant release over time, or a variable release over time. Multiple locations can be also simulated at the same time. Definition of an instantaneous source is the amount of material released to the water column from one barge release over a second. The constant source is defined as the mean loading to the water column from multiple barge releases or barge release over time. A variable source is the time varying loading to the water column as individual barge releases occur according to a set time schedule.

For the New Bedford dredged material management project, the amount of the disposal material and the schedule is not yet determined. Hence we assumed it would be 3000 yd$^3$ per day. Swanson and Mendelsohn (1995) derived this value based on the capability for disposal in order to meet the amount and period of disposal operations in the Boston Harbor Navigation Improvement Plan.

The amount of pollutant released from the disposal material into the water column can be estimated based on the elutriate concentration (EPA, 1991) that is defined by a mass of pollutant constituent to volume of water (mg/L). According to the COE STFATES modeling approach (EPA, 1991; Johnson, 1990), the estimate of the released pollutant amount, M (g), is the triple product of the elutriate concentration, E ($\mu$g/L), the liquid fraction of the sediment, F (%), and the total sediment volume release, D (yd$^3$):

$$M = E \times F/100 \times D \times C, \qquad\qquad (1)$$

where C is a units conversion factor, $(10^3 \text{L/m}^3) \times (0.7646 \text{m}^3/\text{yd}^3) \times (\text{g}/10^6 \mu\text{g})$. For a continuous release over a day, the rate R (mg/s) is

$$R = M \ (\text{g/day}) \times (\text{day}/86400\text{s}) \times (10^3 \ \text{mg/g}). \qquad\qquad (2)$$

The elutriate concentrations for all parameters were not measured for this work. An alternative method was employed to estimate the concentration from available data such as the bulk-chemistry sediment measurements and moisture contents, which is presented in Appendix A. The sediment samplings were taken at 16 stations in both the Inner and Outer Harbor (Lecco, 1998). The data indicated that that FI-A (just north of Fish Island) is the worst contaminated site among the sample stations, especially with chromium, copper, lead, zinc and TPH. Therefore, that station was chosen as a conservative estimate of pollutant loading. A method to predict elutriate concentration follows the equilibrium partitioning model (Di Toro et al., 1991), but it is modified to find an estimate of concentration in the interstitial water by applying the volume of water in the sediment sample. The underlying assumption of the method is that the elutriate concentration in the water column is the same as the interstitial concentration in the wet sediment.

Table 2 lists the estimated elutriate concentrations and resulting release rates for selected constituents in the New Bedford Harbor from station FI-A. Water content (F) used in Eq. (1) is an average of the values that are computed from soil fraction measurements at all 16 sampling stations. Since the ambient water column concentration is not available, the BFMASS predicted concentration in the water column is the excess concentration over ambient. For the complete water quality assessment, however, the total concentration should be determined and compared to water quality criteria.


## 4. BFMASS Results

The WQMAP BFMASS scenarios were set up based on release types and sites as well as hydrodynamic conditions (spring, neap and mean tide). There are two CAD sites proposed: north of Popes Island (PI-CAD) and the federal navigation channel inner area in the lower Inner Harbor (LH-CAD). The disposal sites cover areas of 0.57 km$^2$ (141 ac) and 0.31 km$^2$ (77 ac), respectively. The release for modeling purposes was assumed to be a point source and to be located at the center of each site. BFMASS was run for two sets of release scenarios at each CAD site: an instantaneous loading scenario and a continuous loading scenario. The simulation period was 30 days.

For all the scenarios with an instantaneous release, the pollutant concentration in the water column is large at the time of release. The initial concentration can be estimated as the load divided by the volume of the release cell (Table 3). Most of the pollutant constituents are below the acute USEPA water quality limit, except copper at both CAD sites.

Table 2. Elutriate concentration, and instantaneous and continuous release rates for various constituents based on 3000 yd$^3$/day amount of the disposal material. The elutriate concentration is based on the sediment measurements at site FI-A.

| Constituent | Elutriate concentration µg/L | Instantaneous Release g | Continuous Release mg/s |
|---|---|---|---|
| Mercury | 0.72 | 0.83 | 0.0096 |
| Lead | 162.00 | 185.80 | 2.15 |
| Cadmium | 5.50 | 6.31 | 0.073 |
| Arsenic | 6.66 | 7.64 | 0.0884 |
| Chromium | 335.27 | 384.52 | 4.45 |
| Copper | 866.02 | 993.24 | 11.50 |
| Nickel | 28.60 | 32.77 | 0.379 |
| Zinc | 444.38 | 509.66 | 5.90 |
| PCBs | 0.0276 | 0.0317 | 0.00037 |
| TPH | 3795.00 | 4352.49 | 50.38 |

The BFMASS simulations demonstrated that the magnitude of the concentration drastically decreases over time. Figure 4-a and 4-b show how the mercury concentration changes over a 12-hour period under a mean tidal condition, for instance, when the release is at the PI-CAD site. The maximum concentration predicted 6 hours after the release is about 0.0021 µg/L that is 1.6% of the initial concentration. The maximum concentration is located southeast of the release site (Figure 4-a). Over the next 6 hours the concentration decreases to 0.001 µg/L, 0.8% of the initial concentration. The maximum location is moved back near the release site due to tidal effects (Figure 4-b). These concentration values also change as a result of spring or neap tidal conditions. The highest concentration and smallest spatial coverage area are found during the neap tide, since the pollutant is dispersed by a weaker velocity.

Table 3. Initial concentrations (µg/L) for the release at PI-CAD site and LH-CAD site. The water quality criteria for TPH is not by USEPA. It is a suggested limit by MADEP. Numbers in italic are the concentration values exceeding the water quality criteria. The acute water criteria for PCBs and TPH are not available.

| Constituent | PI-CAD site release | LH-CAD site release | Water Quality Criteria |
|---|---|---|---|
| | | | Acute |
| Mercury | 0.13 | 0.08 | 1.8 |
| Lead | 29.44 | 17.92 | 210 |
| Cadmium | 1.00 | 0.61 | 42 |
| Arsenic | 1.21 | 0.74 | 69 |
| Chromium | 60.95 | 37.08 | 1100 |
| Copper | *157.43* | *95.77* | 4.8 |
| Nickel | 5.19 | 3.16 | 74 |
| Zinc | 80.78 | 49.14 | 90 |
| PCBs | 0.005 | 0.003 | |
| TPH | 689.89 | 419.69 | |

Figure 5-a and 5-b shows the modeled Hg concentration field with the release at the LH-CAD site. At 6 hours after release, the pollutant plume is found near the Hurricane Barrier. The excursion of the plume was larger, compared to the travel distance for the PI-CAD release. The maximum concentration at six hours was smaller by a factor of 2.7 than the PI-CAD release. At 12 hours after release, the plume moved back to the release site. The maximum concentration at 12 hour continued to decrease with the value being about 4.2 times smaller. This is likely due to the fact that the water moves more swiftly in the LH-CAD site than in the other site.

For continuous release scenarios, the simulation lasted for 30 days. Overall results are, first the maximum concentration was always located at the release site. Secondly, the water column concentration varied at semi-diurnal tidal frequency (Figure 6-a and 6-b). Thirdly, the concentration gradually accumulated over time.

For a release at the PI-CAD site, the copper concentration was greater than the chronic criteria regardless of hydrodynamic condition. At the end of the simulation period, the maximum copper concentration reached 9.0, 7.6 and 11.5 µg/L for mean, spring and neap tidal conditions, respectively. These values were greater than the chronic water quality criteria of 3.1 µg/L. Table 4-a summaries the modeled concentrations for metals, total PCBs, and TPH (EPH). These values listed in the table are obtained under the neap tide, with is slightly worse than the other tidal conditions.

The LH-CAD site release resulted in copper again exceeding the USEPA chronic criteria. This occurred only at high slack at simulation day 15 and 29 (Table 4-b).

It was observed that there were always two maximum and one minimum concentration peaks within a tidal cycle. However, these extreme peaks occurred at different times and

at different sites. For the PI-CAD site release, the first maximum occurred at approximately one hour before low tide, and the second peak was found about one hour before high tide. The minimum concentration at the PI-CAD site was found about one hour before slack tide. On the other hand, the first and second maximum concentrations at the LH-CAD site were observed one hour before high and low tide, respectively. The minimum concentration occurred right after slack tide.

Figure 5-a. Modeled mercury (Hg) concentration (ng/L = 0.001 µg/L ) field 6 hours after a 3000 yd$^3$ instantaneous release: A star represents the release site, located at the Popes Island North CAD site (polygon).

Figure 5-b. Modeled mercury (Hg) concentration (ng/L = 0.001 µg/L ) field 12 hours after a 3000 yd$^3$ instantaneous release: A star represents the release site, located at the Popes Island North CAD site (polygon).
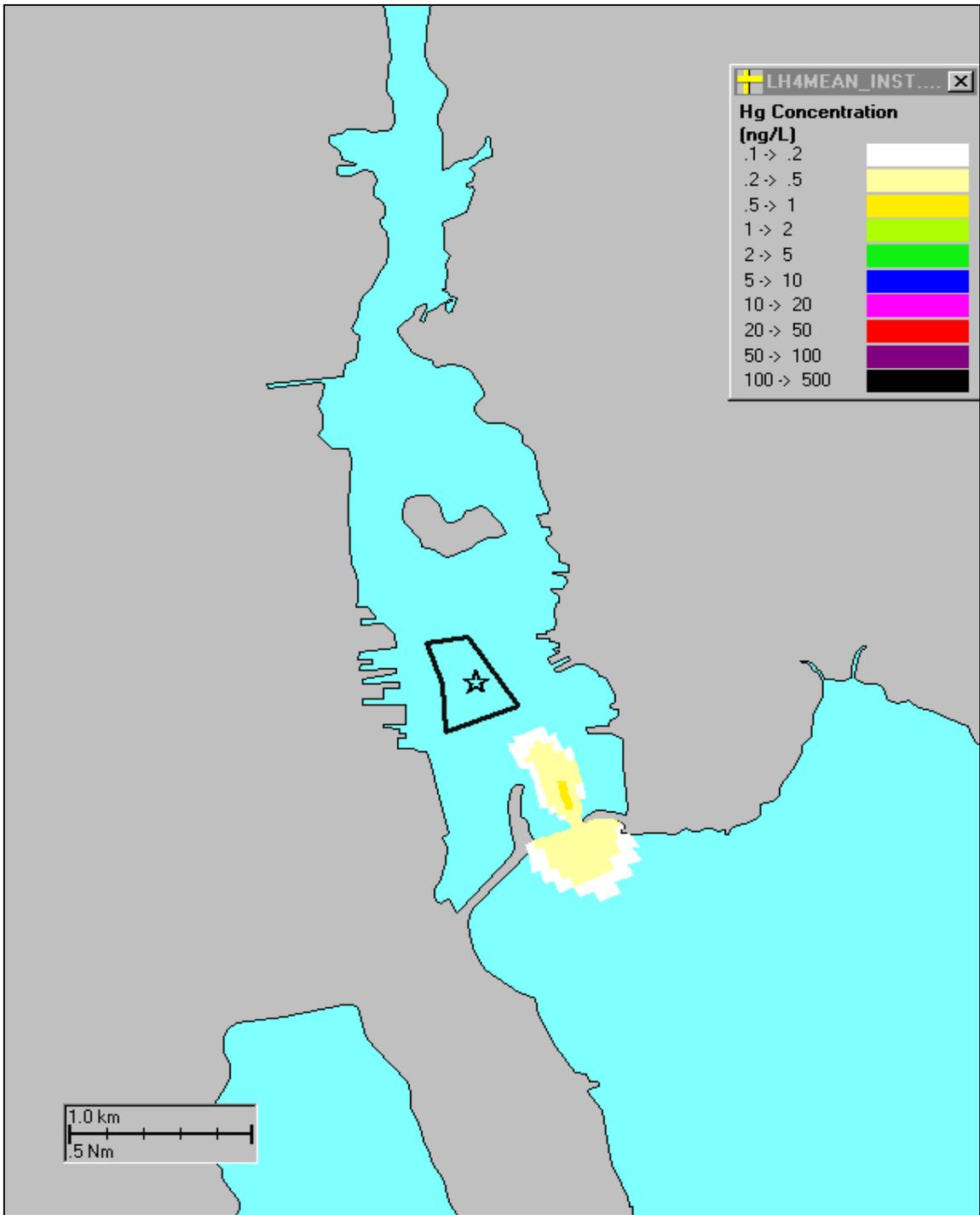
Figure 6-a. Modeled mercury (Hg) concentration (ng/L = 0.001 µg/L ) field 6 hours after a 3000 yd$^3$ instantaneous release: A star represents the release site, located at the federal navigation channel inner CAD site (polygon).
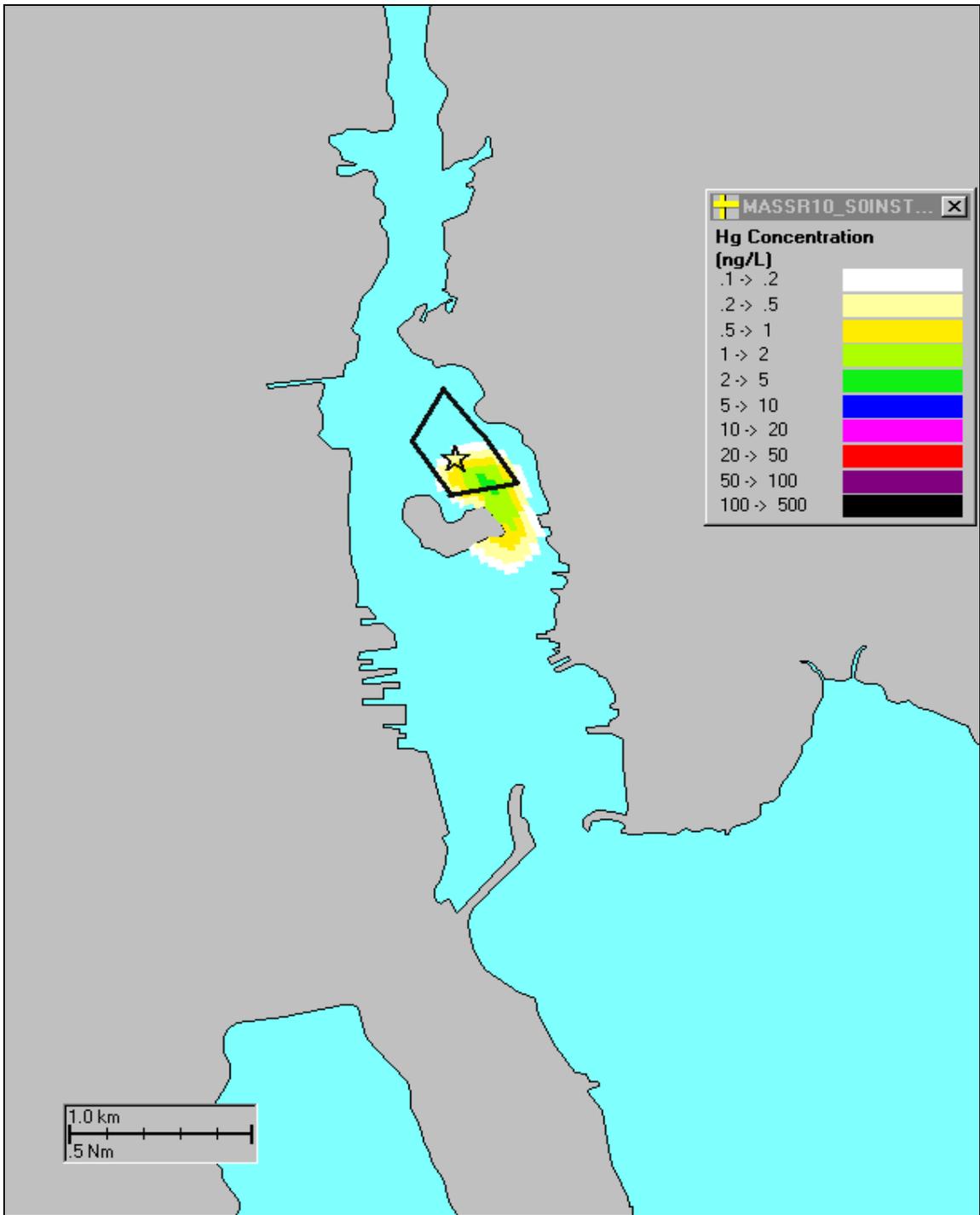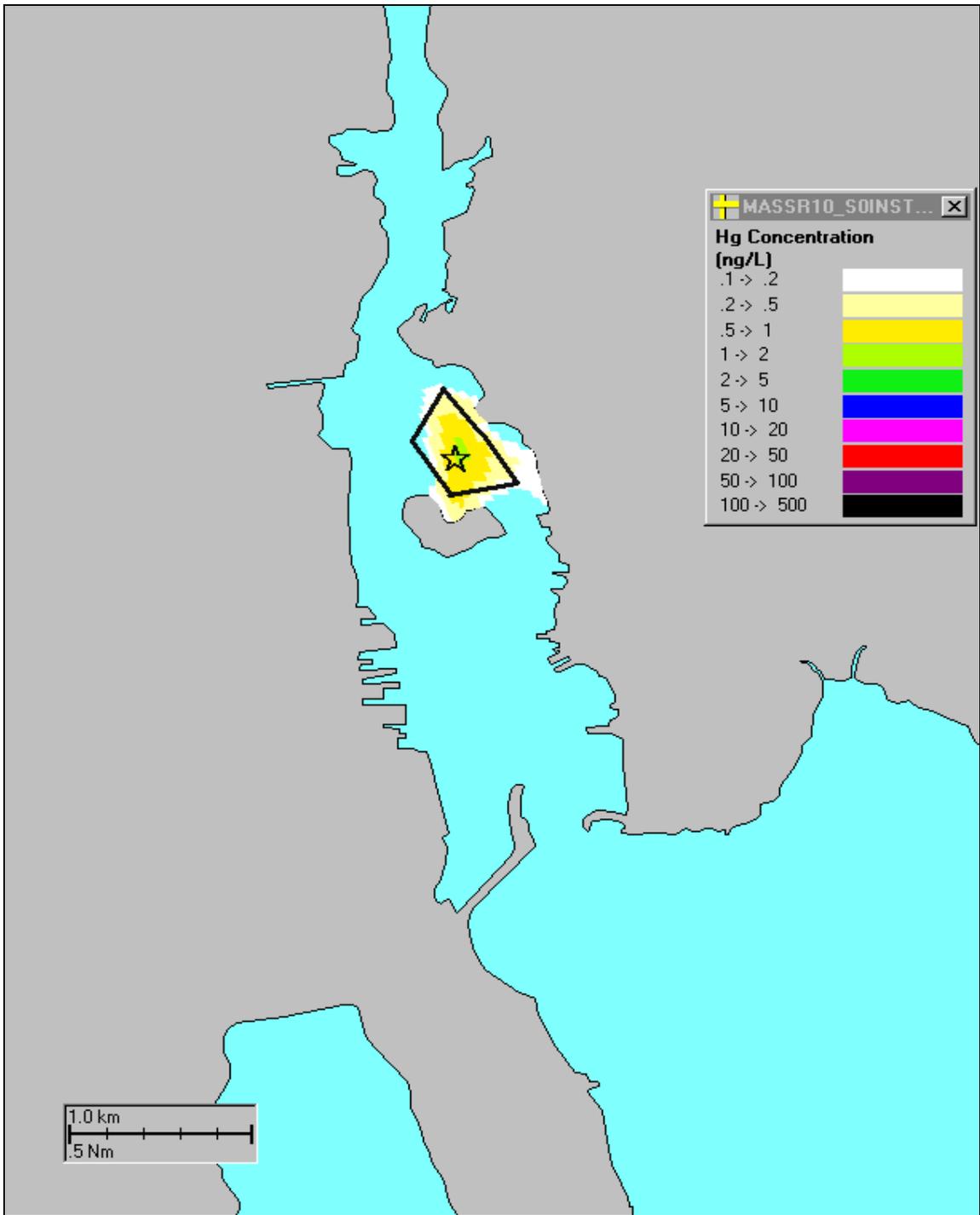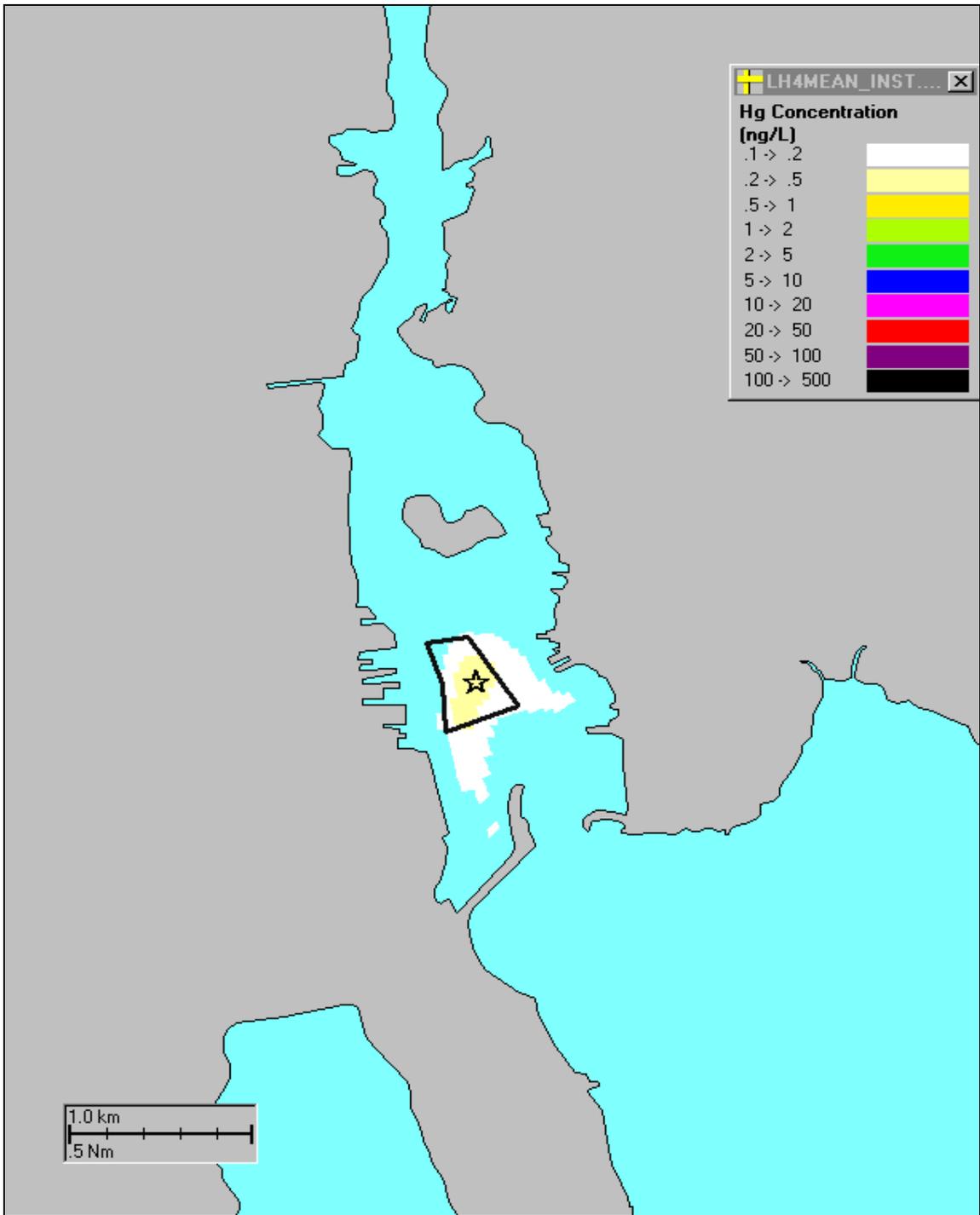
Figure 6-b. Modeled mercury (Hg) concentration (ng/L = 0.001 µg/L ) field 12 hours after a 3000 yd³ instantaneous release: A star represents the release site, located at the federal navigation channel inner CAD site (polygon).
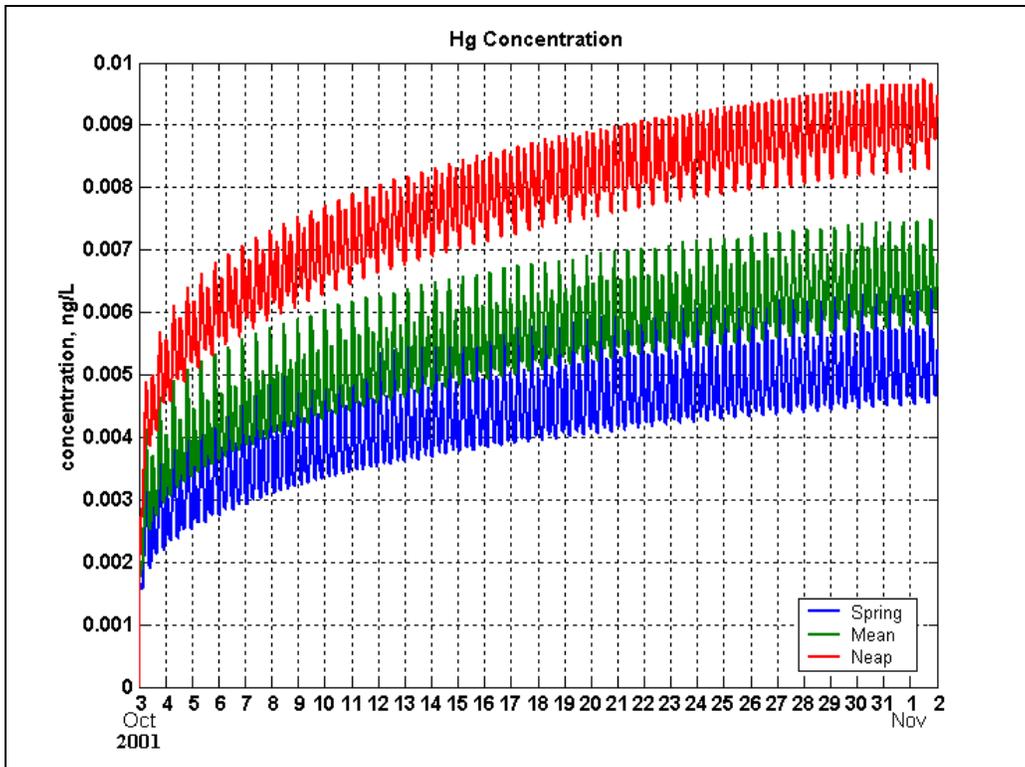
Figure 7-a. Time history of mercury concentration at the PI-CAD site for different tidal conditions. The simulation is performed with a continuous release.
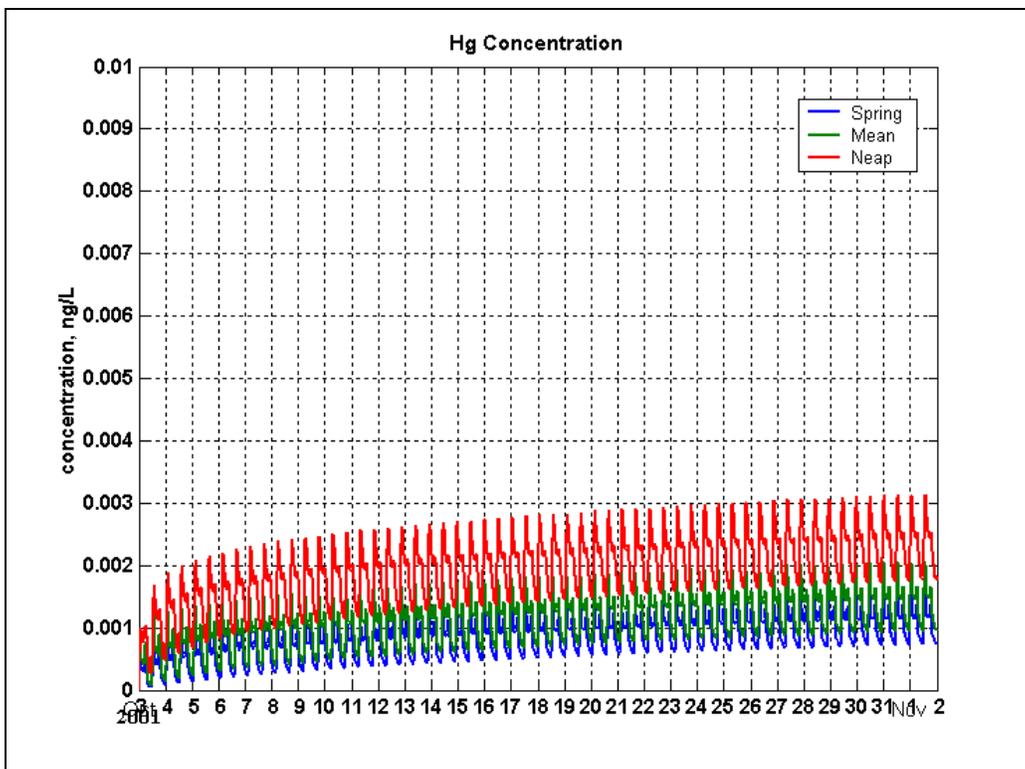


Figure 7-b. Time history of mercury concentration at the LH-CAD site for different tidal conditions. The simulation is performed with a continuous release.

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Table 4-a. Modeled maximum and minimum constituent concentration (µg/L) at 15<sup>th</sup> day and 29<sup>th</sup> day with a continuous release at the PI-CAD site. The hydrodynamic condition is the neap tide. Values in the water quality criteria are of USEPA, except for TPH (*) that is of MADEP (MADEP, 2001). Numeric in italic is the concentration value exceeding the water quality criteria.

| Constituent | Day 15 | | Day 29 | | Water Quality Criteria |
|---|---|---|---|---|---|
| | Max | Min | Max | Min | Chronic |
| Mercury | 0.009 | 0.007 | 0.01 | 0.008 | 0.94 |
| Lead | 1.99 | 1.67 | 2.18 | 1.89 | 8.1 |
| Cadmium | 0.068 | 0.057 | 0.074 | 0.064 | 9.3 |
| Arsenic | 0.082 | 0.069 | 0.089 | 0.078 | 36 |
| Chromium | 4.12 | 3.46 | 4.50 | 3.91 | 50 |
| Copper | *10.59* | *8.94* | *11.55* | *10.10* | 3.1 |
| Nickel | 0.35 | 0.30 | 0.38 | 0.33 | 8.2 |
| Zinc | 5.46 | 4.59 | 5.97 | 5.18 | 81 |
| PCBs | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 |
| TPH | 46.65 | 39.16 | 50.97 | 44.28 | 300* |

Table 4-b. Modeled maximum and minimum constituent concentration (µg/L) at 15<sup>th</sup> day and 29<sup>th</sup> day after a release at the LH-CAD site. The hydrodynamic condition is the neap tide. Values in the water quality criteria are of USEPA, except for TPH (*) that is of MADEP (MADEP, 2001). Numeric in italic is the concentration value exceeding the water quality criteria.

| Constituent | Day 15 | | Day 29 | | Water Quality Criteria |
|---|---|---|---|---|---|
| | Max | Min | Max | Min | Chronic |
| Mercury | 0.003 | 0.001 | 0.003 | 0.002 | 0.94 |
| Lead | 0.64 | 0.33 | 0.71 | 0.40 | 8.1 |
| Cadmium | 0.022 | 0.011 | 0.024 | 0.014 | 9.3 |
| Arsenic | 0.026 | 0.014 | 0.029 | 0.016 | 36 |
| Chromium | 1.31 | 0.68 | 1.46 | 0.83 | 50 |
| Copper | *3.39* | 1.76 | *3.78* | 2.14 | 3.1 |
| Nickel | 0.11 | 0.058 | 0.13 | 0.07 | 8.2 |
| Zinc | 1.74 | 0.90 | 1.94 | 1.10 | 81 |
| PCBs | 0.00 | 0.00 | 0.00 | 0.00 | 0.03 |
| TPH | 14.86 | 7.70 | 16.55 | 9.38 | 300* |

The currents in the Inner Harbor are primarily governed by the semi-diurnal $M_2$ tide. The current speed in the LH-CAD site is almost 2.5 times larger than that in the PI-CAD site. Tides in this study area are typically standing waves such that the flood and ebb currents occur halfway between the high and low waters, having phase lag of about 90°. The $M_2$ tidal ellipses at both CAD sites have slightly different properties (Figure 8). The figure

suggests that the currents at the LH-CAD site are primarily unidirectional along the northwest-southeast direction, whereas the currents at the PI-CAD site are more elliptic with an aspect ratio (semi-minor axis/semi-major axis) of 0.08. The ratio value is about 10 times larger than the value for the LH-CAD site. The figure shows that the PI-CAD ellipse is oriented west less than the other site.

Since the dispersion of mass in the simulation is same all over the model domain, the different occurrence of the concentration peaks may be a result from the different physical dynamics in the ambient currents.
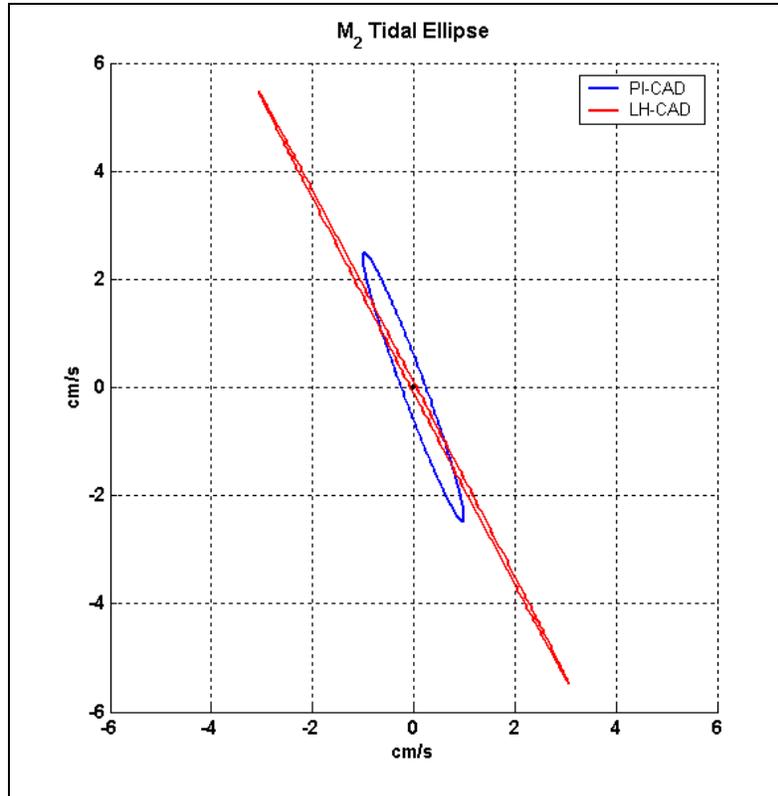


Figure 8. The semi-diurnal M2 tide ellipses at the disposal sites.

The size of the pollutant plume can also be related to different tidal stages. Figures 9-a and 9-b show the modeled copper field at ebb and flood on the 29th simulation day, with the release at the PI-CAD site during the neap tide. The spatial coverage of the copper plume greater than 3.1 µg/L is 0.69 km$^2$ (171 ac) and 0.51 km$^2$ (126 ac) for ebb (Figure 9-a) and flood (Figure 9-b), respectively. The 3.1 µg/L concentration front (a line between blue and green) extends further north during flood by 160 m (525 ft) than during ebb, and further south during ebb by 110 m (361 ft) than during the flood.

For the LH-CAD site release, the plume size of the higher copper concentration is much smaller. For instance, the size of the concentration exceeding 3.1 µg/L is 1,395 m$^2$ (0.34 ac) during the ebb (Figure 10-a) at the 29th simulation day, whereas the area is 2,700 m$^2$ (0.67 ac) during the flood (Figure 10-b).

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Figure 9-a. Modeled copper (Cu) concentration (μg/L ) field during ebb at simulation-day 29 for a continuous release. This simulation is done during the Neap tide. A star represents the release site, located at the PI-CAD site (polygon).
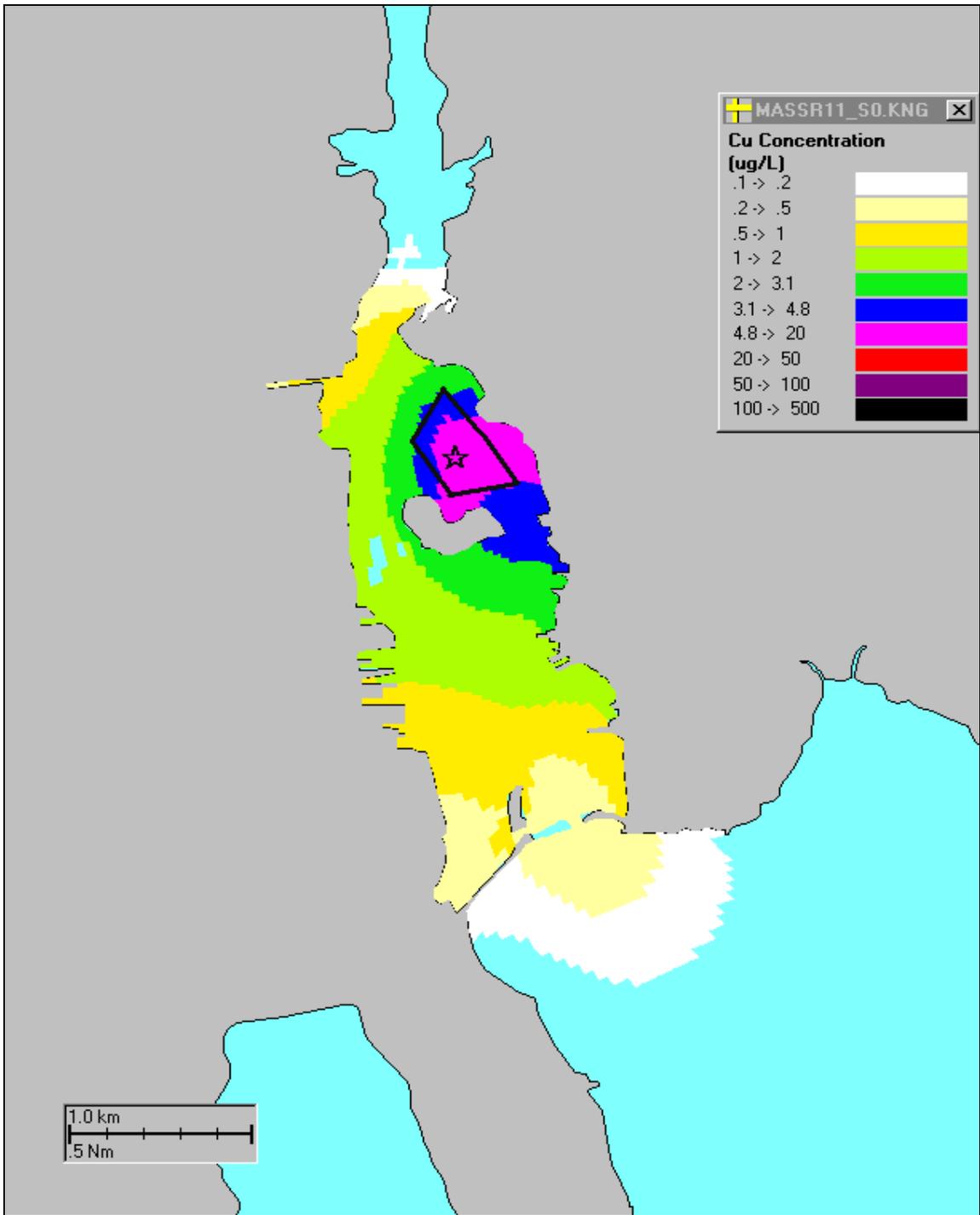
Figure 9-b. Modeled copper (Cu) concentration (µg/L ) field during flood at simulation-day 29 for a continuous release. This simulation is done during the Neap tide. A star represents the release site, located at the PI-CAD site (polygon).
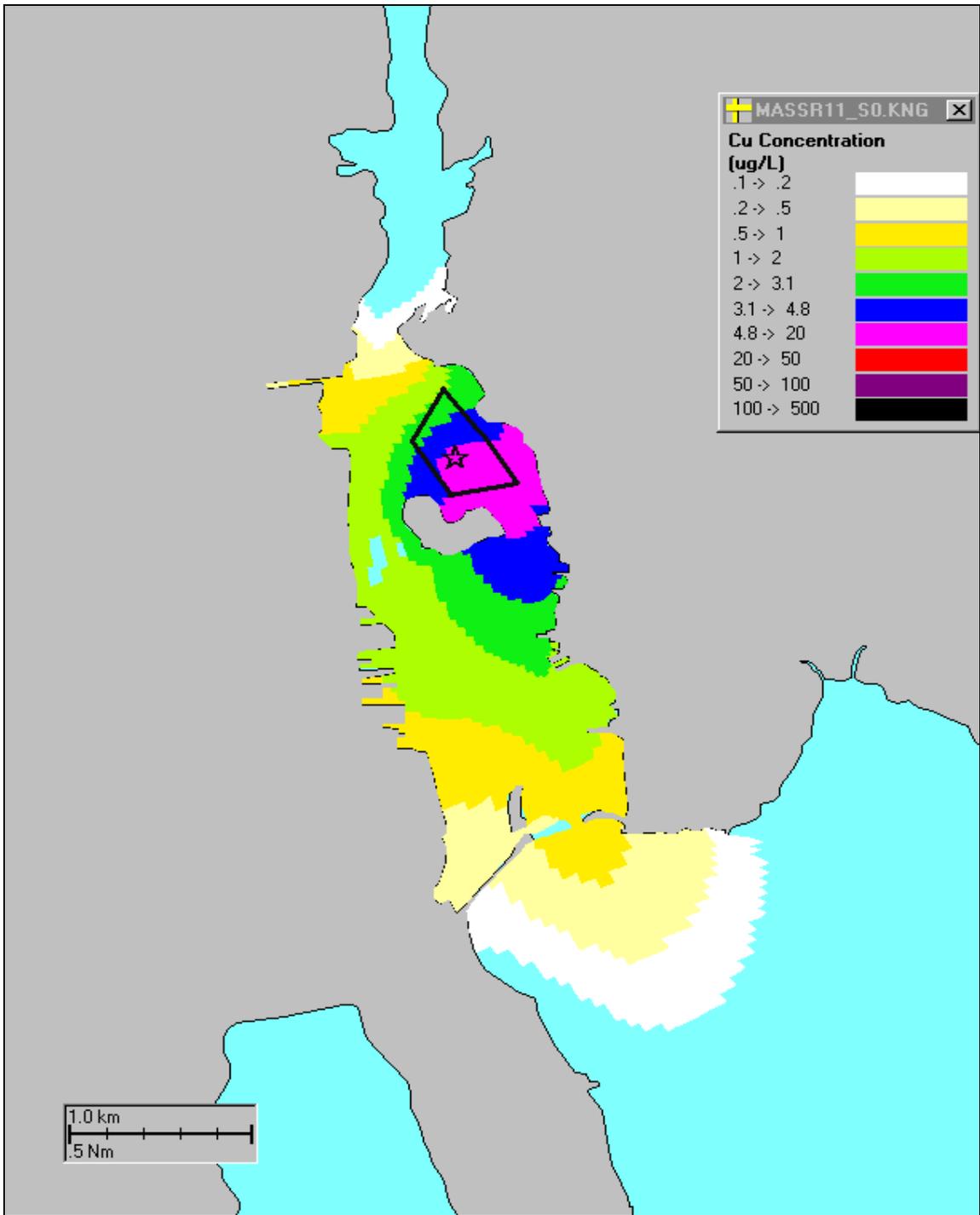
Figure 10-a. Modeled copper (Cu) concentration (μg/L ) field during ebb at simulation-day 29 for a continuous release. This simulation is done during the Neap tide. A star represents the release site, located at the LH-CAD site (polygon).

Figure 10-b. Modeled copper (Cu) concentration (μg/L ) field during flood at simulation-day 29 for a continuous release. This simulation is done during the Neap tide. A star represents the release site, located at the LH-CAD site (polygon).
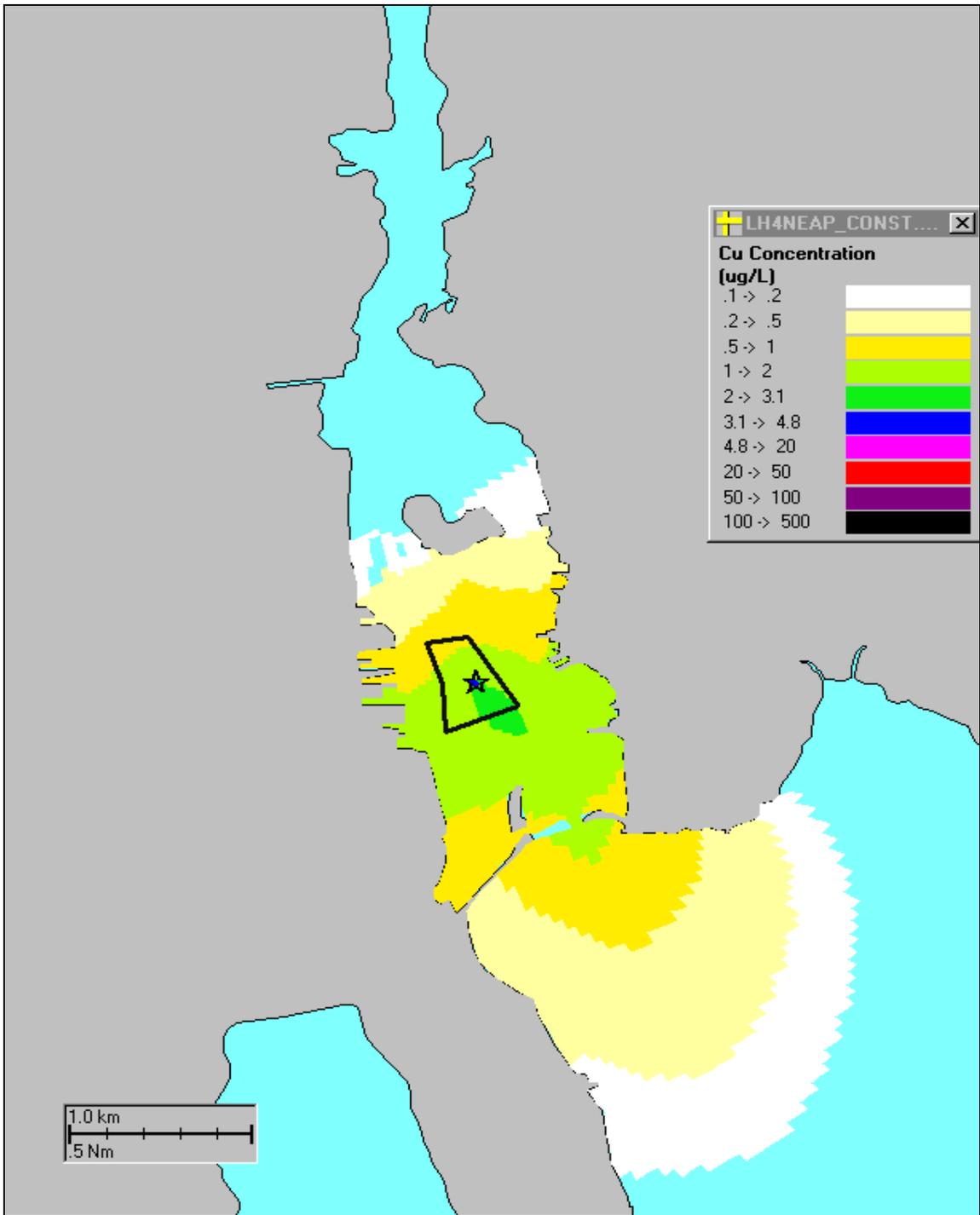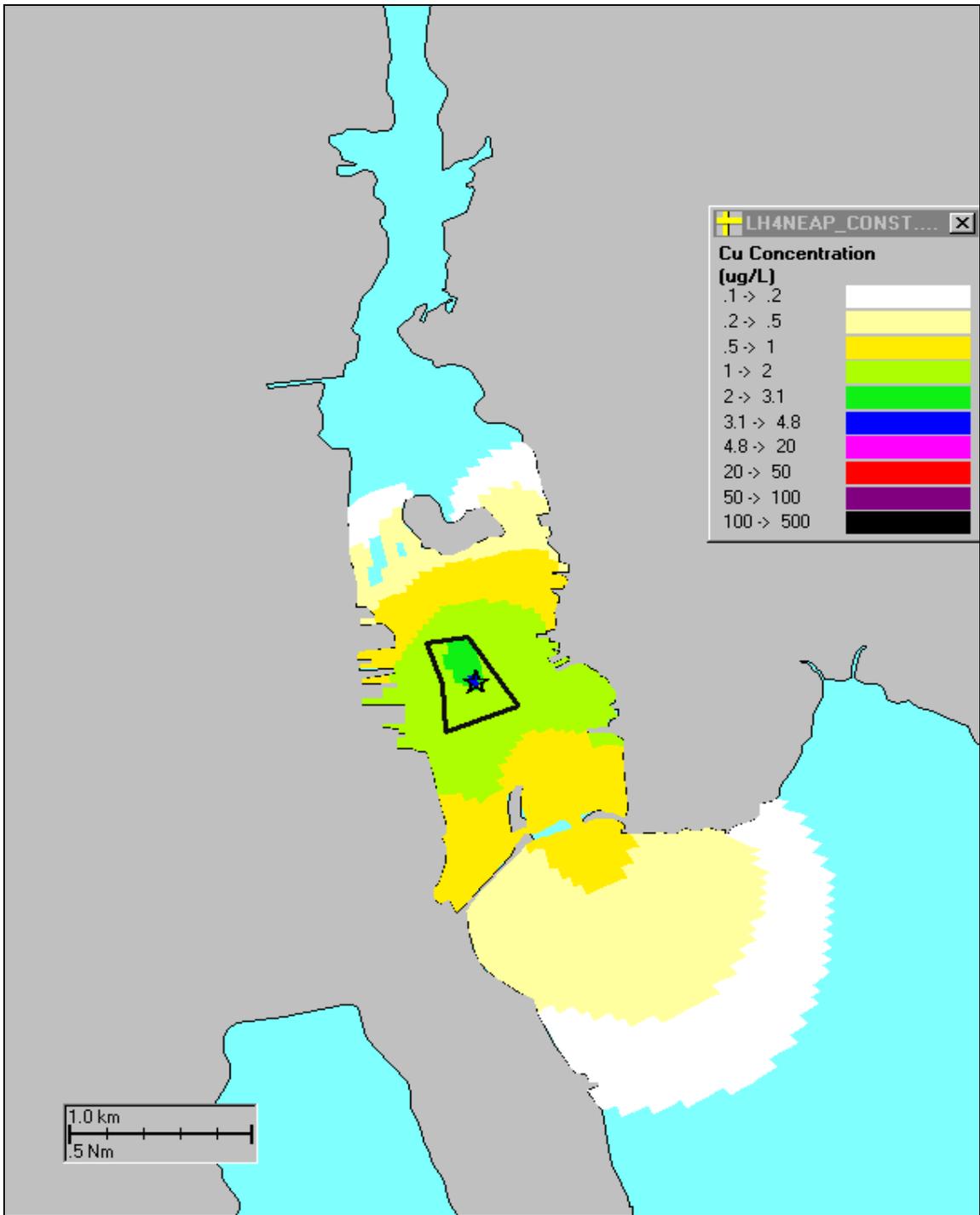
# 5. Summary and Conclusions

A series of preliminary pollutant transport and fate simulations has been performed to estimate the water quality impacts in the water column of the proposed disposal operations for the Inner New Bedford Harbor, as part of the dredged material management project. ASA's WQMAP was used to estimate the water column concentrations of pollutants of interest: various metals (mercury, lead, cadmium, arsenic, chromium, copper, nickel, zinc), polychlorinated biphenyls (PCBs), total petroleum hydrocarbons (TPH), and polynuclear aromatic hydrocarbon (PAH) compounds. The model simulated the transport and fate of the disposal materials at the two proposed sites: north of Popes Island (PI-CAD) and the federal navigation channel Inner site (LH-CAD). Two different release scenarios were set up and run. The instantaneous release simulated acute conditions and the continuous release simulated chronic conditions.

None of the constituents were found to exceed the USEPA water quality criteria under the tested scenarios with one exception. The concentration of copper at the time of instantaneous release was 20 times (LH-CAD site) to 33 times (PI-CAD site) greater than the acute criteria. However, the concentrations decreased with time and quickly fell below the limit. With a continuous release, the pollutant levels increased with time. None of the constituents reached the chronic water quality limit, except copper. At the 29th simulation day, the copper concentration was almost four times the limit at the PI-CAD site release. The pollutant level at the same day was predicted to be 3 to 5 times smaller for the LH-CAD site release than the other site release.

The water quality impact results presented in the work are based on the sediment chemical measurements from the FI-A site, north of Fish Island. Accordingly, the elutriate concentrations used for the mercury, cadmium, arsenic, nickel and PCBs water-column simulations may result in a greater impact than is presented. This is because the elutriate concentrations of the constituents used for the simulation are not the maximum values observed in all the sediment samples. Table 5 lists the maximum elutriate concentrations for the different sampling sites and compares it with the concentrations observed at the FI-A site.

The water quality impacts for mercury, cadmium, arsenic, nickel and PCBs constituents can be estimated by scaling the simulation results from the FI-A site measurements. The loading rate is proportional to the elutriate concentration. The pollutant simulation is two-dimensional and only non-linear process involved in the simulation is the diffusive term that is proportional to the second order derivative of a mass. However, the temporal scale for the diffusivity is much longer than the mass advection by the ambient current. Therefore, a simple linear scaling is reasonable.

The initial concentration for mercury based on the maximum elutriate concentration of 1.34 µg/L, for example, is 0.26 µg/L at the PI-CAD site and 0.16 µg/L at the LH-CAD site. These values are still below the acute criteria of 1.8 µg/L (Table 6). The other

pollutant concentrations are estimated in a similar manner and are far below either the acute or chronic water quality limits (Tables 6 and 7).

Table 5. Comparison of elutriate concentrations (μg/L) at the FI-A site with the maximum concentration from the 16 stations. Numbers with stars represent that the FI-A site has the largest concentration among the measurements at all 16 stations.

| Constituent | FI-A | Maximum/station |
|---|---|---|
| Mercury | 0.72 | 1.34/LH-6 |
| Lead | 162.00* | |
| Cadmium | 5.50 | 5.81/LHC |
| Arsenic | 6.66 | 9.19/LHA |
| Chromium | 335.27* | |
| Copper | 866.02* | |
| Nickel | 28.60 | 29.17/LHC |
| Zinc | 444.38* | |
| PCBs | 0.0276 | 0.0734/FI-B |
| TPH | 3795.00* | |

Table 6. Initial concentration (μg/L) at each CAD site estimated by a scaling. The acute criterion for PCBs is not available.

| Constituent | PI-CAD site release | LH-CAD site release | Water Quality criteria |
|---|---|---|---|
| | | | Acute |
| Mercury | 0.26 | 0.16 | 1.8 |
| Cadmium | 1.06 | 0.65 | 42 |
| Arsenic | 1.67 | 1.02 | 69 |
| Nickel | 5.29 | 3.22 | 74 |
| PCBs | 0.03 | 0.02 | |

Table 7. Maximum water column concentration (μg/L) at 29th simulation day, estimated by a scaling.

| Constituent | PI-CAD site release | LH-CAD site release | Water Quality criteria |
|---|---|---|---|
| | | | Chronic |
| Mercury | 0.02 | 0.006 | 0.94 |
| Cadmium | 0.08 | 0.03 | 9.3 |
| Arsenic | 0.12 | 0.04 | 36 |
| Nickel | 0.39 | 0.13 | 8.2 |
| PCBs | 0.00 | 0.00 | 0.03 |

The size and strength of modeled pollutant plume varied with the location of release. With a release at the LH-CAD site, the simulation resulted in smaller concentration in water column than at the other site. This may be due to the fact that the larger currents exist at the federal channel Inner site than north of Popes Island. The plume also varied with time. For an instantaneous release, the plume quickly decreased not only in size but also in strength. On the other hand, the size and strength of the plume for a continuous release increased gradually at a large time scale and varied at a scale of the semi-diurnal tide.

The fate and transport of the pollutant component simulated in this work is based on a hypothetical loading of 3000 $yd^3$ of dredged material per day. It should be noted that once an actual loading is determined, the simulation results should be scaled by this load to obtain more accurate estimate of pollutant concentrations.

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APPENDIX A
Estimate of interstitial water concentration

**Estimate of interstitial water concentration of pollutant constituent**

The estimate of the source strength, Eq. (1), requires the elutriate concentration. For this project, however, the elutriate concentration is not measured. This appendix presents a method for the estimate of the elutriate concentration from the bulk-sediment concentration measurement. The method is based on the equilibrium partitioning model (Di Toro et al., 1991)

The bulk-sediment concentration is measured by the chemical weight to dried weight of sediment from a wet sample, along with a fraction of solid content. We assume that the bulk-sediment concentration, $Ctot$ (mg/kg), can be separated to the concentration in particulate form, $Ca$ (mg/kg), and dissolved form, $Cd$ (mg/kg):

$$Ca + Cd = Ctot, \tag{A-1}$$

where the $Ca$ and $Cd$ are not directly measured. The pore water concentration, $Cdp$ (mg/L), is defined by equilibrium partitioning (Di Toro et al., 1991) as follows:

$$Cdp = \frac{Ca}{KocFoc}, \tag{A-2}$$

where $Koc$ is the organic carbon-PAH/water partition coefficient (L/kg) and $Foc$ is the fraction of organic carbon in the sediment.

The $Cdp$ is also related to the $Cd$ as follows, since the $Cd$ is chemical constituent in dry weight dissolved in interstitial water:

$$Cdp = Cd\,\frac{Ws}{Vw}, \tag{A-3}$$

where $Ws$ is dry weight of soil and $Vw$ is the volume of interstitial water. If a soil fraction, $Fs$, is known instead, Eq. (A-3) can be written

$$Cdp = Cd\,\frac{Fs\rho_w}{Fm}, \tag{A-4}$$

where $\rho_w$ is the water density (kg/m$^3$) and water content $Fm = 1 - Fs$. Therefore, the $Cd$ can be expressed in terms of $Ca$ from Eqs. (A-2) and (A-5):

$$Cd\,\frac{Fs\rho_w}{Fm} = \frac{Ca}{KocFoc},$$

or

$$Cd = \frac{Ca}{KocFoc}\,\frac{Fm}{Fs\rho_w}. \tag{A-5}$$

When Eq. (A-5) is substituted to Eq. (A-1), the particulate concentration $Ca$ is expressed in terms of $Ctot$:

$$Ca = \frac{Ctot}{1 + \dfrac{Fm}{KocFocFs\rho_w}}. \tag{A-6}$$

Finally, the interstitial concentration $Cdp$ is expressed in terms of known variables:

1

$$Cdp = \frac{CtotFs\rho_w}{1 - Fs + KocFocFs\rho_w}. \qquad\qquad\text{(A-7)}$$

If we assume that a constituent dissolved in the water column is the same as the pore water concentration, the elutriate concentration is obtained from Eq. (A-7).