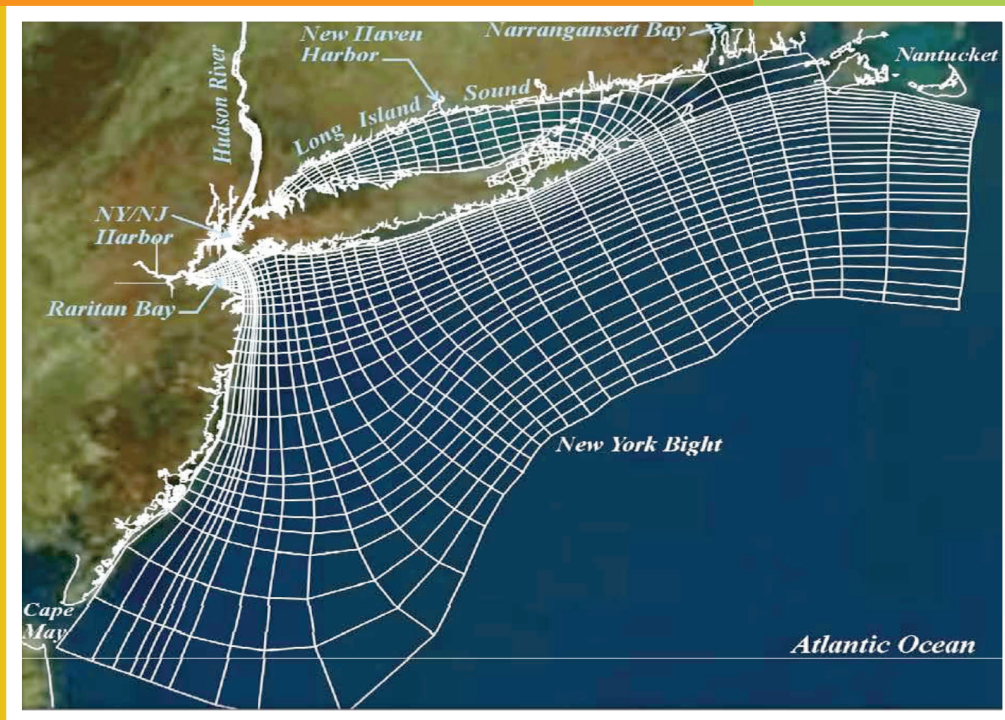# Contamination Assessment and Reduction Project

Summary Report

James Lodge   *Hudson River Foundation*

Robin Landeck Miller   *HDR/HydroQual*

Dennis J. Suszkowski   *Hudson River Foundation*

Simon Litten   *NY State Department of Environmental Conservation (retired)*

Scott Douglas   *NJ Department of Transportation*

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Acknowledgments

Lodge, J., Landeck Miller, R.E., Suszkowski, D., Litten, S., Douglas, S. 2015. Contaminant Assessment and Reduction Project Summary Report. Hudson River Foundation, New York, NY.

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Section 1. Introduction

The Contamination Assessment and Reduction Project (CARP) is a landmark project bringing together federal, state and non-government partners in a determined effort to reduce contamination within the NY/NJ Harbor Estuary, particularly as it relates to dredged material management. Contamination of sediments by PCBs, dioxin and other toxic chemicals is widespread. This has resulted in significantly increased dredging and disposal costs in the Harbor as well as other ecological impacts to the health of the estuary.

CARP began in 1997 and completed the majority of the data collection and modeling activities by 2006. Though CARP's primary focus was on providing guidance about the status and future of contaminated dredged material management, CARP modeling tools and data have been used in the Passaic River and Hudson River Superfund investigations, in the development of Total Maximum Daily Loads (TMDLs), and in several academic research initiatives. The purpose of this report is to provide, in a single place, a summary of all the activities conducted under CARP and a brief overview of the data and modeling results. The report is also meant to serve as a reference tool and roadmap to the more detailed information found in the numerous technical reports, data archives, modeling reports and research papers. Finally, as much of the data collected under CARP are now more than 10 years old, the report provides recommendations for additional work that should be considered to assess the current state of contamination in the Harbor in light of the trends predicted under CARP.

1.1 NY/NJ Harbor Estuary Overview

The NY/NJ Harbor Estuary has been described (Steinberg et al., 2004) as a remarkable place of surprising contrasts: abused but resilient, intensively developed but veined with natural treasures; a thriving port and a teeming estuary; a population center for people; fish; and birds alike. One of the most challenging and serious problems facing the estuary is contamination of its sediments with a variety of chemicals including: polychlorinated biphenyls (PCBs), dioxins and furans, mercury, pesticides, and polyaromatic hydrocarbons (PAHs).

The watershed drainage area (figure 1) of the NY/NJ Harbor Estuary, including Long Island Sound and the New York Bight, is more than 34,700 square miles and includes portions of six states (New Jersey, New York, Connecticut, Massachusetts, New Hampshire and Vermont), 11 major tributary basins, 325 municipal wastewater treatment plants, 750 combined sewer overflows (CSOs), and a population of more than 26 million.

Much of the Harbor exhibits a typical estuarine circulation pattern, a strong upstream movement of flow in near
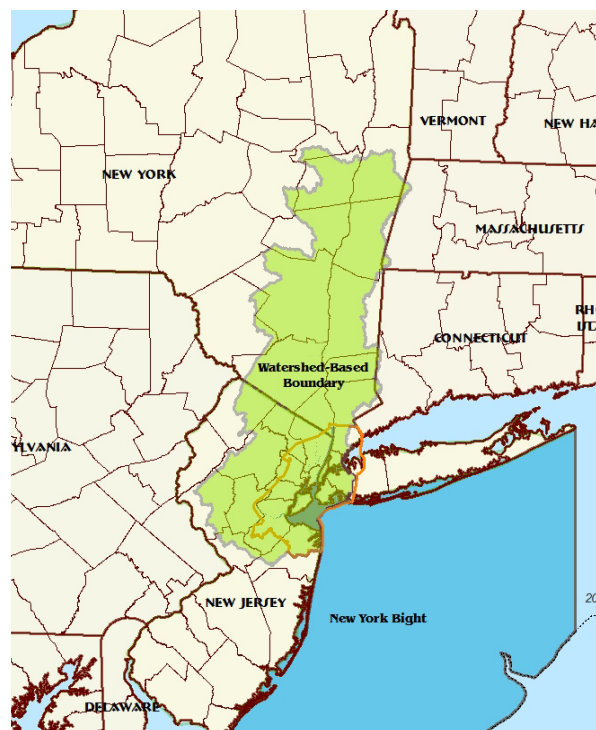
Figure 1. Watershed of the NY/NJ Harbor Estuary

bottom waters and a strong oceanward or downstream movement of flow in near surface waters. The typical estuarine circulation pattern is the result of a large freshwater source (e.g., the Hudson River) interacting with a large saltwater source (e.g., the Atlantic Ocean). Due to strong flow in near bottom waters, resuspension of bed sediments in the Harbor occurs on almost every tidal cycle. The resuspended sediments, as well as bound contaminants, are entrained in the near bottom waters and are carried upstream. This "estuarine trapping" mechanism is one reason why contaminants persist in the NY/NJ Harbor (figure 2) sediments long after external sources of contamination have been discontinued or greatly reduced. This trapping phenomenon is coupled with the oceanward movement of particles from large river inputs (from large storms and spring snow melt conditions) resulting in the continual "reworking" of these sediments in the Harbor.

1.2 Background of the Dredging Crisis

In the fall of 1995, a tug pulling a barge filled with dredged material excavated from the Howland Hook Marine Terminal in Staten Island departed New York Harbor. The tug and barge sailed to the vicinity of the historic Mud Dump Site, where more than 30 years of dredged material from New York Harbor had been placed. Instead of pulling up and dumping its dredged material load at the site, the barge continued on a journey that would take it south along the Atlantic coast, around the Florida peninsula and into the Gulf of Mexico, eventually docking in Corpus Christi, Texas – a journey of over 2,300 miles.

Figure 2. NY/NJ Harbor

The barge's contents were offloaded and placed on a train that traveled another 1,000 miles to East Carbon, Utah, where they were again rehandled and placed within a secure landfill. These New York Harbor sediments made an unprecedented journey of 3,300 miles, at a cost of $118 per cubic yard. The total cost of the Howland Hook dredging and disposal of 150,000 cubic yards amounted to over $20 million. Had the dredged material been placed at the traditional Mud Dump Site in the Atlantic Ocean, the costs would only have amounted to about $5 per cubic yard or $750,000.

So why then did the terminal owners select a disposal site thousands of miles away and pay nearly 30 times the typical rate to dredge and dispose of their sediments? Testing determined that the proposed dredged sediments were unsuitable for ocean disposal because of elevated dioxin levels. Since there were no alternative disposal facilities for contaminated dredged material within the New York/New Jersey metropolitan area, and it was so important for the terminal to be reopened, the owners had no choice but to send the material across the country at enormous cost.

The Howland Hook project highlighted a major dredging crisis that was emerging in New York Harbor, and it foreshadowed two important future scenarios. First, under revised testing protocols, dredged material throughout the harbor would be found to have problematic levels of contaminants, particularly PCBs and dioxins, making virtually all of these sediments unsuitable for placement at the Mud Dump Site. And second, since port operations were critically important to the region, the states

of New York and New Jersey working with the federal government and regional organizations, would have to aggressively seek new and innovative ways of dealing with contaminated dredged material in order to keep the port open and competitive.

One obvious, long-term, solution to the dredging crisis is to reduce the sources of the contaminants winding up in the sediments of shipping channels that periodically need to be dredged. Working through a U.S. Environmental Protection Agency (EPA) initiative called the Dredged Material Forum, a special workgroup developed recommendations for a program that would achieve that goal. In particular, the workgroup was given the task of formulating a plan that would address the following management concerns.

- Which sources of contaminants need to be reduced or eliminated to render future dredged material clean?
- Which actions can yield the greatest benefits?
- What actions are necessary to achieve the future targets recommended in the region's dredged material management plans?

In an effort to resolve the dredging crisis, the Governors of New York and New Jersey signed the Joint Dredging Plan of 1996, a Bi-State Agreement for near, mid and long term actions that were sorely needed. The Port Authority of NY and NJ (Port Authority) provided $130 million, half to each State, to implement the plan. Through financial support from the Bi-State Agreement, and the contributions from several federal, state, regional and private organizations, the Contamination Assessment and Reduction Project (CARP) was launched to address these questions.

The Bi-State Agreement also provided the necessary policy direction that resulted in a streamlining of dredging regulations and permit review, and a move from disposal to beneficial use as a dredged material management strategy. Today, all of the material dredged in the Harbor is beneficially used, from underwater capping and marsh building to brownfield and landfill remediation. However, this comes at a considerable increase in cost. What used to be dredged and disposed of for less than $5 a cubic yard now costs more than $70 per cubic yard, with costs even higher for material from highly contaminated or smaller projects. Nevertheless, in excess of 12 million cubic yards of dredged material have been placed upland since 1997. Ocean placement (capping the Historic Area Remediation Site (HARS)) remains the cheapest management alternative, at less than $15 per yard. With the Harbor requiring 2-4 million cubic yards of dredging per year, and much less than half of that meeting HARS criteria, the legacy of sediment contamination is much more than an environmental problem, it is an economic ball and chain.

1.3 Program Objectives

The four key objectives of the CARP were to:

1. Identify and quantify sources of contaminants of concern to the NY/NJ Harbor Estuary from a dredged material standpoint;
2. Establish baseline levels of contaminants of concern in water, sediments, and fish tissue;
3. Predict future conditions in light of various contaminant reduction scenarios; and
4. Take action to reduce levels of contaminants of concern in water, sediments, and fish tissue.

While the first three objectives have been at least partially achieved, the fourth and arguably the most important objective, still remains to be completed. CARP objectives overlap with the goals of numerous state and federal programs and initiatives including the Hudson-Raritan Estuary Comprehensive Restoration Plan (USACE, 2009), the NY/NJ Harbor & Estuary Program (HEP's) Comprehensive Conservation and Management Plan (CCMP, 1996) and HEP's Regional Sediment Management Plan (RSM, 2008).

Fulfilling the objectives of CARP required extraordinary cooperation and coordination. A multitude of govern-

ment agencies, non-governmental entities, academic institutions, and private contractors were required to support, conduct and oversee the numerous project elements. The various participants formed a management structure—the CARP Management Committee—under the HEP to organize and monitor the work efforts. The CARP Management Committee intended for the CARP data and numerical models to be used not only for management purposes, but also as research tools from which a fuller understanding of the fate and transport of contaminants in the NY/NJ Harbor Estuary could be gleaned. The CARP numerical models are intended to serve as a foundation upon which the next generation of contaminant models can be developed and applied as new management issues arise. As such, the data collected under CARP and all the modeling codes that were developed and applied are publicly available through the CARP website (www.carpweb.org).

1.4 CARP Participants

PARICIPANT	ROLE DESCRIPTION
Port Authority of NY/NJ (PANYNJ)	Through the 1996 Bi-State Agreement, the PANYNJ was the major funding source for CARP and the project sponsor.
New York State Department of Environmental Conservation (NYSDEC) & Empire State Development Corporation (ESDC)	Through the 1996 Bi-State Agreement, the ESDC was a major funding source for CARP. NYSDEC was responsible for collection of water, sediment, and biota samples and coordination of contract laboratories. NYSDEC relied on the NY United States Geological Survey (USGS) and NYCDEP for portions of the data collection.
New Jersey Department of Environmental Protection (NJDEP) & Department of Transportation Office of Maritime Resources (NJDOT OMR)	Through the 1996 Bi-State Agreement, the NJDOT OMR was a major funding source for CARP. NJDEP was responsible for administrating collection of water samples and laboratory analyses by Stevens Institute of Technology (SIT), NJ USGS, Great Lakes Environmental Center (GLEC), Rutgers University (RU), and numerous contract laboratories.
CARP Management Committee (MC)	Co-chaired by the NJDOT OMR and the Hudson River Foundation (HRF), the MC articulated the management needs CARP technical efforts had to address and provided oversight for application of CARP data and models.
Hudson River Foundation (HRF)	HRF provided overall project oversight. HRF commissioned the MEG. HRF specifically administered sub-contract agreements for third-party data validation (Booz-Allan), database construction (Battelle), website development, and model development and application (HydroQual, Inc.).
Model Evaluation Group (MEG)	To ensure that the CARP numerical models were state-of-the-science, an independent MEG was established at the outset of CARP. The MEG continued for the duration of CARP. Experts in organic and inorganic geochemistry, hydrodynamics, sediment transport, and contaminant modeling were included on the MEG.

Table 1. Major Participants and Roles

Section 2. Program Elements

2.1 Data Collection and Monitoring Program (1999 – 2006)

In 2006, CARP partners completed a comprehensive data sampling and laboratory analysis program which began in 1999. The CARP sampling programs were managed by the New Jersey Department of Environmental Protection (NJDEP) and the New York State Department of Environmental Conservation (NYSDEC), and coordinated by the Hudson River Foundation. The New York field program was conducted by NYSDEC personnel working with the US Geological Society (USGS) and the New York City Department of Environmental Protection (NYCDEP). In New Jersey, the NJDEP contracted with Rutgers University, Stevens Institute of Technology, the USGS, and the NJ Harbor Dischargers Group to conduct their field program. In order to accommodate the large number of samples collected, numerous laboratories located throughout the US and Canada were contracted to analyze the samples from the field programs. The US Army Corps of Engineers and the NYSDEC worked with Battelle Ocean Services to develop a computerized management system for the huge volume of data collected by the sampling programs.

CARP sampling included sediments, ambient water, external sources, biota, and trackdown. In order to quantify trace concentrations of contaminants, particularly in water, that in the past were reported as non-detectable,

CARP pioneered the use of new and refined sampling and analytical methods. The publicly available CARP database allows easy access to more than 750,000 measurements.

For ambient water samples and many of the external source characterization and source trackdown samples, hundreds to thousands of liters of water were pumped through filters to collect and concentrate particle associated contaminants suspended in water. Filtered water was then passed through XAD-resin columns, to trap the dissolved fraction of organic contaminants. The filters and resin columns were part of a sampling device, the Trace Organic Platform Sampler (TOPS). Grab samples for the analysis of metals and dissolved PAHs were collected at a sampling port located on the TOPS before the filters. The filters, XAD-resin columns, and grab samples were then analyzed using high-resolution analytical methods. The combination of large sample volumes and state-of-the-art analytical methods resulted in very low minimum detection levels, and thus the acquisition of the first comprehensive data on toxic contamination in the waters of, and sources to, the NY/NJ Harbor. The scope of the CARP data collection program and the high-resolution analytical methods are described below.

2.2 Temporal and Spatial Scope of Data Collection Effort

The CARP data analysis and sampling program had several elements including sediment bed and sediment toxicity, ambient water column, external sources, biota, and trackdown (table 2). Sediment bed, ambient water column, and biota samples were collected as far north on the Hudson River as above the confluence with the Mohawk River and as far south as the New York Bight, spanning as far west as the Raritan River and as far east as Long Island Sound. Sediment bed sampling included

both cores of varying depths and surficial (i.e., top 0-10 cm) sediments.

The external sources sampled included tributary heads-of-tide, urban and rural stormwater, combined sewer overflows (CSOs), sewage treatment plants (STPs), landfill leachate, atmospheric deposition, and the coastal ocean. Biota samples included: cormorant eggs, feathers, blood and plasma; fish muscle and liver tissue; blue

crab muscle tissue and hepataopancreas; amphipods; bivalves; worms; and zooplankton. Trackdown sampling focused on PCBs entering the sewersheds of selected STPs and mercury in the Hackensack River and other minor New Jersey tributaries. Trackdown work within sewersheds took advantage of Passive In-Situ Chemical Extraction Samplers (PISCES). The sampling frequency of each program element varied and the number of laboratory measurements within a program element varied by contaminant.

PROGRAM ELEMENT	RELATIVE MAGNITUDES
sediment/sediment toxicity	more than 200
ambient water column	more than 100
external sources	more than 200
biota	more than 1200
Trackdown	more than 50

Table 2. Major Sampling Components Summary

2.3 NY Data Collection and Monitoring Program

The NY data collection and monitoring program under CARP was divided into four major components: surface water quality, point source discharges, sediments, and biota (plants and animals). The NYSDEC work was conducted harbor-wide and was designed to complement, but not duplicate, the NJ sampling program. State-of-the-science sampling equipment including TOPS was used to collect samples of water, sewage effluent, storm water, and landfill leachate. In addition, sediment samples and biota samples (including zooplankton, benthic invertebrates, fish, crustaceans and cormorants) were collected. High-resolution analytical methods were used to determine contaminant concentrations.

NYSDEC completed several research reports documenting the data collection and analysis of the data

they collected. The reports from these studies are included in Appendix A-1.

Appendix A-1– CARP NY Data Collection and Monitoring Program Reports:

- CARP – Water Chemistry Final Summary Report (NYSDEC)
- NY/NJ Harbor Sediment Report (NYSDEC)
- Polychlorinated Biphenyls (PCBs) in Five Fish Species from the New York-New Jersey Harbor Estuary (NYSDEC)
- Chemical Residues in Cormorants from New York Harbor (NYSDEC)

2.4 NJ Data Collection and Monitoring Program

The NJDEP coordinated several data collection activities and research studies under CARP. Collectively, these studies made up the NJ Toxics Reduction Workplan for NY/NJ Harbor (NJTRWP). The NJDEP data collection program primarily focused on assessing contaminant concentrations in the ambient waters and tributaries of New Jersey and included the following:

- Measuring water column levels and loadings of the toxic contaminants at the head of tide and within the Passaic, Hackensack, Elizabeth, Rahway and Raritan Rivers;
- Water quality monitoring of the Arthur Kill, Newark Bay complex, and Kill van Kull;

- Measuring the loadings of the toxic contaminants discharged from municipal sewage treatment plants, combined sewer outfalls, and storm water outfalls; and

- Monitoring of sediment transport and hydrodynamics within the estuary and its tributaries.

Water quality sampling was conducted using TOPS and traditional grab sampling techniques, which provided separate measurements of dissolved contaminants and contaminants bound to suspended sediment. State-of-the-science high resolution analytical procedures were used to measure extremely low levels of the toxic contaminants.

The separate research reports from these studies are included in Appendix A-2.

Appendix A-2– CARP NY Data Collection and Monitoring Program Reports:

- NJTRWP – Phase One POTW, SWO, and CSO Studies (NJDEP, 2008)

- Study I-C: Concentrations and Loads of Organic Compounds and Trace Elements in Tributaries to Newark and Raritan Bays, New Jersey (USGS, 2007)

- Study I-D/E: Ambient Monitoring of Water Quality Within Major Tributaries and the Estuary (SIT, 2007)

- Study I-E(a): Hydrodynamics of the Newark Bay and Kills System (SIT, 2006)

- Study I-E(b): Hydrodynamics of the Newark Bay and Kills System (Rutgers, 2006)

- Study I-G: POTW and CSO/SWO Discharges NJTWP Project Report (GLEC, 2008)

2.5 Contaminants of Concern and Analytical Methods

CARP focused on contaminants that consistently exceed enforceable water quality standards or assessment criteria for dredged material. These contaminants are also "contaminants of concern" identified by the HEP in the Comprehensive Conservation and Management Plan (CCMP, 1996). These include: PCBs, dioxin/furans, PAHs, pesticides, and selected metals. Coincident measurements of organic carbon and suspended sediment were also made. State-of-the-science analytical methods were utilized to achieve extremely low detection limits (Table 3).

CONTAMINANT	CARP ANALYTICAL METHOD
PCBs	EPA 1668A
Dioxin/Furans	EPA 8290 and 1613B
PAHs	EPA 8270C and 625 with modification
Pesticides	based on EPA 1668A
Mercury	EPA 1631
Methylmercury	Draft EPA 1630 with modification
Cadmium	EPA1638 with modification
Particulate & Dissolved Organic Carbon	EPA 440 - USGS open file 97-380
Suspended Sediment	USGS open file 98-384

Table 3. Analytical Methods

PCBs

Polychlorinated biphenyls include 209 different congeners or chemicals. Each congener represents one of the possible ways one to 10 chlorine atoms can attach to a biphenyl. CARP measured congeners and modeled homologs (PCB congeners having equal numbers of chlorine substitutes).

Dioxins/Furans

Dibenzo-p-dioxins and dibenzofurans include one to eight chlorine atoms substituted for hydrogen on aromatic rings. 75 unique dioxin congeners and 135 unique furan congeners are possible with the one to eight chlorine atom substitutions. CARP measured and modeled seven dioxin and 10 furan congeners.

PAHs

Polyaromatic hydrocarbons include multiple individual chemicals each having two or more fused rings composed of carbon and hydrogen. While hundreds of different PAHs exist, CARP focused on 22 of these, including sixteen designated by EPA as priority and additional oxygenated and methylated forms of parent PAH compounds, which have the potential to be even more toxic.

Pesticides

The organochlorine pesticides, DDT and its metabolites (DDD and DDE) and chlordane, were both measured and modeled by CARP. In total, this group includes 11 different congeners (six for DDT and metabolites, five for chlordane). 2, 4' and 4, 4' substitution positions were considered for DDT/DDD/DDE. For purposes of CARP, total chlordane, octachloro-4,7-methanohydroindane $(C_{10}H_6Cl_8)$, was defined to include five isomers/contaminants: α-chlordane (also known as cis-), γ-chlordane (also known as trans-), oxychlordane, cis-nonachlor, and trans-nonachlor. The nonachlors were selected for modeling because, along with oxychlordane, they are the dominant forms of chlordane usually found in fish.

Mercury and Cadmium

Decades of industrialization has led to mercury and cadmium becoming a focus of ecological and human health concerns (Gillis, 1993). Modeling mercury contamination was a particular challenge for CARP because certain microorganisms can change mercury into methylmercury (MeHg). CARP measured and modeled cadmium, mercury, and methylmercury.

2.6 Quality Assurance and Quality Control

On behalf of CARP, the Hudson River Foundation hired an independent contractor – Booz, Allen, Hamilton (BAH) – to perform a third-party Quality Management Review (QMR) of the data collected by CARP. The QMR included QA document reviews, field and laboratory on-site audits, and data validation and usability determinations for the analytical data collected. The goal of the QMR was to ensure that all CARP environmental data collection activities were scientifically valid, and that the data collected are complete, representative, comparable, and of known, documented, and suitable quality. BAH assessed the quality of CARP data generation efforts at selected field and laboratory sites, determined the usability of CARP data using a combination of automated (CARP Automated Validation and Evaluation System, (CAVES)) and manual validations and provided QA support in addition to that being provided by the agencies collecting the data (i.e., NYSDEC, NYUSGS, NJUSGS, SIT, NJHDG, RU) for the NY and NJ programs to achieve project objectives.

The QA document review included in the CARP QMR included reviews of various laboratories' Standard Operating Procedures (SOP's), state work plans, and state quality assurance plans. BAH specifically looked for potential issues that might have affected comparability of data between the NY and NJ data collection programs (e.g. comparability of detection limits) as well as comparability of data analyzed by the many different laboratories. With regard to the conduct of on-site and field audits, BAH followed EPA quality assurance guidelines and industry-accepted practices. BAH found that the audited laboratories possessed the requisite equipment, skilled personnel, and quality systems to produce usable and valid data for CARP.

Appendix A-3 Quality Management Review Report

2.7 Data Management

Under the direction of the Hudson River Foundation and with support from the US Army Corps of Engineers and the NYSDEC, Battelle Ocean Services was hired on behalf of CARP to develop a computerized management system for the huge volume of data collected by the sampling programs. The data collected under CARP are stored in a Microsoft Access database enabling users to access the data with standard Microsoft Access tools or through a customized interface available on CD-ROM. The customized interface provides tools to search, view, and export data in Microsoft Excel format. The CD-ROM is available through an online request (see www.carpweb.org).

2.8 CARP Model Evaluation Group(MEG)

An important aspect of the CARP model development was the involvement of a Model Evaluation Group or MEG (table 4). The CARP MEG consulted with the Hudson River Foundation (HRF) in the selection of Hydro-Qual as the CARP modeling contractor. The MEG participated in many discussions related to the appropriate and scientifically supportable use of the CARP data. The MEG was also involved in frequent and ongoing peer review of every aspect of the CARP model development and application process. Review comments provided by the MEG are included in the technical reports describing the development and application of the CARP models. The MEG comments and final peer review are included in **Appendix A-4.**

CARP MEG MEMBER	DISCIPLINE/FOCUS AREA
Joel Baker, *University of Maryland*	Organic contaminant cycling
Frank Bohlen, *University of Connecticut*	Sediment transport, dredging
Richard Bopp, *RPI*	Organic contaminant cycling
Joseph DePinto, *LimnoTech, Inc.*	Water quality modeling
Joseph DiLorenzo, *Najarian and Associates*	Hydrodynamics
William Fitzgerald, *University of Connecticut*	Mercury and metals cycling
W. Rockwell Geyer, *Woods Hole Oceanographic Institution*	Sediment transport/hydrodynamics
Lawrence Sanford, *University of Maryland*	Sediment transport
Jay Taft, *Harvard University*	Organic carbon/water quality modeling

Table 4. CARP Model Evaluation Group

Section 3. Numerical Modeling

HydroQual, Inc. developed and calibrated numerical models for CARP that serve as both diagnostic and predictive tools for Harbor contamination. The detailed mathematical mass balance models were developed so that the relationships between contaminant loadings and contaminant concentrations in water, sediment, and biota could be evaluated. The CARP models provide causal explanations for the measured ambient contaminant concentrations and have predictive capacity for assessing the consequences of existing or future contaminant loads and allow managers to predict results of contemplated regulatory and remedial actions. The CARP models simulate the movement of contaminants through the Estuary and predict how continuing contaminant inputs (from atmospheric deposition, sewage treatment plants,

combined sewer overflows, stormwater, tributaries, runoff, in-place sediments and the ocean) affect concentrations of contaminants in water, sediment and biota in the estuary now and over the next four decades.

Given the vast complexities of the Harbor and the processes that affect contaminant fate and transport, CARP modeling was a great technical challenge. HydroQual's modeling work for CARP is distinguished from other contaminant fate and transport modeling efforts in terms of the extent of the spatial domain, the number of contaminants considered simultaneously, the inter-jurisdictional coordination, and the inter-agency interest. The features of the CARP numerical models are described in more detail in the section below.
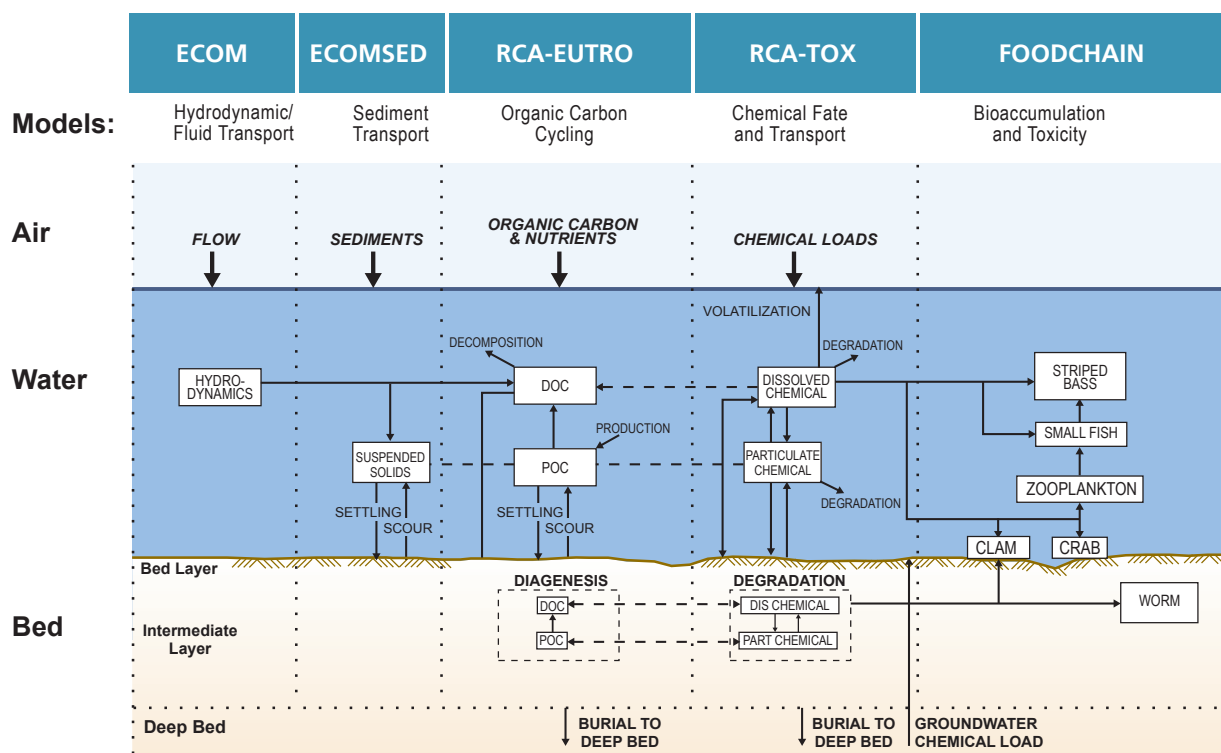

Figure 3. CARP Model Linkages

3.1 Numerical Modeling Features

The models constructed by HydroQual for CARP were developed around a spatial domain covering the entire Hudson/Raritan Estuary as well as Long Island Sound and the New York Bight. The models are fully time-variable and three dimensional. The CARP modeling framework includes linked hydrodynamic, sediment transport, carbon production, contaminant fate and transport, bioaccumulation, and food chain models. These models account for the causal link between external sources of contaminants, such as tributary headwaters, sewage treatment plants, urban runoff, combined sewer overflow, atmospheric deposition, and landfill leachate, to ambient concentrations of multiple contaminant classes in water, sediment, and biota of the Harbor. The relationship between the various CARP numerical models as well as the various media considered (i.e., air, water, sediment, and biota) are shown diagrammatically in figure 3.

The contaminant classes considered for CARP modeling include PCBs, dioxin/furans with 2,3,7,8 substitutions, organochlorine pesticides related to DDT and chlordane, PAHs, and the metals: cadmium, mercury, and methylmercury. Separate contaminant fate and transport kinetics were developed for hydrophobic organic compounds, metals, and methylmercury. Each of the CARP models required both detailed forcing information, which was based upon analysis of CARP data (refer to Section 4), and specification of model constants and coefficients, based on literature values and values used for similar project areas when site specific data were lacking.

Critical to the successful completion of the CARP modeling was the System Wide Eutrophication Model (SWEM) previously developed by HydroQual for the New York City Department of Environmental Protection (Landeck Miller and St. John, 2006). SWEM includes both hydrodynamic and organic carbon production models.

3.2 Hydrodynamic Transport Modeling

Hydrodynamic transport modeling for CARP involved applying SWEM, the previously calibrated and validated hydrodynamic transport model, for the CARP 1998-2002 data collection period. SWEM is based on the Estuarine, Coastal, and Ocean Model (ECOM) (Blumberg and Mellor, 1987) source code. The model is driven by measured water level, meteorological forcing, spatially and temporally varying surface heat flux and freshwater fluxes from the numerous rivers, wastewater treatment plants, combined sewer overflows, runoff from the land, and landfills that enter the NY/NJ Harbor Estuary, Long Island Sound, and the New York Bight. The hydro-

dynamic model solves a coupled system of differential, prognostic equations describing conservation of mass, momentum, heat and salt. Skill assessments of the performance of the hydrodynamic model under 1998-2002 conditions were made using data collected by CARP as well as data collected by other agencies in ongoing, routine monitoring programs. Detailed information on the development and application of the hydrodynamic modeling is included in Appendix A-5.

Appendix A-5 CARP - Hydrodynamic Sub-model Report

3.3 Sediment Transport and Organic Carbon Production Modeling

HydroQual's effort on the CARP sediment transport/organic carbon production model represents one of the first attempts to apply a sediment transport model to a domain as large and complex as the NY/NJ Harbor-Bight-Sound complex. Because field data for sediment transport model calibration were limited, the sediment transport model was initially developed based on simplified formulations and a set of geographically constant coefficients to describe the relevant processes of settling and resuspension. Spatial variations in settling (based on variations in salinity and fluid shearing rates), resuspension (based on consolidation in sediment), and bottom shear (based on wind waves) were then adopted to provide a better description of sediment transport throughout the CARP model domain. This sequential process of adjusting model coefficients and providing a physical justification for the adjustments is an important aspect of the CARP model calibration.

In addition to developing and calibrating a new sediment transport model for the Harbor-Bight-Sound complex, HydroQual's effort included incorporating the newly developed and calibrated sediment transport model into the previously calibrated and validated SWEM organic carbon production model, effectively forming a new combined sediment transport and organic carbon production model, Sediment Transport-SWEM (ST-SWEM). This necessitated both verification that the original calibrations/validations of the organic carbon production model from SWEM had not been compromised when the sediment transport model formulations were incorporated and skill assessment of the ST-SWEM organic carbon production model performance using data collected by CARP and other agencies during the 1998-2002 period.

SWEM calculates the production and fate of particulate and dissolved organic carbon throughout the water and sediment of the New York-New Jersey Harbor Estuary (Landeck Miller and St. John, 2006). The organic carbon is the phase to which hydrophobic organic contaminants sorb. The application of a eutrophication model in the context of a contaminant problem for CARP was a novel approach. Typically, contaminant modeling efforts, constrained by budget and technical expertise in eutrophication, statically assign the fraction organic carbon of the solid phase and ignore the type of organic carbon (e.g., phytoplankton, fresh detritus, refractory organic material). Earlier work (Farley et al., 2006) conducted with Hudson River Foundation funding by Kevin Farley, a HydroQual principal investigator on the CARP model development, and observed by others (Skoglund and Swackhammer, 1999) suggested that sorption of PCBs to phytoplankton is important in controlling the partitioning of PCBs to suspended matter. The CARP organic carbon production model includes a dynamic calculation of several different types of organic carbon.

The CARP sediment transport model development effort included hourly to daily specification of suspended sediment, organic carbon, and nutrient loadings to the NY/NJ Harbor based on data that were comprehensive in terms of representing various loading source types but were limited in terms of temporal frequency. Flow measurements were available at much greater temporal frequency than suspended sediment or POC measurements. Accordingly, historically observed relationships between suspended sediments and POC loadings and river flow under both baseline and storm event conditions were used to specify the suspended sediment and POC loadings. Detailed information on the development and application of the sediment transport/organic carbon production model is included in Appendix A-6.

Appendix A-6 Sediment Transport/Organic Carbon Prodction Sub-model

3.4 Contaminant Fate and Transport Modeling

The CARP contaminant fate and transport and bioaccumulation models originate from a simpler mathematical model of the long-term behavior of PCBs in the Hudson River Estuary (Thomann et al., 1989) and an integrated model of organic chemical fate and bioaccumulation in the Hudson River Estuary (Farley et al., 1999; 2006), collectively called the Thomann-Farley model. Some of the technical advantages of the CARP contaminant fate and transport and bioaccumulation models over the Thomann-Farley model include: better spatial resolution of contaminant hot spots and dredging areas; vertical resolution of the water column to capture estuarine two-layer flow dynamics (represented in 10 vertical depth layers); open boundaries away from the zone of influence of NY/NJ Harbor contaminant loads; inclusion of the Historic Area Remediation Site (HARS) within the model domain; a mechanistic consideration of hydrodynamic transport; suspended sediment and organic carbon through linked sub-models; incorporation of kinetics for a broader range of hydrophobic organic contaminants; incorporation of kinetics for metal contaminants including mercury methylation/demethylation processes; and inclusion of additional species in bioaccumulation calculations (e.g., polychaete worms, clams, striped bass, white perch, American eel and blue crab).

The water quality model source code underlying both the CARP contaminant fate and transport and sediment transport/organic carbon production sub-models is Row Column Aesop (RCA). RCA originates from the Water Analysis Simulation Program (WASP) developed by Hydroscience (HydroQual's predecessor firm) in the 1970's (DiToro et al., 1981, DiToro and Paquin, 1984). RCA code has been used to develop numerous models outside of the NY/NJ Harbor region.

CARP contaminant fate and transport model kinetics, collectively referred to as RCATOX, include separate routines for hydrophobic organic, divalent metal and methylmercury contaminant groups. CARP bioaccumulation model kinetics within RCATOX include calculations of both Biota Accumulation Factors (BAFs) and Biota Sediment Accumulation Factors (BSAFs) from site-specific data as well as more detailed steady-state and time variable mechanistic equations which help explain the behavior of observed BAFs and BSAFs at several pelagic and benthic trophic levels.

Significant aspects of the CARP contaminant modeling include development of contaminant loadings from CARP data (see Section 4) and the development of site-specific, three-phase partition coefficients for the hydrophobic organic contaminants with temperature and salinity dependencies. The development of metal speciation and mechanistic mercury methylation kinetics within the CARP model is state-of-the-science.

The calibration process for the CARP contaminant fate and transport model involved a current conditions calibration to CARP data collected between 1998-2002 for 10 PCB homologs, 17 dioxin and furan congeners with 2,3,7,8 substitutions, 22 PAH compounds, six DDT related chemicals, five chlordane related chemicals, and the metals cadmium, mercury, and methyl mercury. The calibration process also included a hindcast verification for ^{137}Cs, 2,3,7,8-TCDD and several PCB homologs in which model simulations were started in 1965 and carried foward to 2002. For ^{137}Cs, the historical loadings were well known. For 2,3,7,8-TCDD and the PCB homologs, reasonable estimates were made of historical loadings. Hindcast model results were compared to data from dated sediment cores. Detailed information on the development and application of the contaminant fate and transport and bioaccumulation production models is included in Appendix A-7.

Appendix A-7 Contaminant Fate and Transport and Bioaccumulation Sub-models, Section 8 – Food Chain / Bioaccumulation Modeling Approach

Section 4. "Current" (Year 2000) Contaminant Conditions

As detailed in Section 2, CARP conducted an extensive field and laboratory analysis program, producing an enormous set of baseline data characterizing current levels of contaminants in sediment, water, biota and external loading sources (i.e., tributary head waters, sewage treatment plant effluents, stormwater runoff, combined sewer overflows, and landfill leachates) throughout the Estuary. CARP represents the first time that the major sources of contaminants of concern to the NY/NJ Harbor Estuary have been successfully identified and quantified.

4.1 Levels of Ambient Contamination

PCBs

PCB contamination of the sediments, water and biota is widespread throughout the entire Estuary. CARP data and modeling results show that most of the Harbor's surficial sediments (i.e., the top 10 centimeters) are exceeding the benchmark limits established to determine whether dredged sediments can be used as remediation material at the Historic Area Remediation Site (HARS) in the Atlantic Ocean. In addition, CARP data show that average concentrations of PCBs in white perch and American eel currently exceed U.S. Federal Food and Drug Administration FDA limits (for interstate commerce involving edible fish) at most locations sampled in the Harbor and in the mid-Hudson at Poughkeepsie (figure 4). Similarly, water column standards and criteria are broadly not attained across much of the Estuary.

Mean Total PCB Concentration by Species and Area

Legend: Mummichog, White Perch, American Eel, Striped Bass, Winter Flounder, FDA Human Consumption Tolerance
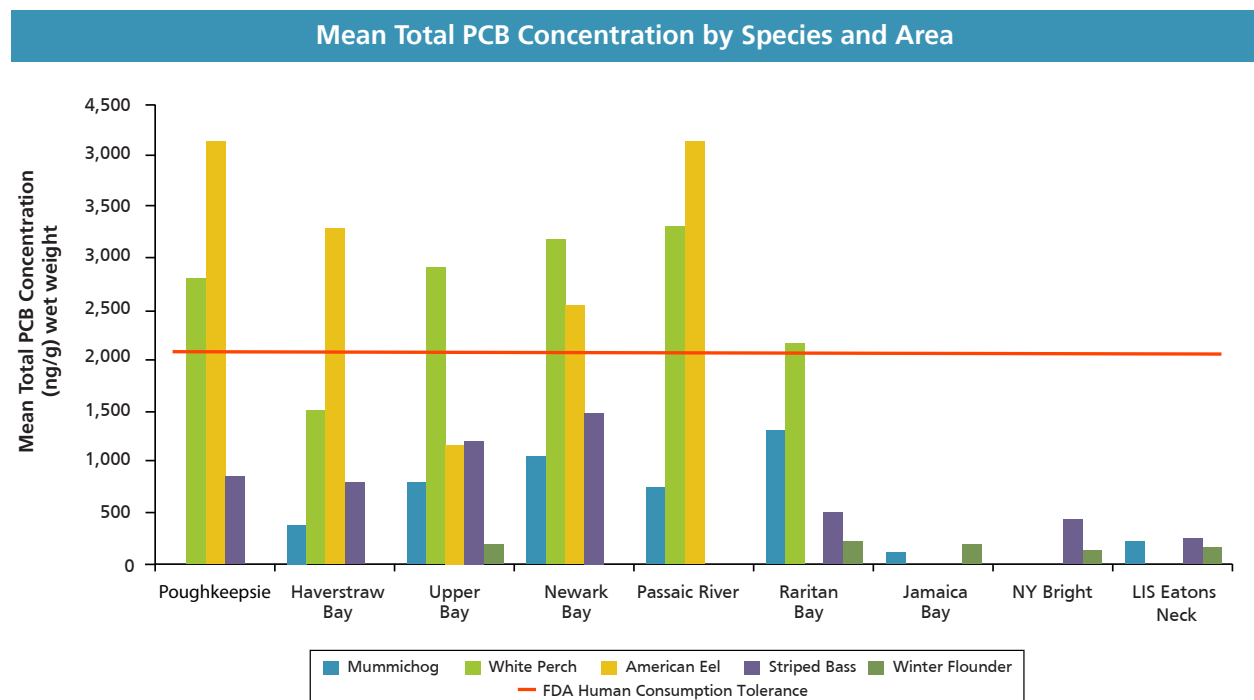
Figure 4. Mean Total PCB Congener Concentrations by Species and Area (PCBs in Five Fish Species – NYSDEC, 2004)

Dioxins and Furans

Dioxin and Furan contamination is prevalent in the sediments, water and biota throughout the Estuary. The Harbor area having the highest concentration of dioxin and furan contamination is Newark Bay and the tidal portions of the Hackensack and Passaic Rivers. Dioxin toxicity equivalence factors (TEQs) calculated from CARP sediment data are highest in Newtown Creek and Newark Bay. Concentrations decrease with distance from these waterways. Applicable endpoints for assessing current dioxin/furan contamination include: for 2,3,7,8-TCDD in the water column, a NY wildlife standard and an EPA/NJ human health criterion/standard; for the summation of 17 dioxin and furan congeners, a NY human health criterion; for 2,3,7,8-TCDD in fish, an EPA risk value; and for 2,3,7,8-TCDD in worms and clams, a HARS ecological value. Most of the CARP water column data and model results violate the NJ/EPA and NY human health standards and criteria. All measured and most calculated CARP 2,3,7,8-TCDD body burdens in fish exceed the EPA risk value. There are also CARP calculated and measured violations of the HARS dredged material assessment criteria.

Mercury

Mercury contamination is most problematic in the Hackensack and Passaic Rivers, but violations of enforceable state standards also occur in other Harbor waterways.

Mercury levels measured and modeled by CARP violate the EPA methylmercury criterion for fish tissue in many areas of the harbor. Further, less stringent state/FDA standards for fish are also violated. In addition, state standards for mercury in the water column are also violated on both a total and dissolved basis according to measurements and model results. Since the States' standards for total and dissolved mercury are human health based, calculated and measured means were also compared to the standards and means were in violation of the NY standard. Comparisons of measured and modeled mercury levels in clams and worms to benthic (i.e., HARS) endpoints are more favorable, suggesting only marginal violations at these somewhat lower trophic levels.

Cadmium

Cadmium levels measured and modeled by CARP on a dissolved basis in the water column are almost an order of magnitude lower than applicable state standards and federal criteria. Total cadmium data and model results in the water column are also fully compliant with the standards and criteria. All of the benthic data collected by CARP meet the HARS limit. Similarly, worm and clam body burdens calculated by the CARP model meet the HARS limit more often than eighty percent of the time. Further, cadmium was rarely found in CARP sediment samples at concentrations greater than the federal Effects Range Median (ERM) guidance value.

4.2 "Current" (Year 2000) Contaminant Loadings

Due to innovative sampling techniques and advances in chemical analysis (providing reliable concentration range estimates for sources) and the numerical modeling work of HydroQual (providing time variable volumetric rate and concentration estimates for sources), CARP represents the first time that the major sources of contaminants of concern to the NY/NJ Harbor Estuary have been successfully identified and quantified. Summary pie chart diagrams of the calculated "Current"

(year 2000) external inputs of contaminants to the NY/NJ Harbor Estuary are included in Appendix A-8. The pie chart diagrams capture time-varying model inputs specified for 34 tributaries, 99 STPs, six landfills, >700 CSOs, >1000 stormwater outfalls, and atmospheric deposition for each contaminant, as well as suspended sediment, organic carbon, and nutrients. The pie chart diagrams do not, however, illustrate the continuing and important role of legacy contamination stored in bed sediments.
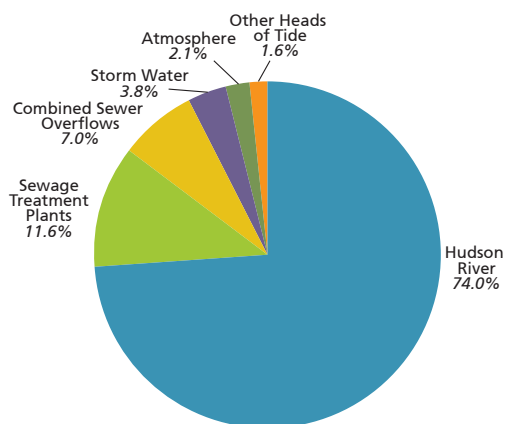
Di+Tetra+Hexa+Octa-CB Loads (Kg/d)

Figure 5. Loading of PCBs to the NY/NJ Harbor Estuary

Appendix A-8 External Loading of Contaminants – Summary Pie Charts

PCBs

The Upper Hudson River PCBs Superfund Site is the dominant external source of PCBs to the Estuary (i.e., below the Troy dam to the ocean). Looking at all the inputs to the Estuary, the load from above the Troy Dam accounts for an estimated 74% of the loading of PCBs to the core model domain (figure 5).

Dioxins and Furans

The Passaic River Superfund site is the dominant source of dioxin to the Estuary. However, because this source is internal (within the model domain) to the model, the load is not depicted on these charts. Of the external sources considered, storm water is the largest contributor accounting for an estimated 58% of the 2,3,7,8 TCDD load (figure 6). The next largest contributors are the heads of tides, not including the load from above the Troy Dam (17.5%).

Cadmium and Mercury

External inputs of methylmercury are a small fraction of total mercury inputs. Of the current external inputs, head-of-tide and storm water are most important for both cadmium and mercury. The continuing releases of mercury from storm water runoff and tributary head-of-tide are consistent with the expected role of atmospheric sources of mercury.

2,3,7,8-TeCDD Loads (Kg/d)
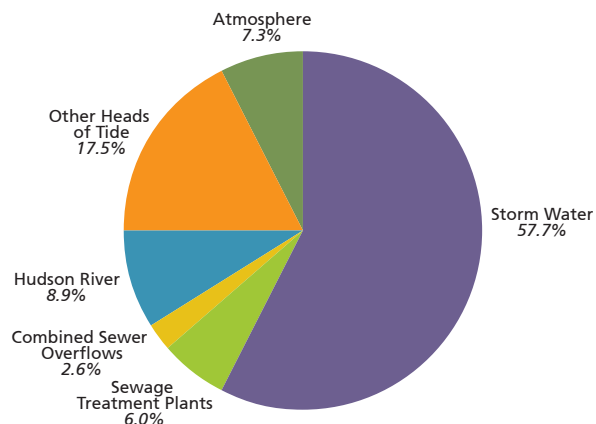
Figure 6. External Loading of Dioxin to the NY/NJ Harbor Estuary

4.3 Bioaccumulation of Hydrophobic Organic Compounds (HOCs)

The calculation of biota-to-sediment accumulation factor (BSAF) and bioaccumulation factor (BAF) using measured chemical concentrations in various organisms (i.e., zooplankton, white perch, striped bass, mummichog, American eel, winter flounder, blue crab, clams, and worms) sampled by CARP and the corresponding exposure concentrations from the water column and sediment, either based on data or extracted from the CARP contaminant fate model, produced interesting re-sults, particularly for the accumulation of hydrophobic organics in worms.

Regarding bioaccumulation of hydrophobic organics in worms, HydroQual specifically observed (1) a variation in BSAFs for PCB homologs as a function of K_{OW} and (2) significant differences in BSAFs for discrete locations within the Inner (i.e., Arthur Kill, Newark Bay, and Upper Bay) and Outer (i.e., Long Island Sound, Jamaica Bay,

and Sandy Hook) Harbor. These homolog and spatial patterns are shown on figure 7. Given the serious implications for setting dredged material quality endpoints that the observed difference in BSAFs could have, HydroQual evaluated possible reasons for the spatial differences using a mechanistic steady-state bioaccumulation model and bioenergetic parameters from the literature.

The observed spatial variation in BSAFs could be modeled or explained by either (1) differences in chemical assimilation efficiencies (presumably attributable to quality of food supply to the worms) for the Inner and Outer Harbor sites, (2) differences in respiration or growth rates (presumably associated with environmental stressors) for the Inner and Outer Harbor sites, or (3) the presence of predatory worms at Outer Harbor sites. Based on CARP sensitivity modeling alone, it is not possible to definitively ascribe the differences in BSAFs at the Inner and Outer Harbor sites to differences in the quality of food supply, in the bioenergetics of the worms, in the presence of predatory worms at the outer Harbor sites, or some combination of the three. HydroQual's analysis of additional NY/NJ Harbor PCB bioaccumulation data presented by others (Meador et al., 1997) confirms that there is a geographic difference in BSAFs for NY/NJ Harbor worms. Further, since these data included only a single worm species, they rule out the possibility that differences in worm populations or the presence of predatory worms could explain the differences in BSAFs observed by CARP at Inner and Outer Harbor sites. Lastly, there is some evidence that there are differences in growth and possibly other bioenergetic behaviors between Inner and Outer Harbor worms (Rice et al., 1995).

CARP bioaccumulation data and modeling results suggest that varying levels of contamination throughout the NY/NJ Harbor may be affecting bioaccumulation behavior of benthic organisms. Further, the modeling and data suggest that dioxin/furan metabolism may be occurring in fish. Detailed information on the development of BAFs and BSAFs is included in Appendix A-7.

Appendix A-7 CARP - Contaminant Fate & Transport & Bioaccumulation Sub-models, Section 8 – Food Chain/Bioaccumulation Modeling Approach

Biota Sediment Accumulation Factors for Select PCB Homologs
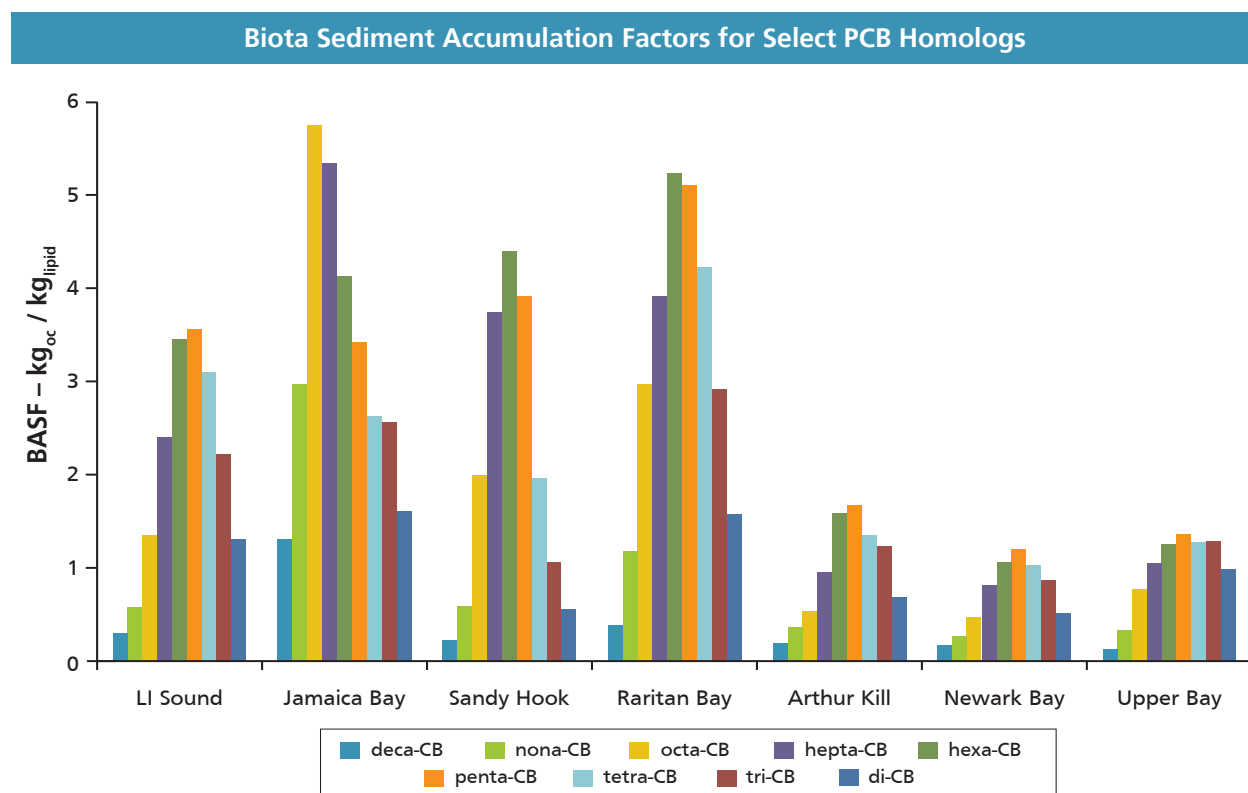
Figure 7. Biota Sediment Accumulation Factors (BASF) for PCB Homologs.

Section 5. Modeling Results

As a result of the development of the CARP models, the region now has scientifically credible tools to evaluate the relative contributions of various sources of contaminants to contaminant levels observed in the water, sediment, and biota of the entire Estuary. The CARP Model Evaluation Group (MEG), which considered and evaluated the overall CARP effort, generally found that the CARP modeling effort did a very credible job of characterizing the relationships between contaminant loadings and concentrations in the environment and advanced the overall understanding of contaminant behavior in the Estuary. The MEG review is included in appendix A-4.

Although still only a small fraction of the wealth of information available from the CARP data and modeling efforts have been carefully considered, CARP has already provided some extremely valuable information about the functioning of the Estuary and the role of contaminants. The CARP modeling and data analyses confirm that the Estuary is a dynamic system where, in some cases, contaminants have been transported great distances from their sources and have dispersed throughout many of the interconnected waterways. Sediments in the Harbor, however, still contain large quantities of persistent contaminants from historic releases. These legacy sediments are a continuing source of contamination and generally play a larger role than the ongoing external loadings in controlling contaminant levels in water, sediment and biota in the Estuary. Therefore, sediment remediation will likely be an important future method of source control.

In general, CARP model simulations indicate that ambient levels of contaminants in all media will continue to decline even if the onging loads remain constant. Burial of contaminated sediments by "cleaner" sediments and resuspension with transport to other areas are among the dominant natural processes that result in the lowering of surficial sediment concentrations over time. Severe storms could potentially be a mechanism for mobilizing deeper layers of highly contaminated sediments and causing elevations of contaminants in some surface sediments. Although severe storms were not specifically modeled as part of the CARP, the CARP models could be applied for this purpose.

Specific CARP model results are described in the section below. While each of the CARP numerical models has its own set of independent and instructive results, the discussion here will focus on the results of applying the various CARP models in series. The development and calibrations of the hydrodynamic and sediment transport/organic carbon production were sufficiently detailed and the controlling processes were effectively modeled to successfully force the contaminant fate and transport and bioaccumulation models. The current conditions calibrations for the CARP hydrophobic organic and metals models demonstrate that source, sink, transport, and transformation terms are correctly represented. The hindcast verification exercise demonstrates that the model has the time dynamic correct for exchange processes between the water column and sediment bed. Correct representation of the time dynamic for exchange processes between the water column and sediment bed is critical for projecting future conditions.

5.1 Model "Clean Bed Analysis"

At an interim point in the CARP model calibration process, a sensitivity analysis was performed on the assignment of initial contaminant concentrations in the sediment bed. For purposes of these sensitivity calculations, the initial sediment bed concentrations of 10 PCB homologs and seventeen dioxin/furan congeners were set to 0 rather than interpolated from data collected in the field. "Clean bed" model simulations were carried out for 96 years. The "clean bed" analysis provided useful, albeit preliminary, information on the time behavior of the system and the observed sediment bed contaminant concentrations by apportioning those associated with either current-day or legacy source inputs.

The "clean bed" analysis showed that the time to steady state, or the time required for the contaminant in the sediment bed to increase to a steady concentration in response to a continuous loading source, is less than 96 years for most areas in the core of the NY/NJ Harbor as represented by the CARP model computational grid. Residence time of contaminants in the system and the time to steady state are related to exchange between the water column and sediment bed. For most of the CARP model domain, the particle mixing rate controls this exchange. One exception to this is the majority of the East River where shear stresses are extremely high and suspended solids concentrations are relatively low. In major portions of the East River, almost no particle accumulation or particle exchange occurs and the dissolved mixing rate controls exchange between the water column and sediment bed. When and where diffusive mixing controls, particularly for high K_{ow} compounds, time to steady state can be upwards of one hundred years. The exercise provided an important check on the modeling of these exchange rates. If any of the mixing processes were overestimated, the CARP model would not be able to maintain the elevated contaminant concentrations in the sediment bed.
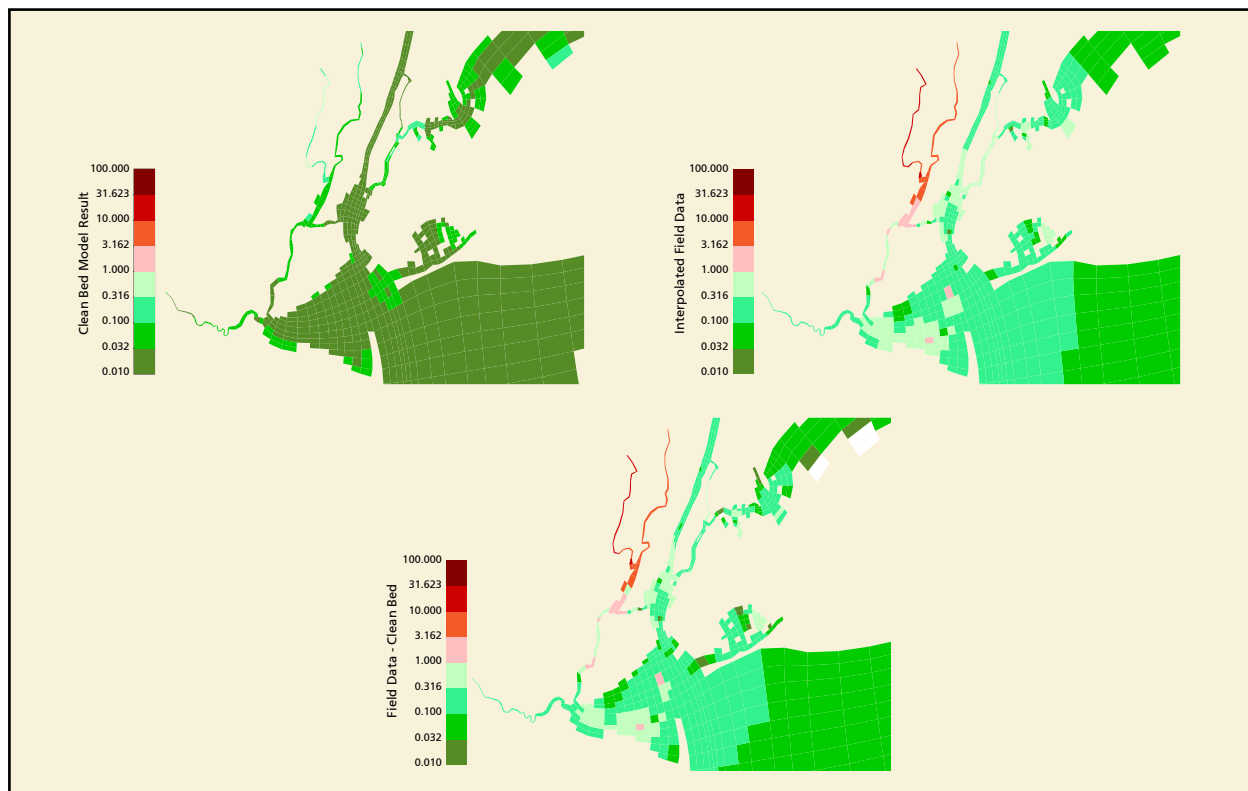

Figure 8. Dioxin-2,3,7,8-TCDD (ng/gm-DW) Concentrations in Surface Sediments Calculated in Clean Bed Analysis.

From the perspective of a sensitivity calculation, the results from the "clean bed" analysis show that:

- For most of the CARP domain, the time for the top 10 cm of the sediment bed to reach steady state is approximately 30 years.

- Some areas at the outer fringes of the CARP model domain required 100 years or longer to reach steady state.

- The "clean bed" analysis results indicate that the "memory" of harbor sediments to past contaminant loads is likely on the order of 30 years (since it takes that long for sediments to reach a steady-state with current continuous loadings) and that the assignment of initial contaminant conditions in the sediment bed is critical in computing long-term responses.

It is noted that in addition to mixing rates, the effects of sediment transport and "estuarine trapping" also impact the time to steady state. Over the course of a 96 year simulation, particulate phase contaminants are continually resuspended, transported (oftentimes by bottom waters moving in a net landward direction), and redeposited, and this process works to further impede the loss of contaminants to the ocean.

The "clean bed" analysis shows how much of the contaminant concentrations observed in surficial bed sediments today can be accounted for by continuing external loading sources. As an example, calculated dioxin (2,3,7,8-TCDD) concentrations in the sediment bed are presented in figure 10 in three ways: interpolated field data; results of a CARP model "clean bed" simulation; and the subtraction of the "clean bed" simulation results from the interpolated field data. The field data represent the contamination due to both the ongoing external loads and legacy sources of contamination. The "clean bed" simulation results represent contamination due only to the ongoing external loading sources included in the CARP model. The subtraction of the "clean bed" results from the field data indicates the contribution to sediment contaminant concentrations from loading sources not included in the CARP model, interpreted to be legacy sources.

For the majority of the contaminants, the observed contaminant concentrations in the sediment bed cannot be explained by the ongoing external loadings and are therefore likely due to historical sources. This is particularly evident for some of the higher chlorinated PCB homologs, 2,3,7,8-TCDD, and 1,2,3,4,7,8-HxCDF. In figure 8, note the small differences between the interpolated field data and the subtraction of the "clean bed" simulation concentrations from the field data. The results of the "clean bed" analysis suggest that historical sources were much larger than current sources for most contaminants. Further, the clean bed results indicate that if NY/NJ Harbor sediments were to undergo remediation, current day sources would likely produce some surficial recontamination, but not to the extent of current (year 2000) observed levels of contamination. For more information, see the clean bed analysis and discussion section of the Contaminant Fate & Transport & Bioaccumulation Sub model report. The report is available in Appendix A-7.

Appendix A-7 – Contaminant Fate & Transport & Bioaccumulation Sub-models, Section 5 – Contaminant Fate and Transport Model Sensitivities

5.2 CARP Model Loading Component Analysis

"Clean bed" results were subsequently confirmed when the final CARP model was used to perform a loading source component analysis. In the loading source component analysis, each of the loading source categories (e.g., sediment initial conditions, tributary head-of-tide, runoff, sewage treatment plants, combined sewer overflows, atmospheric deposition) was activated in the model on a stand-alone basis to isolate the impacts of a particular loading source category on contaminant concentrations in water, sediment, and biota throughout the system over thirty-two years of simulation. Like the "clean bed" results, the loading component results indicate that legacy sediments are a major component of observed contamination, particularly for 2,3,7,8-TCDD. The component results further demonstrate that of the current loading sources, runoff and head-of-tide inputs appear to be most important. Loading component results suggest that over time, overall contaminant levels in surficial sediments will drop and the surficial sediment contamination will become less attributable to legacy sources.
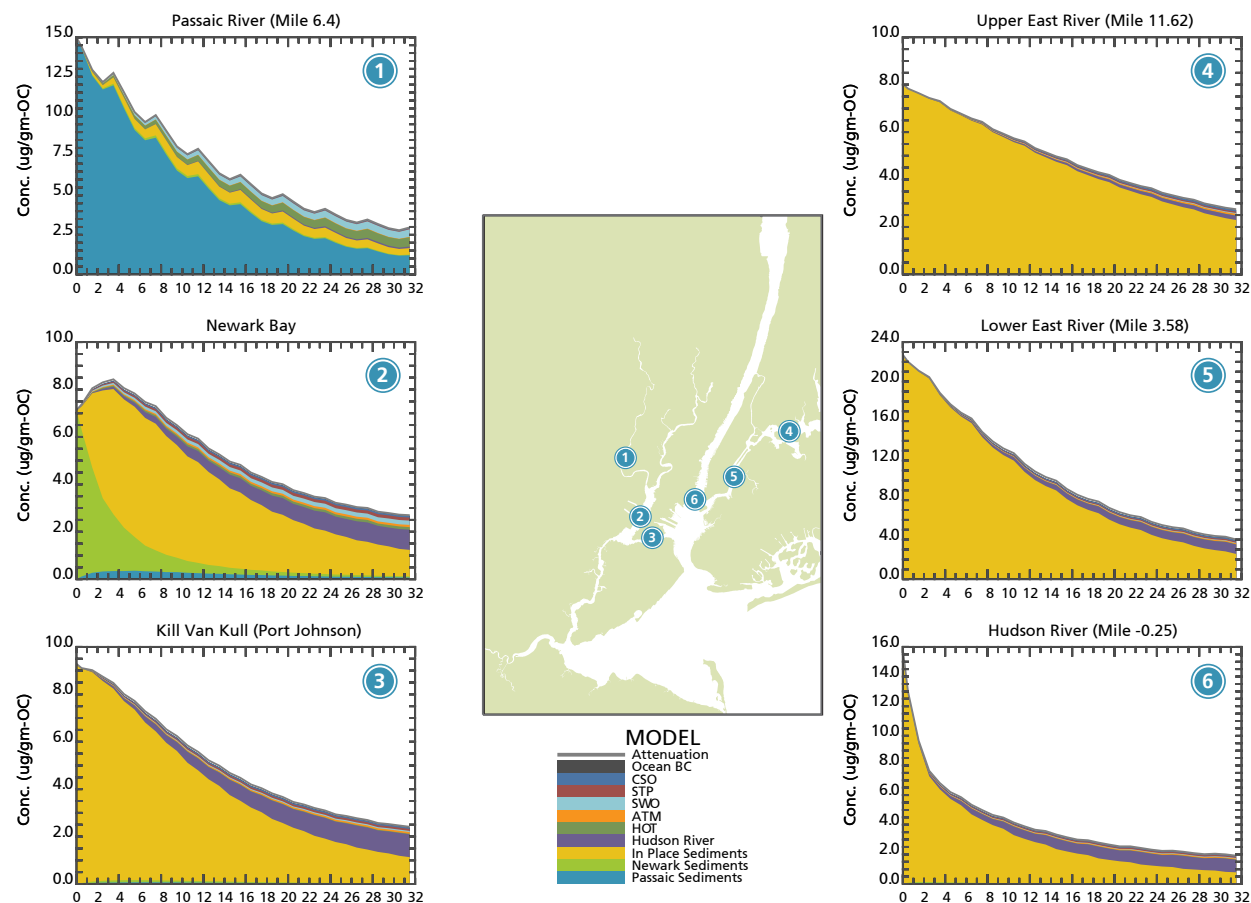
5.3 Component Results for PCBs

Figure 9. Component Run Sediment Time Series for Tetra-CB (ug/gm-OC)

CARP modeling shows that PCBs from the upper Hudson are transported throughout the estuary, including Newark Bay. In both the water column and sediments in western and eastern portions of the NY/NJ Harbor estuary, head of tide loadings are a dominant source for di-CB. Head of tide loadings are less important for tetra-CB, hexa-CB, and octa-CB. In the case of the upper Hudson River PCB source, this observation is consistent with the upstream source signature which is more heavily weighted toward lower chlorinated homologs. For hexa-CB and octa-CB, runoff and STPs appear to be important sources.

The role of legacy sources represented by sediment initial conditions becomes more apparent for the higher chlorinated homologs. This is consistent with the fact that higher chlorinated compounds are more strongly associated with particles and therefore have greater residence time in the system due to estuarine trapping, decreased volatilization and smaller effects of other diffusive exchange processes.

An illustration of CARP component results over time at selected locations for tetra-CB is shown in figure 9. More information and additional component modeling results are available in Appendix A-7.

Appendix A-7 – Contaminant Fate & Transport & Bioaccumulation Sub-models, Section - 12.1.1 - Loading Component Simulations Results for Selected PCBs

5.4 Component Runs for Dioxins and Furans

CARP component simulation results show that legacy sources of 2,3,7,8-TCDD contamination represented by sediment initial conditions have a greater effect than ongoing external inputs on future 2,3,7,8-TCDD concentrations in surficial sediments and the water column. The contributions of the ongoing sources to ambient 2,3,7,8-TCDD concentrations are due mainly to stormwater runoff and, at certain locations, head-of-tide loadings. Similar to 2,3,7,8-TCDD, the results for the 2,3,4,7,8-PCDF component simulations show that legacy sources of contamination reflected in sediment initial conditions are larger than ongoing sources and are the dominant contributors to future contaminant concentrations in water and sediment. The contributions from the ongoing sources to ambient 2,3,4,7,8-PCDF concentrations are due mainly to stormwater runoff and, at certain locations, head-of-tide loadings. An illustration of CARP component results over time at selected locations for 2,3,7,8-TCDD is shown in figure 10. More information and additional component modeling results are available in Appendix A-7.

Appendix A-7 – Contaminant Fate & Transport & Bioaccumulation Sub-models, Section 12.1.2 - Loading Component Simulations for 2,3,7,8-TCDD
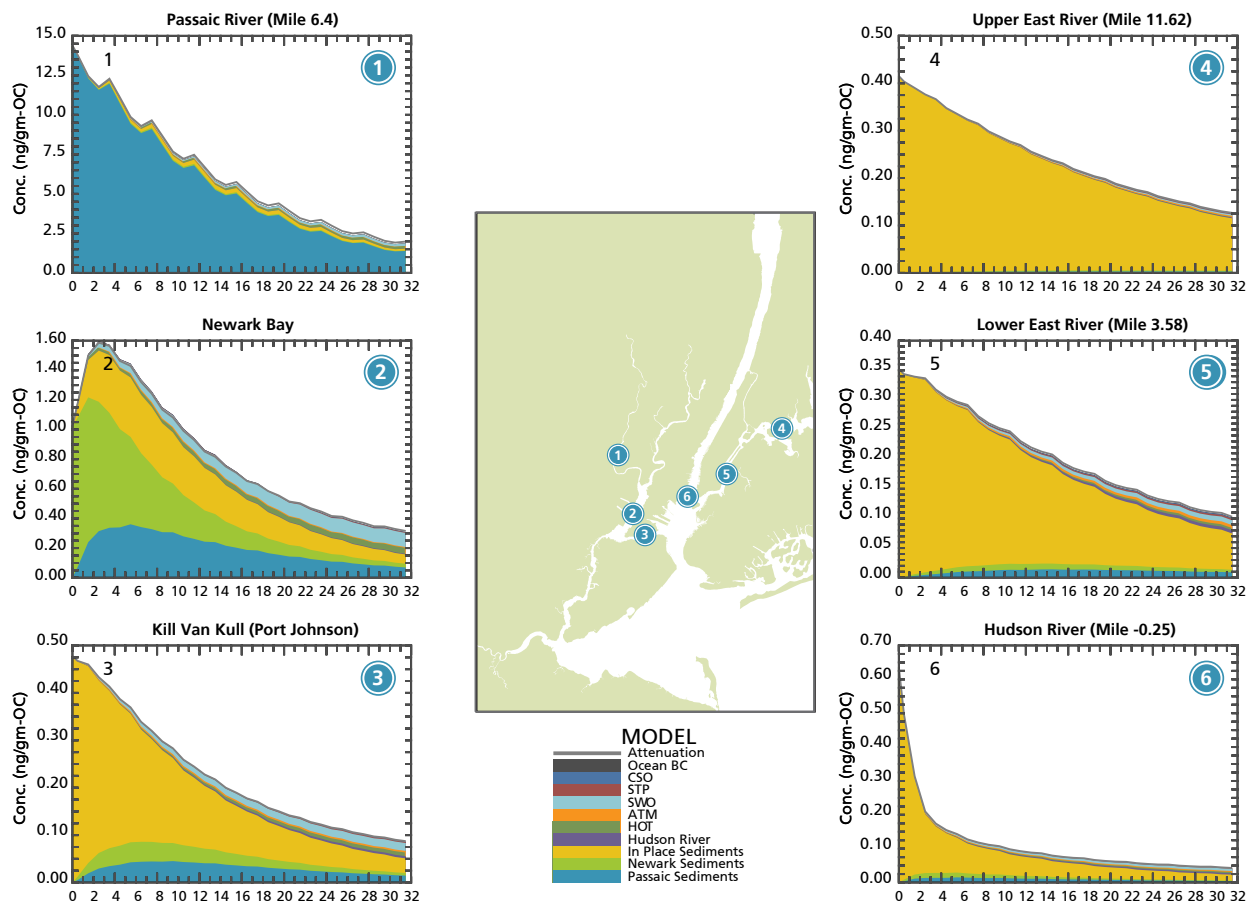
Figure 10. 2,3,7,8-TCDD concentrations

5.5 CARP Loading Component Response Matrix Tool

Using the loading component simulations, CARP also developed an interactive spreadsheet tool (Component Response Matrix) to allow users to observe how specific load reduction strategies may affect contaminant levels throughout the Estuary. The spreadsheet tool allows users to perform "what if" evaluations in a matter of minutes without having to perform lengthy CARP model simulations. Spreadsheet tool users can scale individual loading components either up or down, one at a time or concurrently, and observe expected changes in ambient contaminant concentrations in all media throughout the NY/NJ

Harbor Estuary. The matrix tool is available on the CARP website and accessible through the link at the end of the section.

One of the outputs of the matrix tool is shown in figure 11. It shows projected concentrations of PCBs in surface sediments at various sites in the estuary, from the Troy Dam on the left (bar #1) to the ocean on the right (bar# 39), and includes Newark Bay and other connecting waterways in the middle of the figure. The colors of the bars are derived from the component modeling

runs and represent the source of the PCBs. The light blue color represents PCBs that have entered the estuary from the upper Hudson River. This analysis demonstrates that the upper Hudson River load of PCBs is the dominant source of PCBs throughout the tidal Hudson River and in many portions of the NY/NJ Harbor Estuary as well, including Newark Bay (bar# 19).

The red line in figure 11 represents the guidance value for judging whether dredged sediments can be utilized as remediation material at the HARS. Since much of surface sediments of the region are forecasted to exceed the HARS limits into the future, the matrix tool can be used to evaluate how much load (by percentage) from a particular source (or sources) needs to be reduced in order to meet the HARS guideline for PCBs.
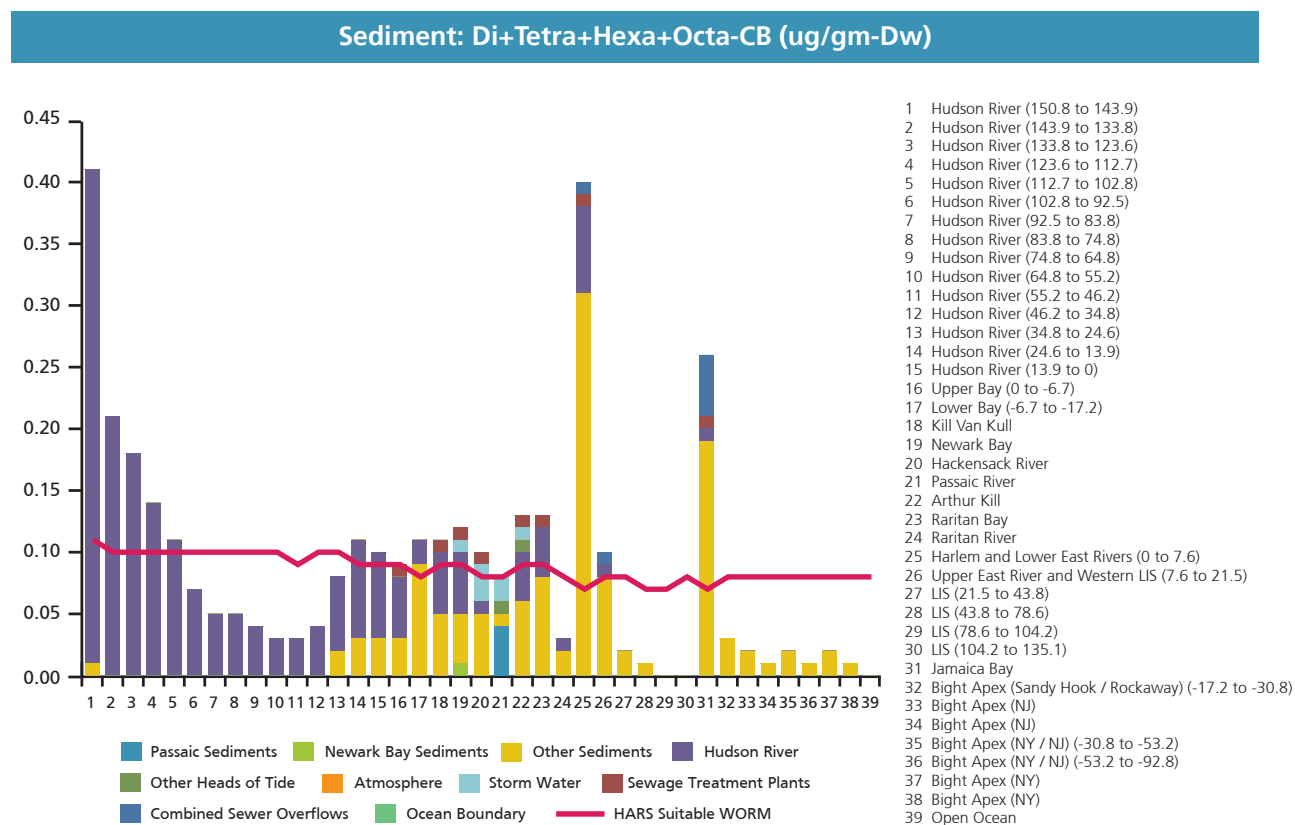
http://carpweb.org/modeling_code/downloads/CARP_Matrix.xls

Sediment: Di+Tetra+Hexa+Octa-CB (ug/gm-Dw)

1   Hudson River (150.8 to 143.9)
2   Hudson River (143.9 to 133.8)
3   Hudson River (133.8 to 123.6)
4   Hudson River (123.6 to 112.7)
5   Hudson River (112.7 to 102.8)
6   Hudson River (102.8 to 92.5)
7   Hudson River (92.5 to 83.8)
8   Hudson River (83.8 to 74.8)
9   Hudson River (74.8 to 64.8)
10 Hudson River (64.8 to 55.2)
11 Hudson River (55.2 to 46.2)
12 Hudson River (46.2 to 34.8)
13 Hudson River (34.8 to 24.6)
14 Hudson River (24.6 to 13.9)
15 Hudson River (13.9 to 0)
16 Upper Bay (0 to -6.7)
17 Lower Bay (-6.7 to -17.2)
18 Kill Van Kull
19 Newark Bay
20 Hackensack River
21 Passaic River
22 Arthur Kill
23 Raritan Bay
24 Raritan River
25 Harlem and Lower East Rivers (0 to 7.6)
26 Upper East River and Western LIS (7.6 to 21.5)
27 LIS (21.5 to 43.8)
28 LIS (43.8 to 78.6)
29 LIS (78.6 to 104.2)
30 LIS (104.2 to 135.1)
31 Jamaica Bay
32 Bight Apex (Sandy Hook / Rockaway) (-17.2 to -30.8)
33 Bight Apex (NJ)
34 Bight Apex (NJ)
35 Bight Apex (NY / NJ) (-30.8 to -53.2)
36 Bight Apex (NY / NJ) (-53.2 to -92.8)
37 Bight Apex (NY)
38 Bight Apex (NY)
39 Open Ocean

Legend: Passaic Sediments, Newark Bay Sediments, Other Sediments, Hudson River, Other Heads of Tide, Atmosphere, Storm Water, Sewage Treatment Plants, Combined Sewer Overflows, Ocean Boundary, HARS Suitable WORM

Figure 11: CARP Matrix Results: Projected PCB Concentrations in Sediment, by Source, for Various Portions of the Estuary. Concentrations Above the Red Line Indicate Exceedances of the HARS PCB Bioaccumulation Limit

5.6 CARP Model Future Scenarios Evaluation

As illustrated by CARP loading component analysis results, legacy contamination of sediments is a major factor controlling levels of contamination in the Harbor. Several large-scale sediment remediation Superfund projects are being studied in the Estuary. The two largest projects: the Upper Hudson River and Lower Passaic River were modeled as part of the CARP future scenarios evaluations. Scenarios involving implementation of the Hudson River PCB Superfund Site dredging and remediation of the highly contaminated sediments in the Lower Passaic River were modeled over a more than three decade simulation period.

The CARP model scenarios were intended to demonstrate the potential for these sites, remediated or not, to influence future water and sediment quality in the Harbor. Of particular interest to CARP is the improvement in Harbor sediment quality in relationship to the current bioaccumulation guidelines used to determine suitability of dredged material for use as remediation material at the HARS. These CARP scenarios evaluate the effect of the removal (though dredging, capping of upland remediation) of these sources on the suitability of future sediments, dredged from throughout the Harbor, for placement at the HARS. Figure 12 shows the expected levels of total PCBs in sediments in 2040 under "Current"-year 2000-level loading conditions and figure 13 shows expected levels after remediation of the Upper Hudson River and Lower Passaic River Superfund proj-

ects. The expected levels are shown as multiples of the HARS guidelines with a red (i.e, fail HARS criteria) and green (i.e., pass, suitable for placement at the HARS) color scale. The intensity of the color illustrates the magnitude of passing or failing the HARS guidelines.

CARP completed modeling scenarios for future sediment bed concentrations of PCBs and dioxin for a "with action" scenario (remediation project implemented) and for a 'No action" scenario. The remediation of the Upper Hudson River is included from the start of the simulation in the "with action" cases, following the projected time series of PCB loadings over the Troy Dam from the Upper Hudson River Superfund Record of Decision. The remediation of the Lower Passaic River was implemented in the sixth year of the "with action" CARP model simulations.
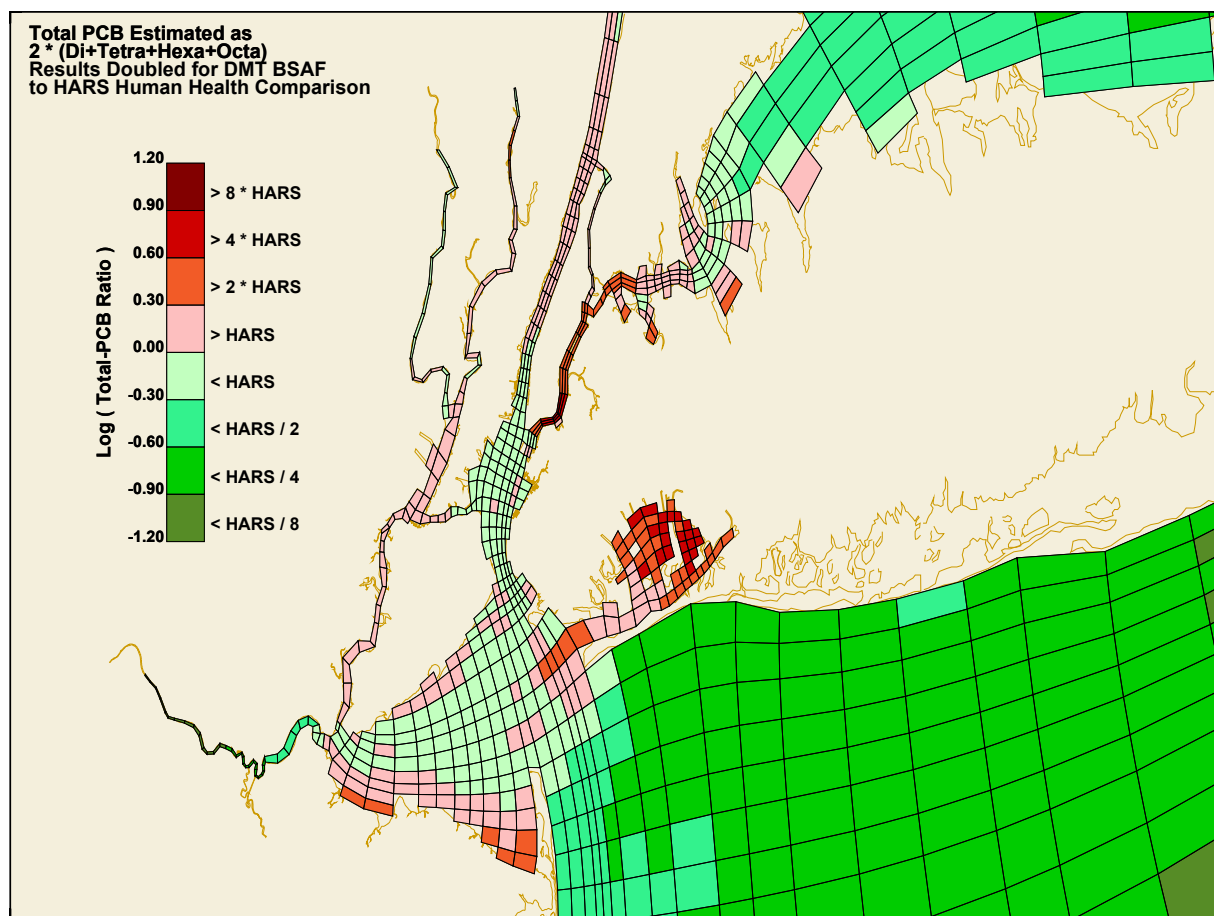

Figure 12. Ratio of Sediment Total PCB to the Guideline for Placement at HARS - Future (approximately 2040) with Year 2000-Level Loads Continuing

If PCB loadings continue at current (year 2000) levels, surficial sediments in most of the Harbor are likely to remain unsuitable for HARS placement due to PCB bio-accumulation, even three decades from now (figure 12). However, if the Upper Hudson River PCB Superfund Record of Decision's estimated load reductions are attained and the Lower Passaic River sediments are also remediated, CARP modeling (figure 13) indicates that much of the Harbor's surficial sediments are likely to become HARS-suitable with respect to PCBs within the next three decades.

In the absence of major storms or other events that could result in the resuspension of highly contaminated buried sediments in the Passaic River, CARP model simulations indicate that surficial sediments in Newark Bay may become HARS-suitable with respect to dioxin with-

in three decades, even without sediment remediation in the Lower Passaic River. About 10-20 years would be necessary for major portions of Newark Bay and Jamaica Bay to reach HARS suitable levels for dioxin without remediation. Major portions of the Passaic River would require 30-35 years and portions of the Hackensack River up to 35 years. However, sediment remediation in the Lower Passaic River would significantly reduce the time needed to achieve this benchmark.

More information and additional model projection scenario results are available in Appendix A-7.

Appendix A-7 – Contaminant Fate & Transport & Bioaccumulation Sub-models, Section 13.1 - Scenario Evaluations/Future Projections
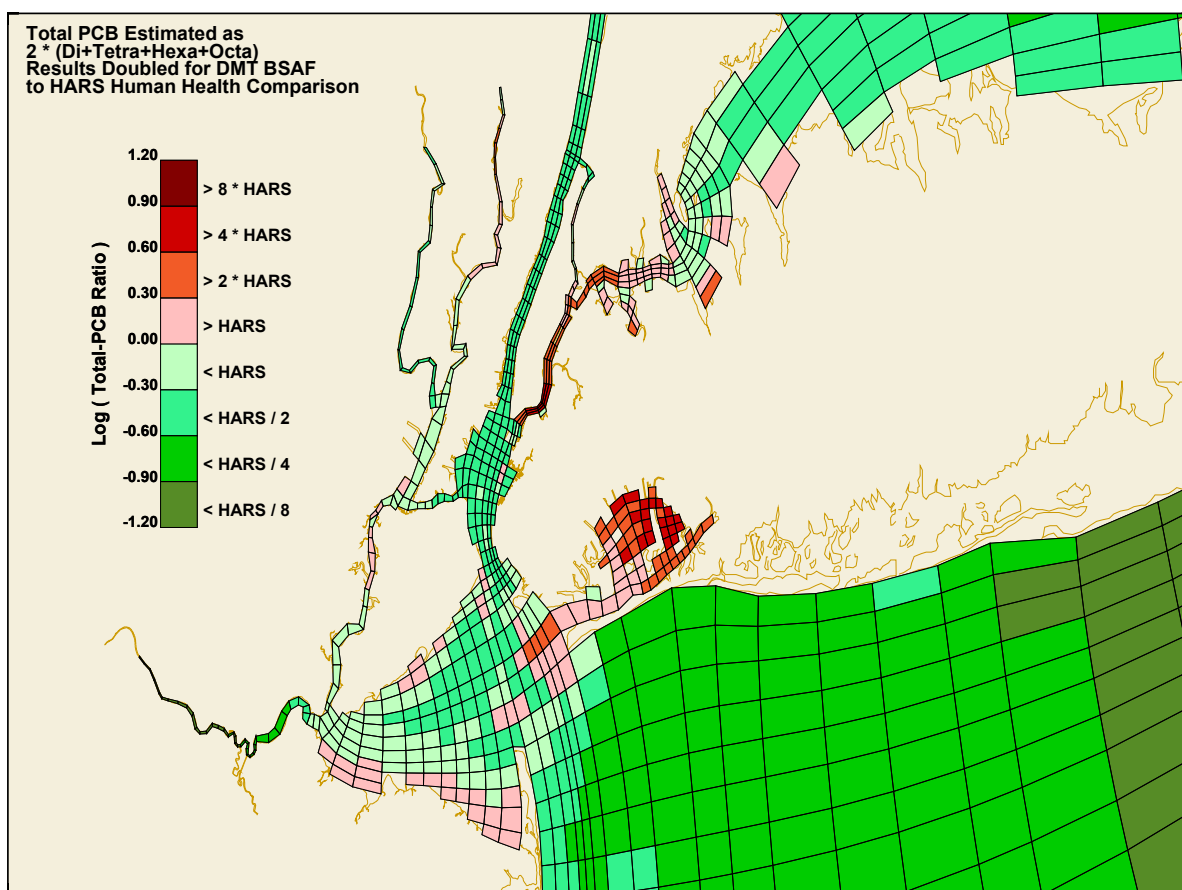
Figure 13. Ratio of Sediment Total PCB to the Guidance Value for Placement at HARS - Future (approximately 2040) with Superfund Dredging Implemented

Section 6. CARP Management Questions

The exercise of developing, calibrating, and applying the CARP models thus far has led to many important conclusions regarding the contamination of sediments and dredged material quality in the NY/NJ Harbor both for today as well as for what might be expected in the future. More specifically, it is clear that the evaluation of the combination of both field data and the corresponding model results are critical in evaluating contaminant fate and bioaccumulation behavior as it relates to dredged material quality. The CARP modeling results also highlight the important role of natural processes including tidal resuspension and estuarine circulation in controlling the long-term trapping of particle-bound contaminants in the NY/NJ Harbor. As a result of the long-term estuarine trapping of particles and the persistence of many of the contaminants, contamination observed in Harbor surficial sediments are due to both current day and historical legacy sources.

6.1 Dredged Material Management Questions

CARP was initiated in response to a need to address three primary dredged material management questions:

1. Which sources of contaminants need to be reduced or eliminated to render future dredged material clean?
2. Which actions can yield the greatest benefits?
3. What actions are necessary to achieve the future targets recommended in the region's dredged material management plans?

As a result of CARP, the tools (i.e., data and models) are now in place to begin to answer these important questions. Through further CARP application under the leadership of a number of cooperating agencies and regulatory programs (e.g., TMDL, CERCLA, NRDA, etc.) CARP tools can be used to refine and improve our ability to answer vvthese questions. The answers obtained thus far under CARP are briefly summarized below.

Regarding the sources of contaminants that need to be reduced or eliminated to render future dredged material clean, CARP data and source component simulations identified in-place sediment contamination over ongoing sources as the dominant contributor of contaminants to the system for the next three decades. Moreover, for ongoing sources, nonpoint source runoff and tributary headwaters are more significant than point sources such as STPs or CSOs. CARP modeling illustrated the benefits of implementing the Upper Hudson River and lower Passaic River Superfund projects. Namely, that much of the Harbor sediments, including Newark Bay sediments, could be HARS suitable for both dioxin and PCBs by 2040.

The understanding of where additional source reductions are needed and the expected benefits from these reductions continues with the on-going applications of the CARP models for TMDL and dredged material planning purposes. Under the HEP TMDL program, CARP model results and data were used to screen out contaminants in violation of HARS and other regulatory endpoints both now and in the future. The list of contaminants of concern for HARS suitability and other regulatory endpoints has been narrowed significantly because of CARP data and modeling. The TMDL program includes a number of sub-workgroups to the HEP Toxics Workgroup which are addressing applying the CARP models for additional evaluation of in-place sediment contamination and land-based sites contributing to contaminants being delivered to the estuary via overland runoff. Reports from these additional modeling exercises are included in Appendix A-9.

Regarding which actions can yield the greatest benefits, CARP provided a spreadsheet based matrix tool which can

be used to explore "what-if?" scenarios and gain an understanding of the relative benefits of different source reductions. The TMDL program is expanding upon this tool by including more finely resolved loading components to consider and loading components for additional contaminants.

CARP also ran a number of scenarios which examined the effect of two large Superfund projects: Hudson River and Passaic River. The Upper Hudson River PCBs Superfund site is the dominant external source of PCBs to the Harbor. It is estimated that three quarters of the PCB load currently entering the Harbor originates in the Upper Hudson River. The CARP scenarios showed that the planned remediation of Hudson River PCBs, would cause large sections of the Hudson Estuary to reach HARS suitability with respect to total PCB concentrations by 2040. However, for much of the Harbor area, including Jamaica Bay and the East River, the levels of PCB in the sediments would still exceed the HARS criteria (figures 12 and 13).

2,3,7,8-TCDD from the Passaic River Superfund site is the dominant problematic dioxin compound in sections of the western Harbor (i.e., the Passaic and Hackensack Rivers, Newark Bay and the Arthur Kill). Current sources of 2,3,7,8-TCDD to the Harbor are very small in relationship to the historic discharge of this compound but extremely high levels still persist in sediments of the Lower Passaic River region. CARP modeling scenarios looked at the benefit of remediating the full 17 miles of the Lower Passaic River vs. only the lower 7 miles. Outside of the Lower Passaic River, CARP modeling predicted only limited benefit to dredged material quality in terms of PCB and dioxin concentrations for remediation of 17 miles vs. 7 miles of the Lower Passaic River. Figures 14 and 15 show expected levels of 2,3,7,8-TCDD in sediments in 2040 after remediation of the Upper Hudson River for the 7 and 17 miles remedial dredging scenarios for the Lower Passaic River.
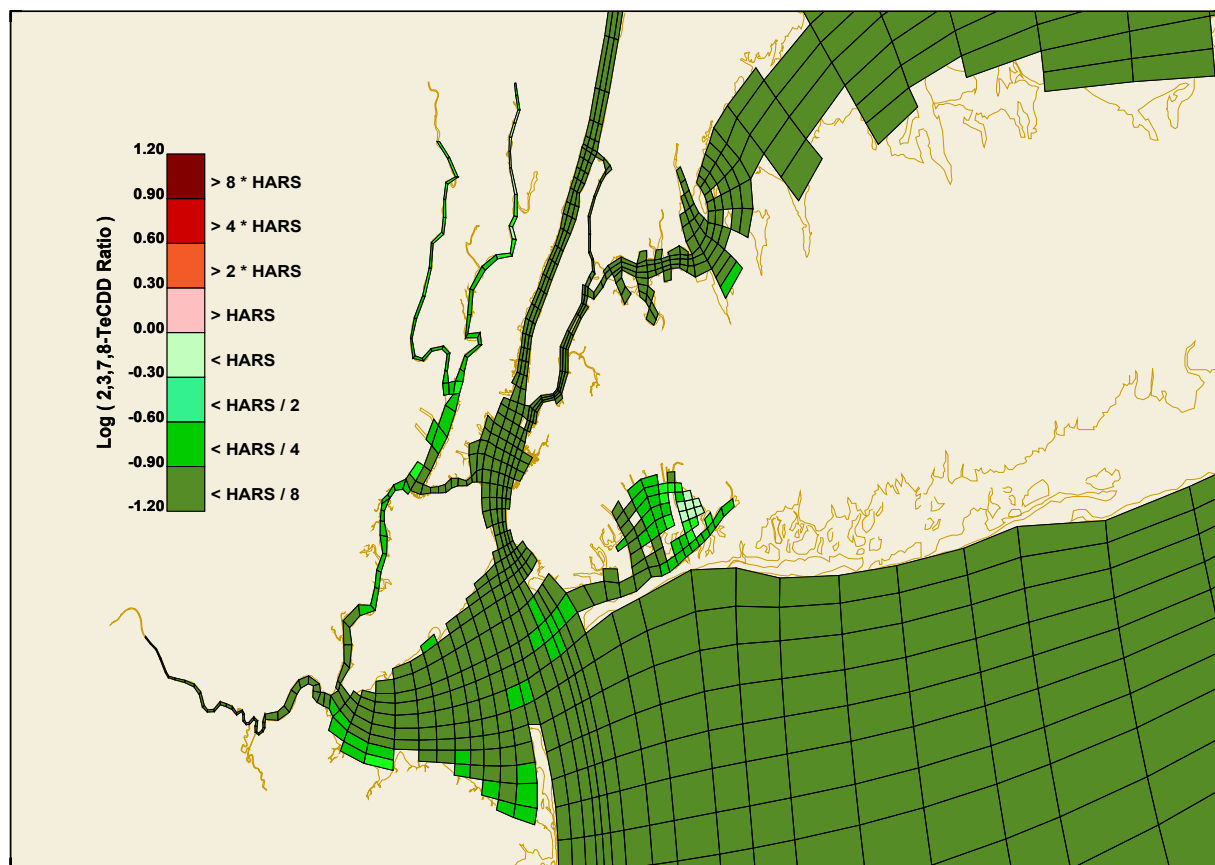
Figure 14. Ratio of 2,3,7,8-TCDD to the Guidance Value for Placement at HARS - HR Superfund Remediation Completed and 17 Miles of the Passaic River Superfund Implemented in ~2040
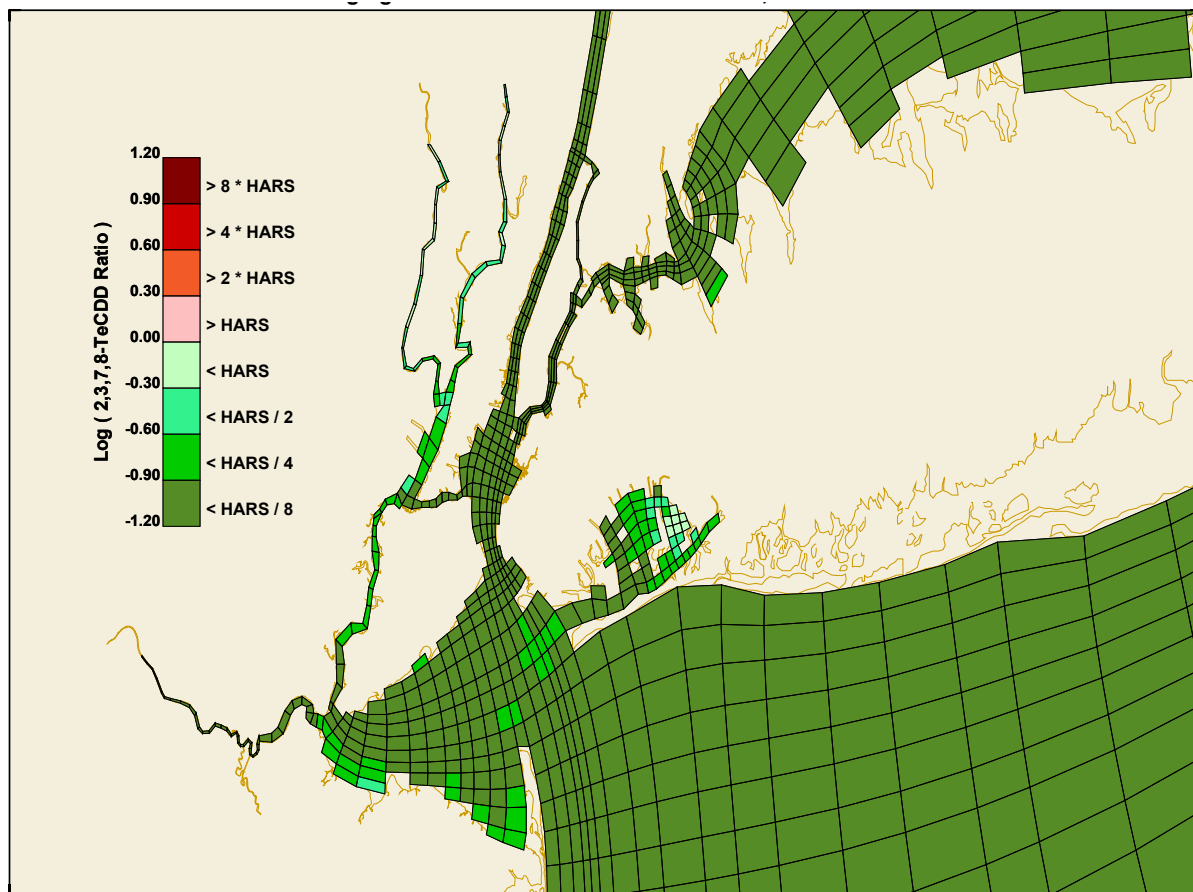
Figure 15. Ratio of 2,3,7,8-TCDD to the Guidance Value for Placement at HARS - HR Superfund Remediation Completed and 7 Miles of the Passaic River Superfund Implemented IN ~2040

Section 7. Summary of Accomplishments and Findings

CARP was successful in collecting an unprecedented data set that was integrated into a series of numerical models. Major accomplishments include the following:

- CARP identified and quantified all major sources of contaminants of concern to the NY/NJ Harbor Estuary.

- CARP produced a large set of baseline data characterizing levels of contaminants in sediment, water, biota and wastewaters (sewage treatment plants effluents, stormwater and combined sewer overflows) throughout the estuary.

  - Sampling and analytical methods were refined to quantify very low concentrations of contaminants, particularly in water, that were reported as non-detectable in the past.

  - The publicly available CARP database allows easy access to more than 750,000 measurements.

- A series of numerical models have been developed and calibrated to simulate movement of contaminants through the estuary and to predict the concentrations of these contaminants in water, sediment, and biota in future years under a variety of scenarios.

  - Model loading component simulations predict how continuing contaminant inputs (from atmospheric deposition, sewage treatment plants, combined sewer overflows, stormwater, tributaries, runoff, in-place sediments and the ocean) at current (year 2000) levels affect concentrations of contaminants in water, sediment and biota in the estuary over the next three decades.

  - Using the model loading component simulations, an interactive spreadsheet (Component Response Matrix) was developed to allow users to see how specific load reductions would affect contaminant levels in water, sediment and biota throughout the estuary.

  - Future Scenarios involving implementation of the Hudson River PCBs Superfund Site dredging and potential remediation of the highly contaminated sediments in the lower Passaic River were modeled over a thirty-seven year simulation period (i.e., to the year 2040). The scenarios predict the effect that remediation will have on the suitability of future dredged sediments for placement at the Historic Area Remediation Site (HARS).

7.1 Overall Findings

Modeling and data analysis have provided new insights about contaminant fate and transport in the NY/NJ Harbor Estuary. Major findings include the following:

- The NY/NJ Harbor Estuary is a dynamic system where, in some cases, contaminants have been transported great distances from their sources and have dispersed throughout many of the interconnected waterways.

- Sediments in the Harbor still contain large quantities of persistent contaminants from historic releases. These legacy sediments are a continuing source of contamination and generally play a larger role than loadings in controlling contaminant levels in water, sediment and aquatic organisms in the Estuary.

- In general, CARP model simulations indicate that levels of contaminants in all media (i.e., water, sediment, and biota) will continue to decline even if ongoing loads remain constant.

- Though not specifically designed to do so, municipal sewage treatment plants were shown to effectively limit the concentrations of contaminants in wastewater discharged to the estuary by removing particles and particle associated contaminants.

- Burial of contaminated sediments by cleaner sediments and resuspension of sediments with transport to other areas are the dominant natural processes that result in lower surficial sediment concentrations over time. It is important to note, however, that severe storms were not modeled by CARP and they could be mechanisms for mobilizing deeper layers of contaminated sediments.

- Into the future, legacy sediments are expected to be the dominant influence in controlling contaminant levels in all media of the Estuary for many contaminants. Sediment remediation will therefore likely be the most significant future method of source control.

7.2 Findings Related to PCBs

- PCB contamination is widespread throughout the entire estuary. Data and modeling results show that most of the Harbor's surficial sediments (i.e., the top 10 centimeters) are exceeding the benchmark limits established to determine whether dredged sediments can be used as remediation material at the HARS in the Atlantic Ocean.

- CARP data show that average concentrations of PCBs in white perch and American eel currently exceed U.S. Federal Food and Drug Administration FDA limits (for interstate commerce involving edible fish) at most locations sampled in the Harbor and in the mid-Hudson at Poughkeepsie.

- The Upper Hudson River PCBs Superfund Site is the dominant external source of PCBs to the Harbor. It is estimated that three quarters of the PCB load currently entering the Harbor originates in the Upper Hudson River.

- Modeling shows that PCBs from the Upper Hudson Superfund Site upriver source are transported throughout the estuary, including Newark Bay.

- If PCB loadings continue at year 2000 levels, modeling indicates that surficial sediments in most of the Harbor are likely to remain unsuitable for HARS placement due to PCB bioaccumulation, even three decades from now. In addition, white perch and American eel will continue to exceed FDA tolerance limits in portions of the Hudson River.

- If the Hudson River PCBs Superfund dredging is completed (and the Record of Decision's estimated load reductions are attained) and Passaic River sediments are remediated, modeling indicates that much of the Harbor's surficial sediments are likely to become HARS-suitable with respect to PCBs within three decades.

- Organic pigment manufacturing was found to be producing and releasing inadvertently synthesized PCBs. During the CARP sampling period, approximately 45% of sewage treatment inputs of PCBs to the Harbor (or 5% of the total PCB load) came from these pigment manufacturing companies discharging via sewage treatment plants. At least one of these companies no longer discharges these PCBs.

- Two sewage treatment plants were discovered to be receiving and discharging unusually high concentrations of commercial PCBs. Trackdown investigations found the PCBs to be widely distributed in their sewersheds. Specific sources have yet to be identified.

7.3 Findings Related to Dioxins

- Dioxins and furans are a group of 17 different compounds. Various types of sources to the Estuary can show different relative abundances, or signatures, of these individual compounds. CARP found dioxin signatures associated with defoliant manufacture (which produced relatively high amounts of 2,3,7,8-TCDD), urban waste water, and incineration activities.

- Even though 2,3,7,8-TCDD is the dominant problematic dioxin compound in sections of the Harbor (i.e., the Passaic and Hackensack Rivers, Newark Bay and the Arthur Kill), other dioxin compounds are being introduced throughout the estuary, resulting in exceedances of the New York State water quality standard.

- Year 2000 level sources of 2,3,7,8-TCDD to the Harbor are very small in relationship to the historic discharge of this compound that resulted in extremely high levels that still persist in sediments of the Lower Passaic River region. Of the small "current" inputs, stormwater is the largest contributor, accounting for more than half of the "current" external load to the Harbor.

- In the absence of major storms or other events that would result in the resuspension of highly contaminated buried sediments in the Lower Passaic River, CARP model simulations indicate that surficial sediments in Newark Bay may become HARS-suitable with respect to dioxin within three decades even without sediment remediation in the Lower Passaic River. However, sediment remediation in the Lower Passaic River would reduce the time needed to achieve this benchmark.

7.4 Findings Related to Other Contaminants

- In addition to PCBs and dioxin, 37 other contaminants or contaminant groups, measured and sometimes modeled by CARP, have enforceable New York or New Jersey water quality standards. Of these, 10 contaminants have been identified as violating an applicable standard within the Harbor and are the subject of ongoing EPA and State review, possibly leading to 303(d) listing and TMDL calculations and promulgation. The contaminants of greatest regulatory concern include: mercury, the polyaromatic hydrocarbon (PAH) benzo(a)pyrene, and several pesticides (hexachlorobenzene, heptachlor epoxide, chlordane, DDT and its metabolites, and dieldrin).

7.5 Application of CARP Results

- The U.S. Environmental Protection Agency, along with the States of New York and New Jersey, are utilizing the CARP data and modeling products to inform their determinations about which contaminants require development of Total Maximum Daily Loads (TMDLs).

- The NY-NJ Harbor and Estuary Program will use CARP products to formulate contaminant reduction targets and develop the Regional Sediment Management strategy.

- CARP data and models are being used to develop sediment remediation strategies in connection with the U.S. Army Corps of Engineers' Hudson-Raritan Estuary Comprehensive Restoration Study.

- CARP products were used in connection with the Lower Passaic River and Upper Hudson River Superfund Projects.

7.6 Recommendations for future Work:

While CARP collected a wealth of scientific information and significantly enhanced the understanding of the fate and transport of contaminants in this region, additional scientific inquiry is required to unravel the complexities of contaminant behavior in the system, including biological effects. This is particularly important for reducing uncertainties in dredged material management decisions. It is recommended that additional research be conducted and new data be collected to increase confidence in the CARP model projections, measure progress and trends, and better understand relevant effects of contaminants. Important topics to consider include:

- Understanding sediment transport and deposition mechanisms in the Passaic River, Newark Bay and the Hudson River;

- Improving estimates of contaminant loading from stormwater and combined sewer overflows;

- Evaluating sampling and analytical procedures for PAHs;

- Determining how spatially varying levels of sediment contamination affect bioaccumulation;

- Determining the factors causing sediment-related toxicity; and

- Applying the models under a broader range of conditions or for a severe event which could alter the delivery of suspended sediment, organic carbon, and contaminants from tributary headwaters and/or change sediment shear stresses, deposition, and erosion;

The scope and complexity of CARP made it a learning experience for all of the CARP participants. The lessons learned from CARP will inform future monitoring and modeling efforts related to the management of contaminated sediments in the NY/NJ Harbor estuary. Many of the important lessons learned are specific to small details of the individual CARP elements and have been acknowledged and discussed in various technical reports specific to individual CARP elements which are available in the appendices of this report and through the CARP website (carpweb.org), NYSDEC, and NJDEP. CARP lessons learned have already been incorporated into the formulation of specific additional research needs. In a broader sense, perhaps the most important lessons learned from CARP include:

- The importance of temporal and spatial coordination across the sampling of external loadings and ambient water, sediment, and biota for contaminants, organic carbon, and solids.

- The importance of comprehensive (i.e., high spatial resolution) measurements of contaminants in sediments given the magnitude of legacy contamination as compared to current loadings and the impact current sediment bed concentrations will continue to have on conditions in water, sediment, and biota for several decades.

- The importance of continued peer review of data collection and modeling throughout the project.

- The importance of having focused objectives and a management structure with strong leadership, flexibility, and commitment on the part of its many partners to accomplish those objectives.

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Appendicies

The following reports and other additional materials are available on the Hudson River Foundation website: Http://Hudsonriver.org/CARP/Appendicies

Appendix A-1. CARP NY Data Collection and Monitoring Program Reports
- CARP – Water Chemistry Final Summary Report for (NYSDEC)
- NY/NJ Harbor Sediment Report (NYSDEC)
- Polychlorinated Biphenyls (PCBs) in Five Fish Species from the New York-New Jersey Harbor Estuary (NYSDEC)
- Chemical Residues in Cormorants from New York Harbor (NYSDEC)

Appendix A-2. CARP NJ Data Collection and Monitoring Program Reports
- NJTRWP – Phase One POTW, SWO, and CSO Studies (NJDEP, 2008)
- Study I-C: Concentrations and Loads of Organic Compounds and Trace Elements in Tributaries to Newark and Raritan Bays, New Jersey (USGS, 2007)
- Study I-D/E: Ambient Monitoring of Water Quality Within Major Tributaries and the Estuary (SIT, 2007)
- Study I-E(a): Hydrodynamics of the Newark Bay and Kills System (SIT, 2006)
- Study I-E(b): Hydrodynamics of the Newark Bay and Kills System (Rutgers, 2006)
- Study I-G: POTW and CSO/SWO Discharges NJTWP Project Report (GLEC, 2008)

Appendix A-3. Quality Management Review Report
- CARP Quality Management Review Report (BAH, 2006)

Appendix A-4. Model Evaluation Group Final Peer-Review Report
- CARP Model Evaluation Group Summary Report (Baker et al. 2007)

Appendix A-5. Hydrodynamic Sub-Model Report
- CARP Hydrodynamics Sub-Model Report (HydroQual, 2006)

Appendix A-6. Sediment Transport/Organic Carbon Production Sub-model Report
- CARP Sediment Transport/Organic Carbon Production Sub-model Report (HydroQual, 2008)

Appendix A-7. Contaminant Fate & Transport & Bioaccumulation Sub-model Report
- CARP Contaminant Fate and Transport Sub-model Report (HydroQual, 2008)
- CARP Contaminant Fate and Transport Sub-model Report Appendices (HydroQual, 2008)

Appendix A-8. External Loading of Contaminants – Summary Pie Charts
- External Loading of Contaminants – Summary Pie Charts

Appendix A-9. Reports from Additional Modeling Exercises Utilizing the CARP Models

- Sediment Area Loading Component Analysis and Spreadsheet Tool Development II. Interpretive Technical Memorandum Task 3f (Phase 1) for EPA Region 2 and the NY/NJ Harbor Estuary Program (HydroQual, 2009)

- Evaluation of PCB Concentrations Measured in the Hudson River Near Waterford, New York (HydroQual, 2010)Sediment Area Loading Component Analysis and Spreadsheet Tool Development II. Hackensack River and Lower Raritan Bays. Interpretive Technical Memorandum for EPA Region 2 and the NY/NJ Harbor Estuary Program (HydroQual, 2010)

- Sensitivity Analysis of Toxic Contaminant Levels in the NY/NJ Harbor Estuary to Particulate Organic Carbon (POC) from Tributary Headwaters (HydroQual 2010)

- Evaluation of Polycyclic Aromatic Hydrocarbon (PAH) Narcotic Toxicity in NY/NJ Harbor Sediments ((HDR/HydroQual, 2013)