
Lower Passaic River Restoration Project

BIOACCUMULATION MODEL FOR THE LOWER PASSAIC RIVER STUDY AREA FINAL

Prepared for:

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Acronyms

AE	absorption efficiency
BAF	bioaccumulation factor
BERA	baseline ecological risk assessment
BHHRA	baseline human health risk assessment
BSAF	biota-sediment accumulation factor
CARP	Contamination Assessment and Reduction Project
CDF	chlorinated dibenzofuran
CFT	contaminant fate and transport
CPG	Cooperating Parties Group
CSM	conceptual site model
CSO	combined sewer overflow
C/O	benthic invertebrate carnivore/omnivore
DDD	dichlorodiphenyldichloroethane
DDE	dichlorodiphenyldichloroethylene
DDT	dichlorodiphenyltrichloroethane
DEP	benthic invertebrate deposit feeder
DET	benthic invertebrate detritivore
DO	dissolved oxygen
dw	dry weight
E_D	dietary chemical transfer efficiency
FF	benthic invertebrate filter feeder
FS	feasibility study
HpCDF	heptachlorodibenzofuran
IR	Interim Remedy
K_M	metabolism biotransformation rate constant
K_{OW}	octanol-water partition coefficient
LPRSA	Lower Passaic River Study Area
MLE	maximum likelihood estimation
NLOC	non-lipid organic carbon
NLOM	non-lipid organic matter

OC	organic carbon
ORLN	Oak Ridge National Laboratory
OU4	Operable Unit 4 of the Diamond Alkali Superfund Site
PC	proportionality constant
PCB	polychlorinated biphenyl
PCDD	polychlorinated dibenzo- <i>p</i> -dioxin
PCDF	polychlorinated dibenzofuran
PeCDD	pentachlorodibenzo- <i>p</i> -dioxin
PeCDF	pentachlorodibenzofuran
ppth	parts per thousand
PRG	preliminary remediation goal
RAIS	Risk Assessment Information System
RI	remedial investigation
RM	river mile
ROD	Record of Decision
RPD	redox potential discontinuity
SPAF	species predictive accuracy factor
SPI	sediment profile imaging
SSO	sanitary sewer overflow
SWAC	spatially weighted average concentration
TCDD	tetrachlorodibenzo- <i>p</i> -dioxin
tetraCB	tetrachlorobiphenyl
TEQ	toxic equivalent
TOC	total organic carbon
total DDx	sum of all six DDT isomers (2,4'-DDD, 4,4'-DDD, 2,4'-DDE, 4,4'-DDE, 2,4'-DDT and 4,4'-DDT)
USACE	US Army Corps of Engineers
USEPA	US Environmental Protection Agency
VBA	Visual Basic for Applications®
Windward	Windward Environmental LLC
ww	wet weight

1 Introduction

This report presents the calibration of Diamond Alkali Operable Unit (OU) 4 of the Diamond Alkali Superfund site's (herein referred to as the Lower Passaic River Study Area [LPRSA]) mechanistic bioaccumulation model that will be used to support the feasibility study (FS) that has been prepared as part of the LPRSA remedial investigation (RI)/FS. The bioaccumulation model is a mechanistic model used to predict tissue concentrations of hydrophobic organic chemicals in fish and selected invertebrates based on chemical concentrations in the water and sediment. It includes ecological elements (e.g., food web structure, exposure assumptions) and chemical elements (e.g., biotic chemical uptake, depuration processes). Both a steady-state model¹ and a dynamic (i.e., time-varying) model² were developed as part of this effort; the steady-state model was used for initial model calibration, and the dynamic model may be used for future model applications. Three distinct modeling areas were defined for the LPRSA bioaccumulation model, primarily based on differences in salinity and habitat conditions (river mile [RM] 0 to RM 6, RM 6 to RM 14.7, and RM 14.7 to Dundee Dam), covering the entire 17.4 miles of the LPRSA.

This report discusses the selection of the appropriate model for the LPRSA, the parameterization of the model (i.e., the determination of model input values for various chemical and biological parameters), the approach for calibration (i.e., the optimization of model input to improve model predictions), and an evaluation of model calibration. This bioaccumulation modeling report was submitted to the Region 2 US Environmental Protection Agency (USEPA) as a draft in June 2015; both the model and this report have undergone significant modifications in response to numerous interactions between USEPA and Cooperating Parties Group (CPG) representatives since that time.

1.1 MODELING OBJECTIVE

The objective of this modeling effort is to develop a reliable and acceptably accurate tool for understanding the bioaccumulation of hydrophobic organic chemicals in fish and select invertebrates in the LPRSA. The primary purpose of the model is to allow for the estimation of future fish tissue concentrations using projected water and sediment chemical concentrations (along with other related parameters) from the contaminant fate and transport (CFT) model as inputs. The fish tissue concentration projections can

¹ The term "steady-state model" is used in this report to refer to the version of the bioaccumulation model used to look at predicted tissue concentrations for a single set of inputs. This version of the model was important for calibration.

² The term "dynamic model" is used in this report to refer to the version of the bioaccumulation model that reads and responds to time-varying inputs. This version of the model may be used for future applications of the model.

then be used to calculate risks to ecological receptors and human health. The model may also be used to understand future exposure (of people and ecological receptors) based on post-remedy conditions.

1.2 REPORT ORGANIZATION

The remainder of this report is organized as follows:

- ◆ Section 2 – Background, Assumptions, and Technical Description of the Model
- ◆ Section 3 – Model Development
- ◆ Section 4 – Model Calibration and Results
- ◆ Section 5 – Evaluation of Model Calibration
- ◆ Section 6 – Conclusions
- ◆ Section 7 – References

In addition, eight appendices provide supporting information for the calibration of the bioaccumulation model. These appendices include the following:

- ◆ Appendix A – Review of Bioaccumulation Model Applications at Other Contaminated Sediment Sites
- ◆ Appendix B – Changes to Model Code
- ◆ Appendix C – Development of Chemical-specific Metabolic Biotransformation Rate Constant Distributions
- ◆ Appendix D – Supporting Data for Benthic Invertebrate Parameterization
- ◆ Appendix E – Supporting Data for Fish and Crab Parameterization
- ◆ Appendix F – Empirical Tissue Data
- ◆ Appendix G – Model Input and Output
- ◆ Appendix H – Alternate Calibration Results

2 Background, Assumptions, and Technical Description of the Model

This section discusses the bioaccumulation models that have been employed at other contaminated sediment sites, the selection of a bioaccumulation model for the LPRSA, and the key assumptions for this model. In addition, this section discusses how the bioaccumulation model links with other models (i.e., the risk assessment models and CFT model) for the LPRSA and provides a brief description of model documentation, software, programming language, and user information.

2.1 USE OF BIOACCUMULATION MODELS AT OTHER SITES

Mechanistic bioaccumulation models have been used at a variety of sites throughout the United States and in Canada for rivers, lakes, estuaries, and embayments (Appendix A). The models used at these sites have been developed from a variety of sources (e.g., Gobas (1993), Arnot and Gobas (2004), Thomann and Connolly (1984), Connolly and Tonelli (1985)). These models have been used for a variety of purposes, including the following:

- ◆ Development of cleanup goals
- ◆ Evaluation of remedial alternatives to address human health and ecological risks
- ◆ Understanding chemical uptake in biota
- ◆ Developing model methodologies

Appendix A presents a summary table showing the sites where these models have been applied, the types of models used, and the chemicals modeled. As can be seen in this appendix, Gobas-style models have been used extensively in estuarine systems to model bioaccumulation for a list of chemicals, including those of significance to the LPRSA.

2.2 MODELED CHEMICALS

The final LPRSA baseline ecological risk assessment (BERA) (Windward 2019b) and baseline human health risk assessment (BHHRA) (AECOM 2017) identified polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-*p*-dioxins/polychlorinated dibenzofurans (PCDDs/PCDFs) as the primary risk drivers for both ecological receptors and human health.³ Based on this, the bioaccumulation model calibration focused on predictions of concentrations of these chemicals in fish and an invertebrate, namely the blue crab (*Callinectes sapidus*). Specific chemicals for which bioaccumulation model predictions are desired for the LPRSA include total PCBs, 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (2,3,7,8-TCDD), PCB toxic equivalent (TEQ), PCDD/PCDF TEQ, and total TEQ.

Total PCBs and TEQs were not modeled directly because of the wide variation in chemical properties across PCB homolog groups and across PCDDs and PCDFs. Instead, surrogate chemicals were identified for which bioaccumulation model predictions can be translated to estimated tissue concentrations of the target chemicals using regression equations. Initial work to ensure the acceptability of this approach found that there were strong relationships between these chemicals and surrogates (see Figure 2-1 for examples of these regression relationships). Thus, based on discussions with and the concurrence of USEPA, this report focuses on the calibration of the model for three primary calibration chemicals: 2,3,7,8-TCDD, tetrachlorobiphenyl (tetraCB), and 1,2,3,4,6,7,8-heptachlorodibenzofuran (HpCDF).

³ The need for a bioaccumulation model for total DDx (sum of all six dichlorodiphenyltrichloroethane [DDT] isomers (2,4'-dichlorodiphenyldichloroethane [DDD], 4,4'-DDD, 2,4'-dichlorodiphenyldichloroethylene [DDE], 4,4'-DDE, 2,4'-DDT and 4,4'-DDT) – which was also identified as a risk driver in the BERA for select receptors – will be considered as part of future work (i.e., when the model is tested as part of model validation during the "refine and/or validate model" task contained within the Adaptive Management Approach).

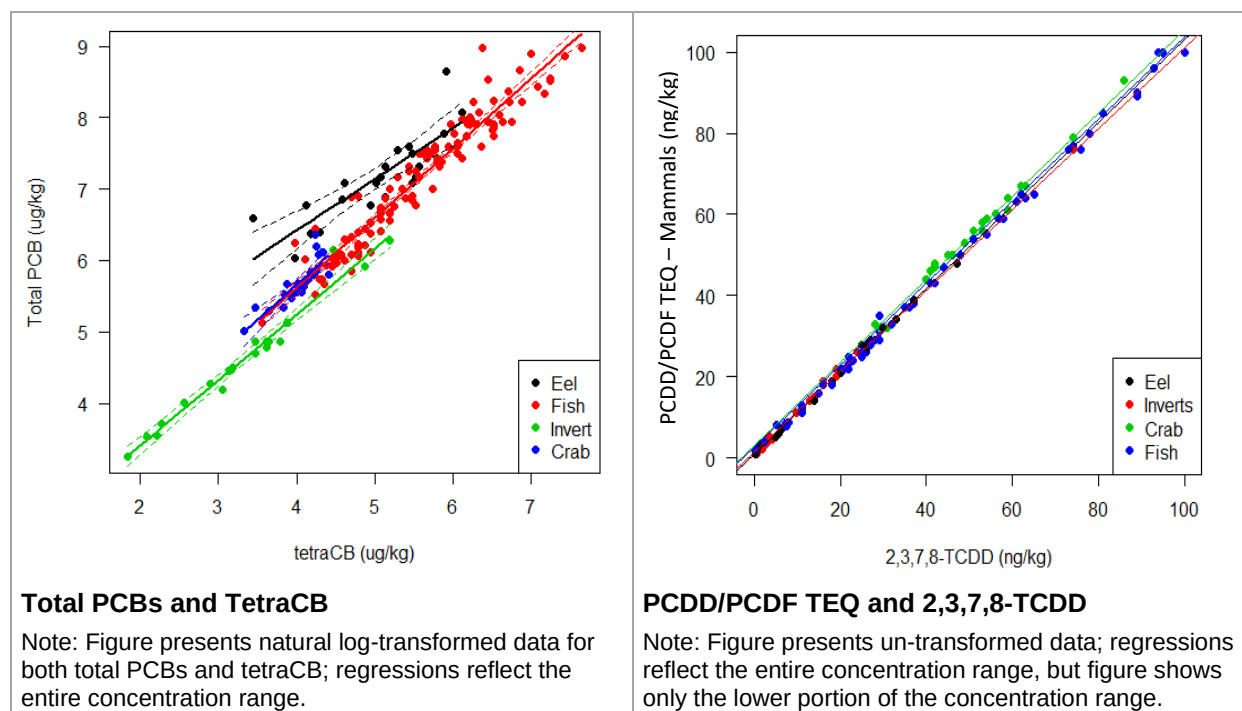


Figure 2-1. Scatterplots of regression relationships for total PCBs and PCDD/PCDF TEQ for different species groups

2.3 MODEL SELECTION

The available mechanistic models are all built on similar phase-partitioning concepts and equations. The Arnot and Gobas model (2004) was selected as the starting point for building the LPRSA bioaccumulation model, because it includes advances from older mechanistic models and is appropriate for modeling hydrophobic organic chemicals (e.g., dioxins/furans and PCBs). The underlying assumption of a Gobas-style model is that the flux of chemicals between water and organisms, between ingested media (i.e., sediment and other organisms) and organism tissue, and between different tissue types (e.g., lipid and non-lipid organic matter) is governed by fugacity relationships (Arnot and Gobas 2004).

A mechanistic bioaccumulation model can be used to assess the relative importance of various pathways and mechanisms, and to produce better estimates of tissue concentrations under varying conditions than statistical models (e.g., biota-sediment accumulation factors [BSAFs]). Mechanistic bioaccumulation models can also account for changes in a variety of chemical and physical parameters (e.g., chemical concentration in water, water temperature, and dissolved oxygen [DO]), rather than only responding to changes in sediment concentrations. This means that the mechanistic model represents a more realistic estimate of bioaccumulation. The mechanistic model is able to respond to modeled changes over time (e.g., when evaluating remedial scenarios) and to modeled changes in various exposure media,

which are known to be of varying importance for different species. Statistical models (e.g., BSAFs) can only respond to changes in sediment and should not be used to extrapolate beyond the conditions represented by the sediment and tissue concentration data that were used to generate the model. Thus, simple models may be less effective in evaluating remedial alternatives or future conditions, depending on the complexity of site conditions.

2.4 KEY MODEL ASSUMPTIONS AND PROCESSES

The Arnot and Gobas model (2004) is based on assumptions about the routes of chemical uptake and elimination and the distribution of chemicals in organisms.

- ◆ **Chemical uptake** – Primary routes for the uptake of hydrophobic organic chemicals by zooplankton, benthic invertebrates, and fish are the ventilation of porewater or water column water and the ingestion of sediment or organisms.
- ◆ **Chemical loss** – Primary routes for the loss of hydrophobic organic chemicals by zooplankton, benthic invertebrates, and fish are metabolism, growth dilution, ventilation of porewater or water column water, and fecal egestion. Chemical losses via egg deposition or sperm ejection are assumed to be negligible.
- ◆ **Phase partitioning within organisms** – Chemicals are assumed to be homogeneously distributed within each tissue phase of the organism (i.e., lipids, water, and non-lipid organic matter [NLOM] [e.g., proteins and carbohydrates] or non-lipid organic carbon [NLOC]⁴).
- ◆ **Exchange with the environment** – Organisms are assumed to be single compartments that exchange chemicals with their surrounding environments.

Justification for these assumptions is provided in Arnot and Gobas (2004).

2.5 MODEL UPDATES

The LPRSA bioaccumulation model incorporates important updates to the Arnot and Gobas model (2004). These updates were developed in collaboration with, and with the concurrence of, USEPA:

- ◆ **Chemical concentration in phytoplankton** – Rather than using the equation in the Arnot and Gobas model (2004), the chemical concentration in phytoplankton was estimated using the concentration in suspended algal particulates calculated by the CFT model.

⁴ NLOC was used as the third phase for chemical partitioning in phytoplankton instead of NLOM, as discussed in Appendix A.

- ◆ **Dietary chemical transfer efficiency (E_D) parameter** – Rather than calculating the E_D parameter based on the octanol-water partition coefficient (K_{OW}) for a given chemical, as is done in the Arnot and Gobas model (2004), the model was updated to allow the E_D to be a separate input parameter. This change was based on USEPA’s review of the poor relationship between E_D and K_{OW} (as discussed during the June 5, 2018, USEPA-CPG bioaccumulation modeling meeting).
- ◆ **Species-specific growth and consumption rates** – Rather than using the generic growth and consumption rate equations in the Arnot and Gobas model (2004), species-specific growth and consumption rate equations were developed for fish and blue crabs using the Fish Bioenergetics 4.0 (FB4) model (Deslauriers et al. 2017). This change was made in response to comments from USEPA regarding discrepancies in the relationship between the growth and consumption rates when the generic equations were used.

A complete description of these updates and the rationale for these changes are provided in Appendix B.

2.6 USE OF THE BIOACCUMULATION MODEL

The bioaccumulation model utilizes select model outputs from the LPRSA CFT model, including chemical concentrations in various media (e.g., surface water, sediment, and particulates) and other physical parameters (e.g., water temperatures). Planned uses of the LPRSA bioaccumulation model include:

- ◆ **Development of PRGs** – The calibrated LPRSA bioaccumulation model is intended to be used to develop initial PRGs for the upper 9 miles of the LPRSA, pursuant to the Adaptive Management Approach (Appendix D) of the USEPA-approved *Upper 9-Mile Interim Remedy Feasibility Study* (Integral et al. 2021b). This study identified the interim remedy (IR) alternative and adaptive management approach for the upper 9 miles of the LPRSA, as selected in the September 28, 2021, Record of Decision (ROD) signed by USEPA Administrator Regan. In addition to exposure from sediment, exposure from non-sediment media (e.g., water or fluff layer) is likely to occur; thus, it is anticipated that PRG development would rely on the output from the CFT model and an understanding of how concentrations in these various media would change during the post-IR monitoring phase following completion of the IR. Details regarding the application of the bioaccumulation model to calculate PRGs will be determined as part of the PRG development process.⁵

⁵ A detailed discussion regarding the approach for PRG development is beyond the scope of this model calibration report.

- ◆ **Ecological and human health risk assessment models** – Bioaccumulation model outputs (i.e., predicted tissue concentrations) may be used as inputs to human health and ecological risk assessment models to calculate risks for the evaluation of remedial alternatives during the development of a final remedy for the upper 9 miles of the LPRSA.

The following subsections provide a summary of how outputs from the LPRSA CFT model are used in the bioaccumulation model. Details regarding the CFT model are available in Anchor QEA et al. (2019).

2.6.1 Steady-state model linkage with CFT model

For use in the steady-state bioaccumulation model, CFT model output (which is provided on a daily-averaged basis) was averaged over the calibration period (September 2007 to August 2010) to develop exposure concentrations for the steady-state model. Predictions are provided for various exposure areas, including the three modeling areas used for the bioaccumulation model (i.e., RM 0 to RM 6, RM 6 to RM 14.7, and RM 14.7 to Dundee Dam). These three modeling areas were primarily based on differences in salinity and habitat conditions; gradients in sediment concentrations and the characteristics of typical foraging areas of modeled fish were also considered (see Section 3.2.5). Average values for these parameters are presented in Section 3.2. A total of 10 parameters, including 6 that are chemical specific, were developed based on CFT model output (Table 2-1).

Table 2-1. Bioaccumulation model parameters derived from CFT model output

Parameter Name	Units	Development of Value for Modeling Areas
Chemical-specific parameters		
Concentration in sediment	ng/g	two-step calculation: depth-weighted to calculate 0-15 cm average, and then area-weighted for each exposure area
Concentration in porewater	ng/g	volume-weighted average
Bioavailable concentration in water	ng/g	area-weighted average of the water column
Concentration in suspended detrital particulates	ng/g	area-weighted average that represents the concentration averaged across the depth of the water column
Concentration in suspended algal particulates	ng/g	area-weighted average that represents the concentration averaged across the depth of the water column
Concentration in near-bottom detrital particulates (detrital) ^a	ng/g	area-weighted average that represents the bottom layer of particulates
Non-chemical-specific parameters		
Mean water temperature	°C	area-weighted average
OC content of sediment	fraction	two-step calculation: depth-weighted to calculate 0-15 cm average, and then area-weighted for each exposure area
OC content of suspended detrital particulates	fraction	area-weighted average that represents the average concentration across the depth of the water column
OC content of near-bottom detrital particulates	fraction	area-weighted average that represents the bottom layer of particulates

- ^a A total of 10 layers are used to model the water column. Each layer consists of 10% of the water column depth in a given cell. Near-bottom particulates are those in the bottom-most layer of the water column and are used to represent the chemical concentrations in detritus at the sediment-water column interface. The uncertainty associated with the use of CFT model output to approximate the near-bottom particulate layer is discussed in Section 5.3.

CFT – contaminant fate and transport

dw – dry weight

OC – organic carbon

2.6.2 Dynamic model linkage with CFT model

The dynamic model uses the same types of inputs as the steady-state model, except that rather than entering a single average value for the parameters shown in Table 2-1, a time series of the input values data is used to generate predicted tissue concentrations on a daily basis. For the purposes of model calibration, the dynamic model was run over the duration of the CFT model simulation (September 2007 to August 2010), and empirical data were compared with predictions for the time period during which fish and crab were collected. Figures showing these input data are presented in Appendix G.

To avoid any issues with equilibration at the start of the model simulation period, initial concentrations of the modeled chemicals for each species were set equal to the measured tissue concentrations used to calibrate the steady-state model. A three-year equilibration period was built into the dynamic model (i.e., the first year of CFT model inputs repeated three times). This equilibration period is important, because it ensures that the dynamic model output is not influenced by the selected initial concentrations.

2.7 TECHNICAL DESCRIPTION OF MODEL

The bioaccumulation model for the LPRSA was originally designed in Microsoft Excel® 2010⁶ and used Microsoft Visual Basic for Applications® (VBA) code. However, as a result of increasing model complexity, particularly for the dynamic version of the model (i.e., the desire to include more modeling segments and more species), the model was translated from VBA code into R code. This change had no impact on model predictions.

The steady-state and dynamic models each have their own R-scripts with functions that read the input Excel® file, run the model, and write outputs to an Excel® file. These R scripts that can be used to perform various analyses related to model calibration, generate graphs and tables of results, and run comparisons (e.g., to evaluate model sensitivity). For the final model, a simple script file containing only three lines of essential code (i.e., read inputs, run model, and write outputs) is needed.

⁶ The LPRSA model incorporates some features that are compatible only with Excel® 2010 or later versions. Some basic functionality is compatible with Excel® 2007.

An Excel® interface is used for parameter input and storing model output for both versions of the model. Most of the model inputs are the same between the two models, although organized differently in some cases to suit the needs of the models (e.g., the dynamic model combines physical and chemical parameter into a single table while the steady-state model keeps them in separate tables):

- ◆ **Input files** – The Excel® input file for the steady-state model has nine tables on different worksheets, while the dynamic model has eight tables on different worksheets. The different tables are organized by category (e.g., physical, chemical, or biological) and whether the parameters in question vary by river segment, modeling area, chemical, and/or organism.
- ◆ **Use of CFT model output** – The CFT model output values are averaged and a single value for each parameter is used as inputs in the Physical Parameters and Chemical Parameters tables in the steady-state model; in the dynamic model, the time-series CFT model output files are read directly by the model for each chemical and modeling area.
- ◆ **Additional inputs required for dynamic model** – The dynamic model needs some additional inputs that are not required for the steady-state model. Thus, the dynamic model input file contains a table for Control Parameters that includes information about the length and number of time steps (i.e., 1,090 one-day time steps for the calibration period [three years]) and the number of time steps to use as an equilibration period (i.e., 1,095 one-day time steps).
- ◆ **Tissue concentrations** – The dynamic model also needs initial tissue concentrations for all organisms in all segments (in this case, set equal to the measured empirical tissue concentrations used to calibrate the steady-state model), whereas the steady-state model requires empirical tissue concentrations as inputs for evaluating model results.

3 Model Development

This section discusses the ecological conceptual site model (CSM), as well as the LPRSA bioaccumulation model structure, input/parameterization, and calibration.

3.1 CONCEPTUAL SITE MODEL

A CSM that accurately describes the LPRSA's ecology was critical to developing the bioaccumulation model, which describes the movement of chemicals through the food web. The subsections that follow, summarized below, describe key aspects of the LPRSA CSM that were important in the development and parameterization of the bioaccumulation model:

- ◆ The LPRSA is typical of an urbanized food web, which influences the expected benthic invertebrate and fish community structure.
- ◆ The near-bottom particulate layer in the LPRSA is the interface between the bedded sediment and the water column; the layer contributes to the uptake of contaminants in the LPRSA food web.
- ◆ An accurate description of the LPRSA benthic invertebrate community is necessary to accurately model the bioaccumulation and transport of chemicals.
- ◆ The LPSRA fish community is dominated by benthic fish, meaning that contaminant concentrations in fish tissue are primarily driven by concentrations in near-bottom particulates and sediment (either directly or via the consumption of benthic invertebrates and small fish).

3.1.1 Urbanized food web

The ecological setting of the LPRSA is typical of urban systems, with its reduced habitat quality and urban inputs of contamination. It has been described in extensive detail in previous reports (Germano & Associates 2005; Iannuzzi et al. 2008; Iannuzzi and Ludwig 2004; Ludwig et al. 2010; Windward and AECOM 2009; Baron 2011; Anchor QEA et al. 2019). The urbanized environmental setting of the LPRSA influences a variety of factors that affect benthic invertebrate habitat and benthic community structure, both of which play important roles in shaping the LPRSA food web.

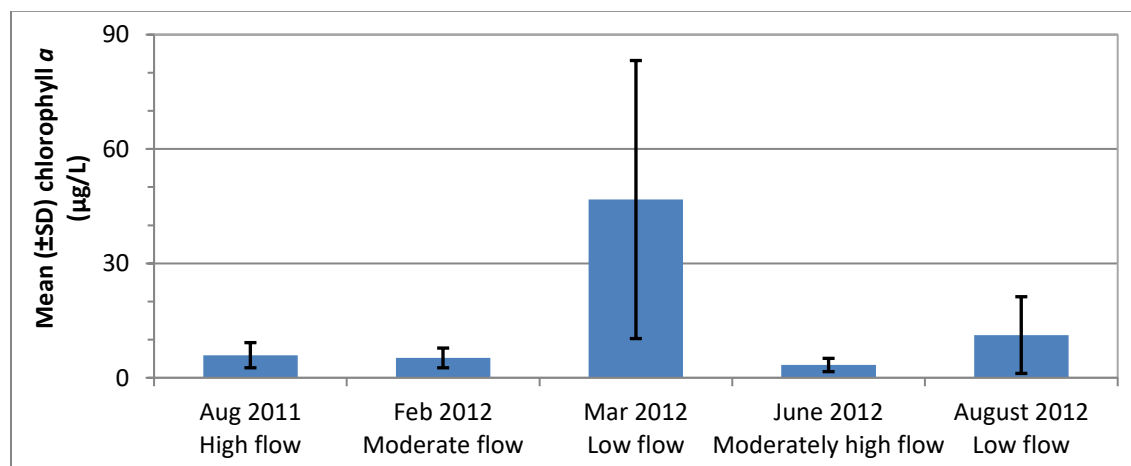
Watershed urbanization results in increased inputs of particulates, nutrients, and contaminants (Droppo et al. 2002; Walsh et al. 2005), all of which diminish habitat quality, complexity, and availability (Eitzmann and Paukert 2010; Layman et al. 2007). These changes affect the entire fish community by reducing benthic diversity and reducing the food web to a smaller number of urbanization-tolerant taxa (Eitzmann and Paukert 2010; Pearson and Rosenberg 1978). The benthic-dominated fish community present in the LPRSA is consistent with the fish community that would be expected in

an urbanized system. The species that are most common in the LPRSA feed on shallow benthic invertebrates (rather than on smaller fish) or opportunistically on whatever prey is abundant. Compressing the trophic structure results in some reduction in the accumulation of biomagnifying contaminants (e.g., mercury and PCBs) in fish tissue (Adams and Paperno 2012; McIntyre and Beauchamp 2007).

3.1.2 Presence of near-bottom particulate layer

The LPRSA is a partially mixed estuary with circulation and salinity patterns that are mainly controlled by a dynamic hydraulic balance between the upstream freshwater flow and the downstream brackish tidal inflow from Newark Bay. The turbulent mixing can cause suspended sediment to flocculate and settle out into a thin, unconsolidated layer of near-bottom particulates that overlies a less erodible bed of sediment. Inputs high in OC (i.e., total organic carbon [TOC] and sewage) in urban areas indicate that labile near-bottom particulates, which are produced by flocculation processes (Droppo et al. 2002), are likely to be important contributors of nutrients to the food web within the LPRSA.

Episodic blooms of phytoplankton also contribute to the near-bottom particulate layer. Data for chlorophyll *a*, which is a surrogate for the measurement of phytoplankton, were collected in the LPRSA in 2011 and 2012 (ddms 2013a, b, c, d, e) and demonstrate that the system undergoes periodic blooms of phytoplankton (Figure 3-1). The nutrients in phytoplankton may be consumed from the water column by filter-feeding fish or at the sediment-water interface by benthic invertebrates and bottom-feeding fish (Hecky and Kilham 1988).



Source: ddms (2013a, 2013b, 2013c, 2013d, 2013e)

Figure 3-1. Average chlorophyll *a* concentrations measured in the LPRSA during five water sampling events between August 2011 and August 2012

As described in Section 2.6.1 (see Table 2-1), the near-bottom particulate layer was estimated using the CFT model, but site-specific particulate data were not available to

verify these concentrations (Anchor QEA et al. 2019). Given the importance of the near-bottom particulate layer for understanding the uptake of contaminants in the LPRSA, the uncertainty associated with the near-bottom particulate layer concentration is discussed in Section 5.3.

3.1.3 Characterization of the benthic invertebrate community

When developing a food web, it is necessary to understand the benthic invertebrate community and the site-specific factors that shape the benthic community structure. This knowledge allows for a better understanding of the bioaccumulation and transport of chemicals and the impact of the benthic invertebrate community structure on the overall LPRSA food chain. The information presented herein describes the role and influence of the benthic invertebrate community in the bioaccumulation of chemicals in the food web and informs model parameterization for the benthic invertebrate compartments (see Section 3.2 and Appendix D).

3.1.3.1 Key site-specific factors influencing benthic invertebrate community

The benthic community in the LPRSA is typical of an urban estuarine system in the lower reaches and a freshwater community in the upper reaches. The LPRSA benthic invertebrate community is influenced by physical disturbances, environmental stressors, fluctuations in salinity, and elevated levels of TOC in the sediment. The ways in which these factors may influence the benthic invertebrate community are discussed below:

- ◆ **Physical disturbances** – Urbanization has altered the physical characteristics of the LPRSA. Over time, the LPRSA has gradually been transformed into a highly channelized tidal estuary, which has resulted in increasingly frequent and severe physical disturbance of sediment (Walsh et al. 2005). Based on visual interpretation of the sediment profile imaging (SPI) data, Germano & Associates (2005) concluded that benthic invertebrate communities in the lower portion of the LPRSA (up to RM 4) were in an early, post-disturbance stage of community succession, most likely due to physical disturbance (e.g., erosion).
- ◆ **Environmental stressors** – Factors such as increased turbidity from natural and anthropogenic inputs (Moffatt & Nichol 2013) and depressed DO levels (Windward 2018c) due to considerable organic and nutrient inputs influence benthic invertebrate community structure and functionality under natural and urban conditions.
- ◆ **Fluctuations in salinity** – Salinity is a major structuring factor in estuarine habitats such as the lower reaches of the LPRSA, where the extent of the salt wedge varies significantly as a result of daily and seasonal variations in tides and river flows. In addition to contributing to increased turbidity in the river system, fluctuating salinity likely contributes to the lower abundance and

species diversity observed in the fluvial estuary and transitional portions of the LPRSA (Windward 2019a).

- ◆ **High levels of TOC in sediment** – The amount of TOC in the sediment also influences the benthic community structure and function (Pearson and Rosenberg 1978; Borja et al. 2008; Carvalho et al. 2005; Carvalho et al. 2011). SPI data collected in 2005 (Germano & Associates 2005) indicated that the LPRSA system is enriched by organic inputs such as leaf litter, inputs from sanitary sewer overflow (SSO)/combined sewer overflow (CSO), and inputs from urban runoff. Although organic matter is an important food source for benthic organisms, excessive OC can cause changes in the benthic community structure (affecting species richness and abundance) through the depletion of oxygen and the buildup of toxic biological waste products, such as ammonia (Diaz and Rosenberg 1995).

In addition to these factors, LPRSA sediments are impacted by legacy contamination and urban inputs, both of which have the potential to adversely affect benthic invertebrates.

3.1.3.2 Primary exposure pathways for benthic invertebrates

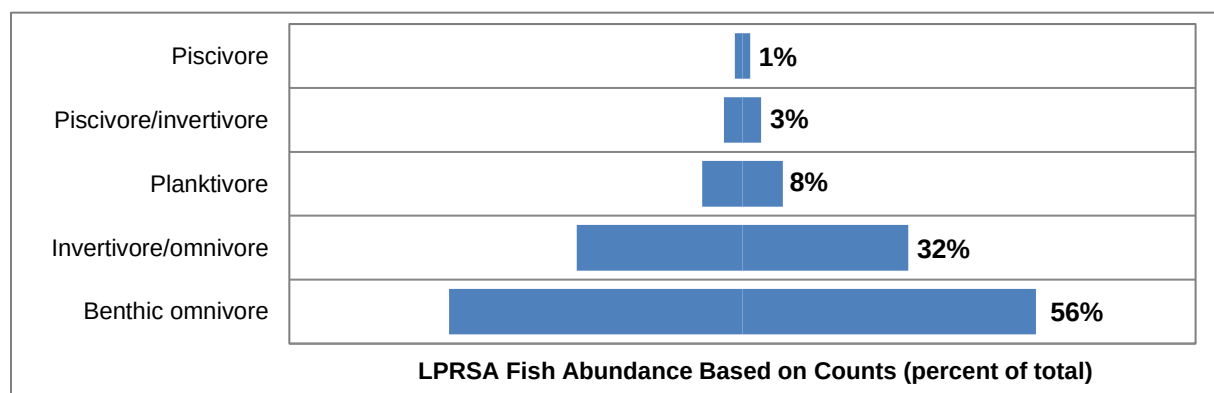
The near-bottom particulates (i.e., fluff layer) and bedded sediment are anticipated to be the primary exposure pathways for invertebrates in the LPRSA. When considering exposure pathways for benthic invertebrates, the depth of sediment to which invertebrates are primarily exposed can be an important consideration. The depth of exposure can be represented by the depth to which benthic organisms (which serve as a food resource for fish and mobile crustaceans) reside and forage for food.

Primary benthic invertebrate exposure depths are likely to be approximately equal to the depth of the redox potential discontinuity (RPD) layer. The SPI survey of the LPRSA (Germano & Associates 2005) found that the average RPD depths for the LPRSA were 1.6 cm for the upper estuary (RM 0 to RM 4), 1.7 cm for the fluvial estuary (RM 4 to RM 13), and 2.1 cm for the tidal freshwater zone (RM 13 to RM 17.4 [i.e., Dundee Dam]). A shallow (~2 cm) RPD layer limits the feeding and burrowing depths of the majority of infaunal invertebrates, thereby limiting their exposure to buried sediment and sediment contaminants (Nilsson and Rosenberg 2000; Pearson and Rosenberg 1978; Grizzle and Penniman 1991).

3.1.4 Benthic-dominated fish community

Understanding the fish community is also important in parameterizing the bioaccumulation model. The results of the LPRSA fish tissue sampling efforts

conducted in 2009 and 2010 – which utilized a variety of sampling methods⁷ conducted over multiple seasons – provide some general information about the LPRSA fish community structure. The relative abundance data from these sampling efforts indicates that the LPRSA is a benthic-dominated food chain; 88% of the fish collected during the 2009 and 2010 LPRSA fish sampling efforts (Windward 2010, 2011) were benthic omnivores or invertivores/omnivores (Figure 3-2). Given that the primary objective of the 2009 and 2010 sampling efforts was to collect target fish species for chemistry analysis, the relative fish abundance data presented in Figure 3-2 reflect only those fish species collected using the sampling methods utilized. However, these data are informative regarding the general trophic structure of the LPRSA.



Note: Figure was developed as part of the BERA for the LPRSA (Windward 2019b) and was based on fish collected during the 2009 and 2010 fish sampling efforts (Windward 2010, 2011).

Figure 3-2. LPRSA fish feeding guild abundance from the 2009 and 2010 fish community surveys

Benthic omnivores (e.g., small forage fish [e.g., mummichog and killifish], carp, and small American eel [*Anguilla rostrata*]⁸) feed near the river bottom and consume primarily benthic invertebrates and detrital material. Of the benthic omnivores, only carp are assumed to consume and thus be directly exposed to sediment. Invertivores (e.g., small white perch) have a varied diet consisting of invertebrates, plant material, small crustaceans, and other small benthic organisms. Thus, it is expected that the bioaccumulation of contaminants in LPRSA fish tissues will primarily reflect the contaminant concentrations in benthic invertebrate tissues, which in turn reflect the concentrations of contaminants in near-bottom particulates and sediment.

⁷ Collection methods included minnow traps, eel traps, box traps, trotlines, cast nets, dip nets, gillnets, beach seine nets, backpack electrofishers, and boat electrofishers. Catch effectiveness of these methods differed across species.

⁸ Small (juvenile) American eel feed primarily on lower-trophic-level prey (e.g., annelids, polychaetes, insect larvae and nymphs, crustaceans, bivalves, and gastropods), while larger (adult) American eel are more piscivorous.

3.2 BIOACCUMULATION MODEL STRUCTURE

This section describes the structure of the LPRSA bioaccumulation model. The subsections that follow present an overview of the general trophic structure and describe the physical exposure media used in the model, the rationale for the selected small benthic invertebrate and fish compartments, and the fish and crab modeling areas.

3.2.1 Overview of model structure

The site-specific bioaccumulation model developed for the LPRSA was constructed to include 15 trophic guild compartments, as described below. Each compartment is represented by a characteristic organism from the trophic guild. The model estimates the steady-state concentrations of hydrophobic organic chemicals in each compartment, using equations that describe the chemical, biological, and ecological properties and processes affecting uptake and loss of hydrophobic organic chemicals. Thus, each compartment has a unique set of equations.

The model's 15 trophic guild compartments include phytoplankton/algae, zooplankton, four benthic invertebrate groups (based on feeding strategies; details presented in Section 3.2.3), three small fish groups, and six upper-trophic-level groups (one of the upper trophic groups, piscivorous fish, has two separate compartments to represent species with different life histories). These compartments reasonably replicate the LPRSA food web without unnecessarily complicating the model. The selection of model compartments was influenced by the availability of empirical data for calibration and targeted species of interest for evaluating risks to human health and ecological receptors (i.e., upper-trophic-level species for which target tissue concentrations may be developed as part of PRG development). The trophic groups and, for the larger fish, the representative species used to parameterize the model, are:

- ◆ Phytoplankton/algae
- ◆ Zooplankton
- ◆ Benthic invertebrate deposit feeders (DEPs)
- ◆ Benthic invertebrate filter feeders (FFs)
- ◆ Benthic invertebrate detritivores (DETs)
- ◆ Benthic invertebrate carnivores/omnivores (C/Os)
- ◆ Small fish – filter-feeding fish⁹

⁹ Filter-feeding fish include young-of-the-year Atlantic menhaden (*Brevoortia tyrannus*) and small gizzard shad (*Dorosoma cepedianum*).

- ◆ Small fish – forage fish¹⁰
- ◆ Small fish – American eel, < 50 cm in length
- ◆ Blue crab
- ◆ Benthic omnivorous fish – common carp (*Cyprinus carpio*)
- ◆ Benthic omnivorous/invertivorous fish – catfish¹¹ (*Ictalurus* spp.)
- ◆ Invertivorous fish – white perch (*Morone americana*)
- ◆ Piscivorous fish – large American eel, > 50 cm in length
- ◆ Piscivorous fish – freshwater bass¹² (*Micropterus* spp.)

Another key element of the structure of the bioaccumulation model is the physical media used as sources of contaminants. Based on the LPRSA CSM information detailed in Section 3.1, the following six physical media were included in the bioaccumulation model:

- ◆ Sediment (top 15 cm)
- ◆ Porewater (i.e., dissolved contaminants in the sediment matrix)
- ◆ Dissolved contaminants in the water column (i.e., bioavailable concentrations)
- ◆ Suspended detrital particulates in the water column
- ◆ Suspended algal particulates in the water column
- ◆ Near-bottom detrital particulates

The general trophic structure, including both the model compartments and the physical media (shown as ovals), is presented in Figure 3-3.

¹⁰ Forage fish include primarily mummichog (*Fundulus heteroclitus*) but also other species, such as shiners (*Notropis* spp.), striped mullet (*Mugil cephalus*), and tessellated darter (*Etheostoma olmstedii*).

¹¹ Catfish include both white catfish (*Ictalurus catus*) and channel catfish (*Ictalurus punctatus*).

¹² Freshwater bass includes both smallmouth bass (*M. dolomieu*) and largemouth bass (*M. salmoides*).

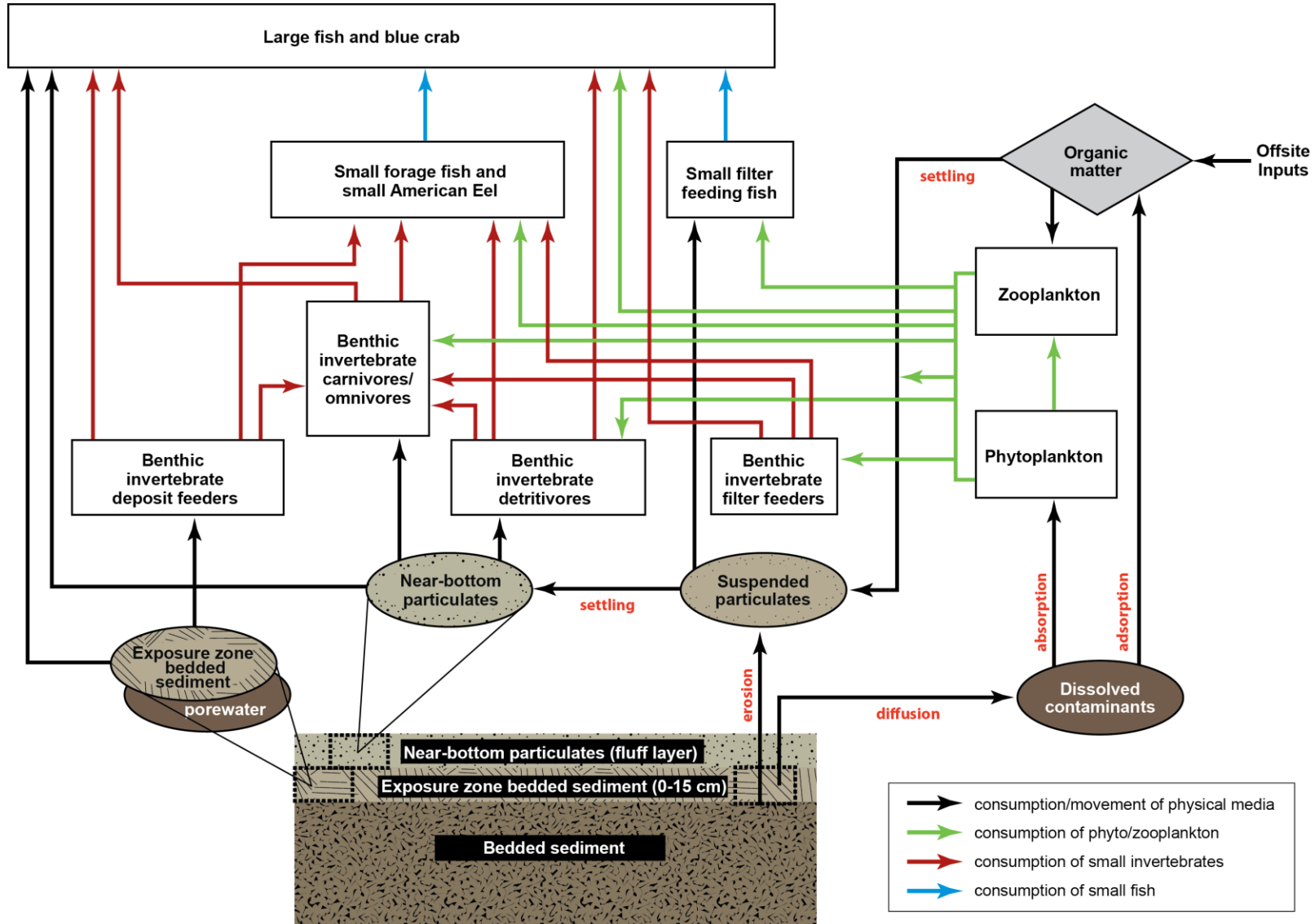


Figure 3-3. LPRSA trophic structure

3.2.2 Physical exposure media

The six exposure media provided by the CFT model were included in the bioaccumulation model:

- ◆ **Concentration in sediment** – The sediment layer to which organisms are exposed is represented by the concentration in the top 15 cm of sediment (henceforth referred to as the 15-cm layer). The 15-cm layer was the interval sampled in the majority of sediment samples collected during RI sampling. The use of this sediment layer is consistent with the CFT model and LPRSA risk assessments.
- ◆ **Concentration in porewater** – The porewater concentration is the bioavailable (i.e., dissolved) chemical concentration in water within the grains of bedded sediment. For the bioaccumulation model, the porewater layer was assumed be the same depth as the 15-cm layer.
- ◆ **Bioavailable concentration in water** – The water column concentration used in the bioaccumulation model represents the bioavailable (i.e., dissolved) portion of the chemical concentration in the water column.
- ◆ **Concentration in suspended particulates** – The CFT model can apportion contaminants between two particulate types in the water column:
 - **Suspended detrital particulates** – The chemical concentration in suspended detrital particulates represents the concentration in the water column detrital particulates that are available as a food source.
 - **Suspended algal carbon particulates** – The chemical concentration in suspended algal carbon particulates is used to calculate the chemical concentration in the phytoplankton/algae compartment in bioaccumulation model.
- ◆ **Concentration in near-bottom particulates** – The chemical concentration in suspended detrital particulates from the bottom 10% of the water column is used as a proxy for the chemical concentration in particulates settling on top of the sediment bed (i.e., the fluff layer). The chemical concentration in settling particulates is not explicitly calculated in the CFT model; rather, it is estimated from the CFT model's output for use in the bioaccumulation model. Thus, there is uncertainty associated with this parameter value, given that no site-specific data representing the near-bottom particulate layer were available to verify these concentrations (see Section 5.3).

3.2.3 Benthic invertebrate compartment details

The benthic invertebrate compartments included in the bioaccumulation model were selected based on LPRSA benthic community survey data from fall 2009 and spring and summer 2010 (Windward 2014a, b) and reflect the feeding strategies of the trophic guilds the LPRSA benthic community: DEPs, FFs, DETs, and C/Os. Benthic invertebrate taxa observed in the LPRSA were assigned to one of these four trophic guilds based on their primary feeding strategies, which are described in Table 3-1. The relative biomasses of the benthic invertebrate model groups reflect the conditions in the LPRSA based on the available data collected for the RI/FS. If future data indicate significant changes to the post-remedy benthic invertebrate community structure, adjustment of these biomass estimates may be considered for future applications of the bioaccumulation model.

Table 3-1. LPRSA benthic invertebrate feeding groups

Group Name	Description of Feeding Strategy	Example Organisms
DEPs	DEPs are invertebrates whose primary feeding strategy involves feeding on organic material mixed with the bedded sediment surface layer. Organisms in this group intentionally ingest sediment in order to digest organic materials (e.g., buried detritus and bacteria) that are sorbed to sediment particles.	DEPs include various oligochaete and polychaete worms (e.g., <i>Limnodrilus hoffmeisteri</i>), clams (e.g., <i>Macoma</i> spp.), and amphipod crustaceans.
FFs	FFs are invertebrates whose primary feeding strategy involves feeding on suspended materials (e.g., particulates and plankton). Organisms in this group passively collect suspended material or actively pump particulates past filtering appendages	FFs include polychaete worms (<i>Boccardia</i> sp.), bivalves (oysters and clams [<i>Corbicula</i> spp.]), crustaceans (e.g., barnacles, mysids, and shrimp), and insects (e.g., caddisflies and midges).
DETs	DETs are invertebrates whose primary feeding strategy involves feeding on surface detritus and near-bottom particulates. Organisms in this group consume predominantly detritus but may also consume other items (e.g., living algae).	DETs include a diverse group of oligochaete/polychaete worms, clams, midges, beetles, amphipods, limpets, snails, and some insects.
C/Os	C/Os are invertebrates whose primary feeding strategy involves feeding on other invertebrates. Organisms in this group predominantly consume other benthic invertebrates or act as parasites. They may also consume small amounts of other prey items.	C/Os include turbellarians, nematodes, leeches, larger insects, decapods (e.g., crayfish and shrimp), and some large polychaetes ^a

^a Larger epibenthic invertebrates (e.g., adult blue crabs) are not represented in this group. Blue crab are addressed as a separate compartment in the bioaccumulation model (see Section 3.2.1).

C/Os – carnivore/omnivores

DEPs – deposit feeders

DETs – detritivores

FFs – filter feeders

LPRSA – Lower Passaic River Study Area

The relative biomasses of the four benthic invertebrate groups presented in Table 3-1 were estimated as follows:

1. Taxa in the benthic community samples were identified and enumerated.

2. The estimated average body weight of an individual of a given taxon was multiplied by the number of individuals present in LPRSA samples to estimate biomass for each taxon in the LPRSA.
3. The feeding strategy of each taxon was used to assign it to one of the four benthic invertebrate trophic groups (i.e., DEP, FF, DET, or C/O).
4. Estimates of biomass for each taxon and its trophic group designation were used to develop an estimate of the relative abundance of each of the four benthic invertebrate groups in the LPRSA.

The biomass estimation process is detailed in Appendix D. Information about the relative biomass (a measure of abundance) of the various benthic invertebrate compartments is critical to understanding the overall structure of the food web, because relative biomass influences prey selection by higher trophic-level species. The estimated relative biomasses of the benthic invertebrate groups were used to assign the predator-specific prey fractions. The results of the benthic community evaluation indicate that DEPs, DETs, and FFs make up the majority of the benthic biomass in the LPRSA, with relative biomasses differing across seasons and spatial areas (Appendix D). Invertebrates categorized as C/Os are a small portion of the infaunal invertebrate biomass, regardless of season or modeling area.

The sampling methods used during the LPRSA seasonal benthic community surveys targeted the collection of infaunal and relatively immobile benthic invertebrates in the LPRSA, as opposed to the relatively larger and more mobile epibenthic invertebrates that might otherwise be included in the C/O category, and that were collected during the 2009/2019 fish/crab community sampling events (e.g., mud crabs [*Rhithropanopeus harrisi*], blue crabs, grass shrimp [*Palaemonetes pugio*]) (Windward 2010, 2011). This possible underestimation of the biomass of C/Os in the LPRSA was accounted for when determining trophic guild-specific dietary prey fractions, as described in Section 3.3.3.

3.2.4 Fish compartment details

The fish compartments included in the bioaccumulation model (Section 3.2.1) capture all of the target species of interest in the LPRSA BHHRA (AECOM 2017) and important potential prey items for ecological receptors in the LPRSA BERA (Windward 2019b). In addition, it was necessary to include sufficient detail in the model to ensure that representative prey were available for all upper-trophic-level species, but without creating an overly complicated model. Thus, fish compartments were developed for the LPRSA bioaccumulation model based on the following:

- ◆ Fish target species of interest from the BHHRA were each assigned to represent a trophic guild. When more than one species was available for a given guild (i.e., for benthic omnivorous fish and piscivorous fish), an

evaluation was conducted to determine how to appropriately model multiple species.

- ◆ The life histories and exposure pathways for small fish were evaluated to determine the appropriate number of small fish compartments that should be modeled.
- ◆ At the request of USEPA and consistent with the BERA, American eel were evaluated to determine if modeling two separate size classes was warranted, because of the wide size range of American eel present in the LPRSA.

Table 3-2 presents a discussion of key decision points for the development of model compartments for fish.

Table 3-2. Summary of fish compartments and rationale

Key Decision Points for Assigning Fish Compartments	Supporting Details ^a
Small non-eel fish	
Small filter-feeding and small forage fish were modeled as separate compartments because of differences in feeding habits and exposure.	Diet – Filter-feeding fish feed primarily in the water column and are preyed upon by other fish, while forage fish are primarily benthic feeding. Exposure – Filter-feeding fish are exposed to surface water and suspended particulates, whereas forage fish are exposed to sediment and benthic invertebrates.
American eel	
American eel were modeled as two separate size classes (small eel < 50 cm in length and large eel > 50 cm in length) because of differences in diets and as representative prey.	Diet – Prey size and the portion of fish in an individual's diet tends to increase with size for American eel. Prey item – Small American eel (i.e., < 50 cm in length) represent a lower trophic level and can be a food source for upper-trophic-level species. Large American eel (i.e., > 50 cm in length) represent those more likely to be consumed by people and higher-trophic-level fish.
Benthic omnivorous fish	
Carp and catfish were modeled as separate compartments to differentiate between benthic omnivores with different diets and body sizes.	Size – Average weights for fish collected in the LPRSA were 3.1 kg for carp and < 1 kg for white and channel catfish. Diet – Carp root in the sediment with their snouts, eating the food that they dislodge (e.g., algae, plants, and infaunal benthic invertebrates) as well as a portion of fine sediment and detritus (Maryland DNR 2007; Garcia-Berthou 2001; USGS 2010; Walburg and Nelson 1966; Pennsylvania FBC 2011). Catfish (both white catfish and channel catfish) are also benthic feeders that disturb and incidentally ingest some sediment, but they are more carnivorous than carp, preying on available invertebrates and small fish (California Fish Website 2013b; FishBase 2014).
The catfish model compartment represents both white catfish and channel catfish because of their similar life histories, diets, and LPRSA body size.	Size – Averages weights for fish collected in the LPRSA were similar (0.85 kg for channel catfish and 0.9 kg for white catfish). Diet – Both channel and white catfish are opportunistic feeders preying on what is available, including larger invertebrates such as amphipods, crayfish, mollusks, insects, and small fish (NJDEP 2001b; Wellborn 1988; California Fish Website 2013a; Turner 1966b). Both catfish are predominately benthic feeders that have some portion of sediment and detritus in their diet.

Key Decision Points for Assigning Fish Compartments	Supporting Details ^a
Piscivorous fish	
Freshwater bass (i.e., largemouth and smallmouth bass) and American eel were modeled as separate compartments to differentiate between piscivorous fish with different salinity tolerances, diets, and life histories.	Diet – Small fish are estimated to make up a larger portion of the freshwater bass diet than the American eel diet. Freshwater bass are opportunistic feeders and primarily feed on available small fish and invertebrates (George and Hadley 1979; Turner 1966a; Wydoski and Whitney 1979). Occurrence – American eel are present throughout the LPRSA; largemouth and smallmouth bass were collected only from areas above RM 7. Both smallmouth and largemouth bass remain in fresh water throughout their lifespans. American eel are a catadromous species that spawn in the Atlantic Ocean, migrate to fresh water as larvae, and remain in fresh water/estuarine areas for 5 to 20 years until sexually mature.
The freshwater bass model compartment represents both smallmouth and largemouth bass because of similar life histories, diets, and body sizes.	Diet – Both largemouth and smallmouth bass are opportunistic feeders and primarily feed on available small fish and invertebrates (George and Hadley 1979; Turner 1966a; Wydoski and Whitney 1979). Size – Average weights were similar between species (0.2 kg for smallmouth bass and 0.3 kg for largemouth bass).^b Occurrence – Both species were collected only from areas above RM 7.

^a See Appendix E for additional LPRSA species-specific details on fish sizes and occurrence based on catch locations.

^b Only smallmouth and largemouth bass > 200 mm in length were considered to be adult bass based on the range of adult bass lengths (200 to 560 mm) reported in Page and Burr (1991) and Edwards et al. (1983).

LPRSA – Lower Passaic River Study Area

RM – river mile

PCB – polychlorinated biphenyl

Small fish are a significant prey item for many larger fish. It was important to account for differences in exposure routes among the three groups of small fish: filter-feeders, forage fish, and small eel (see Table 3-2). As for benthic invertebrates (Section 3.2.3), the estimated proportional abundance of small fish, based on LPRSA data, was used to set the small fish prey fractions for the higher-trophic-level organisms that feed on small fish (see Section 3.3.3). Details of the small fish abundance determination are provided in Appendix E.

3.2.5 LPRSA modeling areas

As discussed during the December 2017 CPG-USEPA meeting, three modeling areas were defined for the LPRSA bioaccumulation model, primarily based on differences in salinity and habitat conditions; other considerations included gradients in sediment concentrations (Section 4.3.1) and the typical foraging areas of modeled fish (Appendix E). The selected modeling areas include the following:

- ◆ **RM 0 to RM 6** – Portion of the LPRSA representing estuarine conditions, with an average salinity generally ranging from 10 to 20 per thousand (ppt)
- ◆ **RM 6 to RM 14.7** – Portion of the LPRSA representing transitional salinity conditions, with an average salinity of generally less than 5 ppt

- ◆ **RM 14.7 to Dundee Dam** – Portion of the LPRSA representing freshwater conditions, with an average salinity of approximately 0 ppt. This portion of the LPRSA is characterized by hard-packed river bottom.

A determination of which species should be included in each modeling area was made based on site-specific catch information and species-specific salinity tolerance. The catch data presented in Figure 3-4 indicate the relative abundance of fish caught during the 2009 and 2010 LPRSA field sampling efforts (Windward 2010, 2011). While these sampling efforts involved a comprehensive survey of the fish community, the absence of a species from a given area (particularly a species that was caught less frequently or may have been better targeted using different catch methods) does not conclusively indicate that the species does not use that area.¹³ Figure 3-4 also presents the available LPRSA salinity information (Windward 2018c), which highlights the variability in salinity in lower portions of the LPRSA as a result of the daily tidal cycles. Based on this information, Table 3-3 summarizes the catch information and salinity tolerances and provides the rationale for the selected modeling areas for each species. With the exceptions of carp and bass, which are not expected to be present in the RM 0 to RM 6 modeling area, all modeled species are assumed to use all three modeling areas.

¹³ The fish tissue/community sampling design for the LPRSA divided the river into 2-mile segments (called reaches) and dedicated equal sampling time to each reach. Sampling methods varied by location depending on site-specific conditions. The most important difference was that electrofishing was used only in freshwater areas due to limitations with the method in saline water. In addition, the shallow water of the uppermost portion of the LPRSA (i.e., RM 16 to Dundee Dam) meant that different collection methods were used in this area (e.g., backpack rather than boat electrofishing).

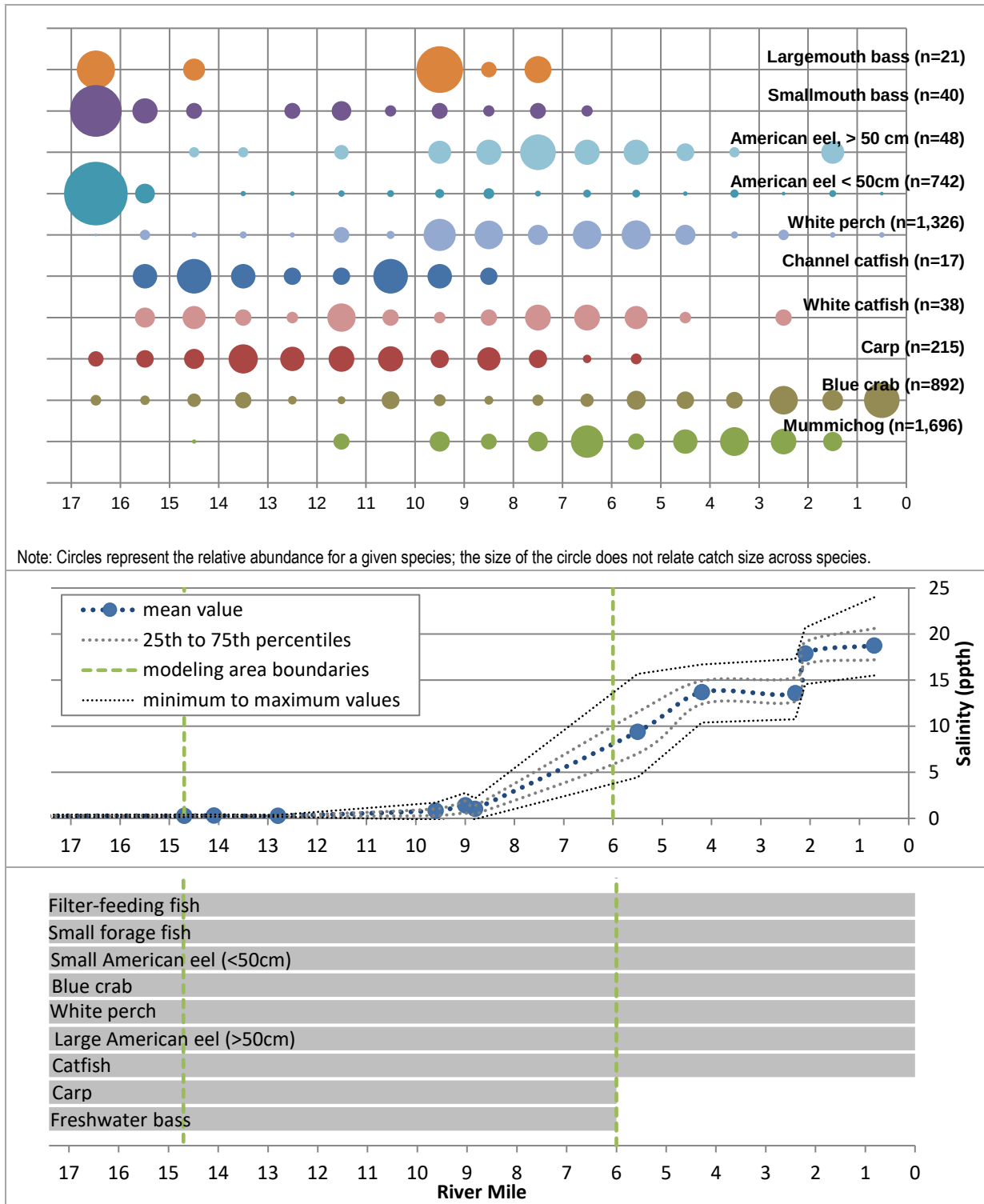


Figure 3-4. Relative abundances of fish in the LPRSA, salinity data, and selected modeling areas for fish compartments evaluated in the bioaccumulation model

Table 3-3. Fish and crab modeling areas for the LPRSA bioaccumulation model

Model Compartment	LPRSA Catch Information	Salinity Tolerance	Selected Modeling Area(s)			
			RM 0–RM 6	RM 6–RM 14.7	RM 14.7– Dundee Dam	Rationale
Small filter-feeding fish	Site-wide – Small filter-feeding fish compartment includes various small fish (e.g., gizzard shad and menhaden) that were caught throughout the LPRSA.	Varies by species – As a group, small filter-feeding fish are present in saltwater, brackish water, and fresh water.	✓	✓	✓	Species are assumed to use all three modeling areas based on catch data (i.e., presence of these species throughout the LPRSA) and high level of salinity tolerance across species in this group.
Small forage fish	Site-wide – Small forage fish compartment includes various small benthic fish (e.g., mummichog, shiners, sunfish, and killifish) that were caught throughout the LPRSA, primarily in mudflat and shallow water areas.	Varies by species – As a group, small forage fish are present in saltwater, brackish water, and fresh water.	✓	✓	✓	Species are assumed to use all three modeling areas based on catch data (i.e., presence of these species throughout the LPRSA, primarily on mudflats) and high level of salinity tolerance across species in this group. Small forage fish are assumed to use only the mudflat areas in the model.
Small American eel (< 50 cm)	Site-wide – American eel < 50 cm in length were primarily caught above RM 16 (potentially as a result of the collection methods used in this area), although some were caught throughout the LPRSA.	High – American eel are a catadromous species (i.e., they reproduce in saltwater but mature in fresh/brackish water) and thus are present in fresh, brackish, and coastal waters.	✓	✓	✓	Modeling areas are based on catch data (i.e., presence of these species throughout the LPRSA, primarily on mudflats) and high level of salinity tolerance.
Blue crab	Site-wide – Blue crab were caught throughout the LPRSA.	High – Blue crab are found in all portions of the estuary, including high-salinity and freshwater areas (Hill et al. 1989).	✓	✓	✓	Species assumed to use all three modeling areas based on catch data and salinity information.

Model Compartment	LPRSA Catch Information	Salinity Tolerance	Selected Modeling Area(s)			
			RM 0–RM 6	RM 6–RM 14.7	RM 14.7–Dundee Dam	Rationale
Carp	Above RM 5 – Carp were caught in all areas above RM 5 but were less abundant toward the lower portion of this area (i.e., below RM 7). Catch data indicate that methods used were highly successful in catching carp where present.	Moderate – Carp have a higher salinity tolerance than do most freshwater fish (Nico et al. 2014) and can tolerate salinities of up to 14 ppth (Lapidge et al. 2011), although they prefer lower salinities (2.5 ppth or less) (NJDEP 2001a).		✓	✓	Catch data and available salinity information confirm that although carp might occasionally be found below RM 6, they are primarily present in the freshwater portion of the LPRSA. Thus, carp are assumed to use only the upper two modeling areas.
Catfish	Above RM 2 – The majority of white catfish caught were collected from RM 4 to RM 16, although two individuals were caught between RM 2 and RM 3. Channel catfish were caught from RM 8 to RM 16. Neither species was caught in high numbers in the LPRSA, so they may be present in areas where they were not caught.	Low to moderate – White catfish were reported to be the dominant species in Chesapeake Bay tributaries with salinities of up to 12 ppth (Kendall and Schwartz 1968), demonstrating a moderate salinity tolerance. Channel catfish have a lower salinity tolerance and prefer salinities of < 4 ppth (FAO 2014), although they can tolerate moderate salinities (of up to 11 ppth) (FAO 2014; McMahon and Terrell 1982; Avault et al. 1969).	✓	✓	✓	Available salinity and catch data (although limited) indicate that channel catfish are constrained primarily to the freshwater portion of the LPRSA, and that white catfish are present in the freshwater and brackish portions of the LPRSA. Thus, as a conservative assumption, catfish were assumed to be present in all three modeling areas.
White perch	Site-wide – Adult white perch (i.e., individuals > 20 cm in length) were caught throughout the LPRSA.	High – White perch are a semi-anadromous species that is present in saltwater to freshwater habitats.	✓	✓	✓	Catch data and salinity information confirm that perch use the entire LPRSA (i.e., are present in all three modeling areas).

Model Compartment	LPRSA Catch Information	Salinity Tolerance	Selected Modeling Area(s)			
			RM 0–RM 6	RM 6–RM 14.7	RM 14.7– Dundee Dam	Rationale
American eel (> 50 cm)	Site-wide – American eel > 50 cm in length were caught below RM 14.7; only smaller eel were caught above RM 14.7. Larger eel were also caught above Dundee Dam. Catch methods that were successful at catching larger eel could not be used above RM 14.7 due to sampling limitations.	High – American eel are a catadromous species (i.e., they reproduce in saltwater but mature in fresh/brackish water) and thus are present in fresh, brackish, and coastal waters.	✓	✓	✓	Catch data and high salinity tolerance indicate that large eel are likely present throughout the LPRSA (i.e., use all three modeling areas). The absence of larger eel above RM 14.7 does not necessarily indicate that they do not use this portion of the river, particularly because of their presence above Dundee Dam.
Bass	Above RM 6 – Both smallmouth and largemouth bass were caught from RM 6 to Dundee Dam.	Low – Both smallmouth and largemouth bass prefer lower salinities (i.e., < 4 ppth) (Brown et al. 2009).		✓	✓	Catch data and available salinity information confirm that although bass may occasionally use somewhat higher-salinity areas (below RM 6), they are primarily present in the freshwater portion of the LPRSA.

LPRSA – Lower Passaic River Study Area

ppth – parts per thousand

RM – river mile

Although the modeling area identified for small forage fish was site-wide, the areas actually used by small forage fish were assumed to be limited to mudflats and shallow areas. This is supported by LPRSA catch data and general habitat data for small forage fish:

- ◆ **Shallow water and nearshore habitat** – During the field efforts conducted in the LPRSA in 2009 and 2010 (Windward 2010, 2011), mummichog and other small forage fish were observed in mudflats and shallow-water habitats that often featured overhanging or shoreline vegetation, observations consistent with their habitat reported in the literature. Shallow areas provide favorable habitat for small forage fish such as mummichog, which prefer shallow water near the shoreline and typically do not go deeper than 3.7 m (12 ft) (Bigelow and Schroeder 1953). They are usually found within 110 m (120 yd) of shorelines along intertidal marshes and mudflats (Armstrong and Child 1965 as cited in Abraham 1985; Hardy 1978 as cited in Abraham 1985; Lotrich 1975).
- ◆ **Areas with fine-grained sediment** – Also during the 2009 and 2010 sampling efforts (Windward 2010, 2011, 2018b), mummichog and banded killifish in the LPRSA were limited to areas with fine-grained sediment; other small forage fish, such as shiners and darters, were present in shallow areas with larger grain sizes. The presence of mummichog and banded killifish in only fine-grained mudflat areas in the LPRSA is also consistent with the flow velocities that these fish can tolerate.

Based on this information, the modeling area for small forage fish was defined to include only mudflat areas (see figures presented in Appendix F). Mudflat areas were defined in the CFT model based on a combination of shallow water depth and low slope. Chemical concentrations for the mudflat areas for use in the bioaccumulation model were predicted using the CFT model and used to estimate exposures for small forage fish and their prey.

3.3 BIOACCUMULATION MODEL INPUTS AND PARAMETERIZATION

Three types of model inputs are required for the bioaccumulation model:

- ◆ Chemical specific
- ◆ General physical and biological
- ◆ Species specific

The calibration improved the consistency between model-predicted fish tissue chemical concentrations and LPRSA tissue data. Details regarding the calibration methods are described in Section 4.1.

For model input, parameter distributions were defined using a point estimate and a range of acceptable values. The term “nominal value” is used throughout the tables in this section to refer to the point estimate prior to site-specific model calibration. In many cases, parameter values and distributions were developed in collaboration with USEPA. Parameter ranges were selected based on empirical/site-specific data whenever possible and were intended to describe uncertainty about the parameter value. When empirical data were not available, literature information was used to develop parameter distributions. No distribution was developed for chemical-specific and general parameters that were CFT model outputs.

3.3.1 Chemical-specific parameters

Chemical-specific parameters included the K_{OW} and E_D (Table 3-4), metabolic biotransformation rate constant (K_M) values for fish and invertebrates (Table 3-5), and chemical concentrations from CFT modeling (Table 3-6). As discussed in Section 2.2, the bioaccumulation model was calibrated for three chemicals: 2,3,7,8-TCDD, tetraCB, and 1,2,3,4,6,7,8-HpCDF. The K_{OW} and K_M values were derived from the literature. Section 4 discusses how values for select parameters were calibrated to improve model performance. To maintain consistency between models, the K_{OW} values used for the bioaccumulation model were the same as those used for the CFT model.

Table 3-4. Chemical-specific K_{OW} and E_D distributions

Chemical	Distribution		Value Used in CFT Model	Rationale/Source
	Nominal Value	Acceptable Range		
Log K _{ow}				
2,3,7,8-TCDD	6.38	5.38–8.93	6.65	Nominal value – ORNL RAIS (2009) Range – <i>Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals</i> (Mackay et al. 2006)
TetraCB	6.00	5.38–6.65	6.00	Nominal value – CARP model (HydroQual 2007), which cited Hawker and Connell (1988) as the source of K _{ow} values for PCB homologues Range – maximum and minimum values for individual congeners within a homologue group (Hawker and Connell 1988)
1,2,3,4,6,7,8-HpCDF	8.03	7.37–9.25	8.67	Nominal value – geometric mean of values provided by Mackay et al. (2006) Range – <i>Handbook of Physical-Chemical Properties and Environmental Fate for Organic Chemicals</i> (Mackay et al. 2006)
E _d				
2,3,7,8-TCDD	0.49	0.10–0.76	na	Nominal value and range are based on available data for 2,3,7,8-TCDD (see Appendix B).
TetraCB	0.57	0.34–0.83	na	Nominal value and range are based on available data for tetraCB (see Appendix B).
1,2,3,4,6,7,8-HpCDF	0.05	0.001–0.31	na	Nominal value is based on single data point for 1,2,3,4,6,7,8-HpCDF; range incorporates values for hexa-CDF and octa-CDF (see Appendix B).

CARP – Contamination Assessment and Reduction Project
CDF – chlorinated dibenzofuran
CFT – contaminant fate and transport
E_D – dietary chemical transfer efficiency
HpCDF – heptachlorodibenzofuran
K_{OW} – octanol-water partition coefficient

na – not applicable
ORLN – Oak Ridge National Laboratory
PCB – polychlorinated biphenyl
RAIS – Risk Assessment Information System
TCDD – tetrachlorodibenzo-*p*-dioxin
tetraCB – tetrachlorobiphenyl

Table 3-5. Chemical-specific metabolic biotransformation rate constants

Model Compartment by Chemical	K _M Distribution		Rationale ^a
	Nominal Value	Acceptable Range	
2,3,7,8-TCDD			
Benthic invertebrates	0.013	0.002–0.082	While a key enzyme (CYP450 1A1) responsible for metabolism in vertebrates is not present in invertebrates, available information suggests that invertebrates may metabolize dioxins/furans using a different mechanism, or that metabolism may serve as a surrogate for some other process(es) reducing 2,3,7,8-TCDD uptake or increasing its loss by benthic invertebrates. No invertebrate-specific rates were available, so the distribution for small fish was applied to invertebrates.
Small fish	0.013	0.002–0.082	<u>Nominal</u> : average of values normalized for 10-g fish <u>Range</u> : 2.5 th to 97.5 th percentile for values normalized for 10-g fish from Arnot et al. (2008)
Blue crab	0.006	0.0005–0.045	No blue crab-specific information was available, so the distribution developed for non-carp fish was applied to blue crab.
Carp	0.003	0.0004–0.013	Species-specific information was available for carp, so the K _M distribution was developed using carp-specific values from Arnot et al. (2008). Carp-specific data was normalized to weight of modeled carp. <u>Nominal</u> : average of weight-normalized values <u>Range</u> : 2.5 th to 97.5 th of weight-normalized percentile values
Catfish, white perch, bass	0.006	0.0005–0.045	Distribution was developed using all available K _M data for 2,3,7,8-TCDD (i.e., rates for all available species) from Arnot et al. (2008). Weight-adjusted K _M values were calculated using weights for these fish species. The same distribution was used for these groups, but calibrated values were allowed to be different. <u>Nominal</u> : average of adjusted values <u>Range</u> : 2.5 th to 97.5 th percentile for adjusted values
American eel (both sizes)	0.006	0.0005–0.045	
TetraCB			
Benthic invertebrates	0	na (point estimate)	Based on a review of the available literature and on precedent from past model applications, K _M values for tetraCB for both fish and invertebrates (with the exception of blue crab and American eel) were assumed to be equal to 0.
Small fish			
Carp			
Catfish, white perch, bass			

Model Compartment by Chemical	K _M Distribution		Rationale ^a
	Nominal Value	Acceptable Range	
Blue crab	0.002	0.0004–0.014	<u>Crab</u> : Available literature (e.g., Porte and Albaiges 1993; Bodin et al. 2007) indicates that unlike other invertebrates, crab (and other larger crustaceans) can metabolize lower-chlorinated PCBs (such as tetraCBs). <u>Eel</u> : Available literature (e.g., Brown 1992) and LPRSA empirical data indicate that unlike other fish, eel can metabolize lower-chlorinated PCBs (such as tetraCBs).
American eel (both sizes)	0.002	0.0004–0.014	<u>Distribution</u> : No crab- or eel-specific rates were available, so all available K _M values for tetraCB congeners from Arnot et al. (2008b) were used to develop the distribution. While the same distrubtion was used for both crab and eel, the calibrated values were allowed to be different. <u>Nominal</u> : weighted average based on percent contribution to sediment for congeners with available K _M values <u>Range</u> : weighted average for 2.5 and 97.5 percentiles
1,2,3,4,6,7,8-HpCDF			
Benthic invertebrates	0.086	0.031–0.24	No information available; used same nominal value and distribution as was developed for small fish.
Small fish	0.086	0.031–0.24	<u>Nominal</u> : average of values normalized for 10-g fish <u>Range</u> : 2.5 th to 97.5 th percentile for values normalized for 10-g fish from Arnot et al. (2008)
Blue crab	0.036	0.007–0.13	No blue crab-specific information was available, so the distribution developed for larger fish was applied to blue crab.
Carp	0.036	0.007–0.13	K _M values were developed using all available K _M data for 1,2,3,4,6,7,8-HpCDF (i.e., rates for all available species) from Arnot et al. (2008).
American eel (both sizes)			Calculated K _M values were based on weights for other modeled species. Same distribution was used for these groups but calibrated value was allowed to be different.
Catfish, white perch, bass			<u>Nominal</u> : average of adjusted values <u>Range</u> : 2.5 th to 97.5 th percentile for adjusted values

Note: Unit for K_M values is fraction/day.

^a Additional information regarding the development of K_M distributions is provided in Appendix C, which presents the *Development of Chemical-specific Metabolic Biotransformation Rate Constant Assumptions*.

HpCDF – heptachlorodibenzofuran

K_M – metabolism biotransformation rate constant

LPRSA – Lower Passaic River Study Area

na – not applicable

PCB – polychlorinated biphenyl

TCDD – tetrachlorodibenzo-*p*-dioxin

tetraCB – tetrachlorobiphenyl

Table 3-6. Chemical-specific concentrations from the CFT model

Parameter by Chemical	Concentration (ng/g) ^a					
	River-wide			Mudflats Only		
	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam	RM 0– RM 6	RM 6–RM 14.7	RM 14.7– Dundee Dam
2,3,7,8-TCDD						
Sediment	0.33	1.39	0.0015	0.27	2.67	0.0015
Suspended detrital particulates	0.11	0.14	0.013	0.10	0.17	0.014
Bioavailable water ^b	8.7×10^{-8}	5.1×10^{-8}	2.3×10^{-9}	8.2×10^{-8}	5.9×10^{-8}	2.2×10^{-9}
Porewater	1.1×10^{-6}	7.2×10^{-6}	2.0×10^{-8}	8.5×10^{-7}	1.0×10^{-5}	2.1×10^{-8}
Near-bottom detrital particulates	0.11	0.14	0.013	0.10	0.16	0.014
Suspended algal particulates	0.43	0.23	0.010	0.42	0.27	0.010
TetraCB						
Sediment	196	548	68	201	743	25
Suspended detrital particulates	123	177	150	120	192	147
Bioavailable water ^b	0.00057	0.00054	0.00040	0.00055	0.00055	0.00037
Porewater	0.0019	0.0097	0.0028	0.0019	0.0086	0.0010
Near-bottom detrital particulates	120	174	148	117	181	139
Suspended algal particulates	1,004	793	597	1,007	816	548
1,2,3,4,6,7,8-HpCDF						
Sediment	0.53	0.55	0.040	0.49	0.72	0.030
Suspended detrital particulates	0.31	0.47	0.40	0.29	0.52	0.40
Bioavailable water ^b	6.4×10^{-9}	1.2×10^{-9}	8.7×10^{-11}	7.3×10^{-9}	1.6×10^{-9}	8.3×10^{-11}
Porewater	1.7×10^{-8}	2.9×10^{-8}	5.0×10^{-9}	1.5×10^{-8}	2.6×10^{-8}	4.0×10^{-9}
Near-bottom detrital particulates	0.30	0.47	0.40	0.28	0.49	0.38
Suspended algal particulates	3.4	0.55	0.040	3.9	0.71	0.038

Note: The CFT model output from August 30, 2021, was used to calibrate the bioaccumulation model; information regarding the CFT model is provided by Anchor QEA et al. (2019). Output from the CFT model was averaged over the calibration period aligning with the time period when tissue samples were collected (see Section 2.6).

^a Units for all parameters from the CFT model are provided in ng/g. For bioavailable water and porewater, these units represent ng/g of water, which (based on the density of water) is equal to ng/ml of water.

^b Estimates of the concentrations of dissolved contaminants in water were provided as part of the CFT model output. Thus, equations in Arnot and Gobas (2004) were not needed to estimate this parameter from empirical or estimated total water concentrations.

CFT – contaminant fate and transport

HpCDF – heptachlorodibenzofuran

RM – river mile

TCDD – tetrachlorodibenzo-*p*-dioxin

tetraCB – tetrachlorobiphenyl

3.3.2 General physical and biological parameters

This section presents values for general physical and biological parameters, including: site-specific values based on CFT model output (Table 3-7), general model constants from literature sources (Table 3-8), and DO saturation assumptions based on

site-specific and literature values (Table 3-9). Note that these model parameters were not calibrated (i.e., no range is provided, and the nominal value is the selected value).

Table 3-7. General parameters provided by the CFT model

Non-Chemical-Specific Parameters	Parameter Value					
	River-wide			Mudflats Only		
	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam
OC content of sediment (fraction)	0.057	0.041	0.017	0.058	0.058	0.016
OC content of water column particulates (fraction)	0.083	0.13	0.12	0.080	0.14	0.13
OC content of near-bottom particulates (fraction)	0.085	0.14	0.13	0.093	0.16	0.15
Water temperature (°C)	12.7 (0 – 26)	13.1 (0 – 29)	13.4 (0 – 31)	na (same as river-wide)		

Note: The CFT model output from August 30, 2021, was used to calibrate the bioaccumulation model; information regarding the CFT model is provided by Anchor QEA et al. (2019). Output from the CFT model was averaged over the calibration period aligning with the time period when tissue samples were collected (see Section 2.6).

CFT – contaminant fate and transport

OC – organic carbon

RM – river mile

Table 3-8. General model constants from the literature

Parameter	Nominal Value	Source
Uptake constant A for organism	6.0×10^{-5}	Arnot and Gobas (2004); Gobas and Arnot (2005)
Uptake constant B for organism	5.50	Arnot and Gobas (2004); Gobas and Arnot (2005)
Dietary transfer efficiency constant A	3×10^{-7}	Arnot and Gobas (2004)
Dietary transfer efficiency constant B	2.0	Arnot and Gobas (2004)
NLOM-octanol PC	0.035	Arnot and Gobas (2004)
NLOC-octanol PC	0.35	Arnot and Gobas (2004)

Note: Constants shown in this table apply to all modeling areas.

NLOC – non-lipid organic carbon

PC – proportionality constant

NLOM – non-lipid organic matter

Table 3-9. DO saturation

River Mile/ Modeling Area	DO Saturation (%)		Rationale
	Measured	Interpolated	
RM 0-1	69%	-	A default assumption for DO saturation of 90% is provided in Arnot and Gobas (2004). The available site-specific data collected as part of the summer/fall 2012 DO monitoring program (Windward 2018c), which included data collected from August to December, were used to modify the default assumption for the LPRSA. Those months were consistent with when the majority of fish and crab in the calibration dataset were collected. Site-specific DO saturation data were available for limited areas; thus, measured site-specific DO saturation data were used to interpolate DO saturation values for RMs for which no data were available. The measured and interpolated values were then used to estimate DO saturation values for the three LPRSA modeling areas. Average percentages for each modeling area were rounded to the nearest 5% for use in the bioaccumulation model.
RM 1-2	66%	-	
RM 2-3	-	65%	
RM 3-4	-	64%	
RM 4-5	63%	-	
RM 5-6	64%	-	
RM 6-7	-	71%	
RM 7-8	-	77%	
RM 8-9	84%	-	
RM 9-10	83%	-	
RM 10-11	-	86%	
RM 11-12	-	89%	
RM 12-13	92%	-	
RM 13-14	-	95%	
RM 14-15	97%	-	
RM 15-16	-	97%	
RM 16-17.5	-	97%	
Values by Modeling Area for Use in the Bioaccumulation Model			
RM 0 to RM 6	65% (64 – 69%)	area average equal to 65%	
RM 6 to RM 14.7	85% (71 – 97%)	area average equal to 86%; rounded to 85%	
RM 14.7 to Dundee Dam	95% (92 – 97%)	area average equal to 97%; rounded to 95%	

DO – dissolved oxygen

LPRSA – Lower Passaic River Study Area

RM – river mile

3.3.3 Species-specific parameters

Species-specific parameter values were selected based on site-specific or literature-reported data. This section provides the initial nominal values, distribution values (i.e., those used for calibration), and information sources for developing the parameter values.

Table 3-10 presents species-specific values for non-diet parameters. Whenever possible, these non-diet species-specific model values were based on LPRSA data. The available LPRSA empirical fish tissue data for weight, lipid fraction, and water content were a mix of individual and composite samples. In cases wherein both individual and composite data were available, the data were treated equally (i.e., samples were not weighted when calculating averages or standard errors). The numbers of samples (for both individuals and composites) are indicated in Table 3-10.

Table 3-10. Species-specific non-dietary fraction parameter distributions and rationale

Parameter by Model Compartment	Unit	Modeling Area	Nominal Value	Acceptable Range	Source Notes
Phytoplankton/Algae					
Lipid fraction of organism	fraction	all	0.0012	0.0008–0.002	Mackintosh et al. (2004)
Water content fraction of organism	fraction	all	0.96	0.94–0.99	Mackintosh et al. (2004)
Fraction of porewater ventilated	none	all	0	na (point estimate)	Live in water column; exposure to porewater assumed to be zero
Zooplankton					
Weight	kg	all	1.4×10^{-7}	na (point estimate)	Giles and Cordell (1998)
Lipid fraction of organism	fraction	all	0.01	0.009–0.011	Evjemo and Olsen (1997)
Water content fraction of organism	fraction	all	0.90	0.80–0.98	Kuroshima et al. (1987), as cited in Delbare et al. (1996)
Dietary AE of lipid	none	all	0.72	0.55–0.85	Data from Conover (1966), as cited in Arnot and Gobas (2004); study involved <i>Calanus hyperboreus</i> eating diatoms and flagellates from Gulf of Maine
Dietary AE of NLOM	none	all	0.72	0.55 –0.85	Data from Conover (1966), as cited in Arnot and Gobas (2004); study involved <i>Calanus hyperboreus</i> eating diatoms and flagellates from Gulf of Maine. Dietary AEs of NLOM and NLOC for zooplankton are expected to be similar (although not necessarily the same) and higher than those for invertebrates (Gobas 2014).
Dietary AE of NLOC	none	all	0.72	0.55–0.85	
Dietary AE of water	none	all	0.55	na (point estimate)	Value from Gobas and Arnot (2005)
Fraction of porewater ventilated	none	all	0	na (point estimate)	Live in water column; exposure to porewater assumed to be zero
Invertebrate AEs (benthic invertebrates and blue crab)					
Dietary AE of lipid	none	all	0.75	0.15–0.96	Data from Roditi and Fisher (1999), Berge and Brevik (1996), Gordon (1966), and Parkerton (1993), as cited in Arnot and Gobas (2004); studies involved zebra mussels from tidal freshwater section of the Hudson River and polychaetes from Cape Cod intertidal flats.
Dietary AE of NLOM	none	all	0.75	0.15–0.96	Data from Roditi and Fisher (1999), Berge and Brevik (1996), Gordon (1966), and Parkerton (1993), as cited in Arnot and Gobas (2004); studies involved zebra mussels from the tidal freshwater section of the Hudson River and polychaetes from Cape Cod intertidal flats.
Dietary AE of NLOC	none	all	0.75	0.15–0.96	
Dietary AE of water	none	all	0.55	na (point estimate)	Value from Gobas and Arnot (2005)
Fish AEs					
Dietary AE of lipid	none	all	0.92	0.90–0.95	Data from Gobas et al. (1999), as cited in Arnot and Gobas (2004); based on 73-day laboratory test with adult rainbow trout and a field study of rock bass.
Dietary AE of NLOM	none	all	0.60	0.50–0.65	Data from Nichols et al. (2001), as cited in Arnot and Gobas (2004); based on study with tetraCB and rainbow trout. Dietary AEs of NLOM and NLOC for fish are expected to be similar and higher than those for invertebrates (Gobas 2014).
Dietary AE of NLOC	none	all	0.60	0.50–0.65	
Dietary AE of water	none	all	0.55	na (point estimate)	Value from Gobas and Arnot (2005)
Benthic Invertebrate DEPs					
Weight	kg	RM 0–RM 6	1.5×10^{-4}	1.7×10^{-7} – 1.5×10^{-4}	
		RM 6–RM 14.7	3.6×10^{-5}	1.2×10^{-7} – 4.0×10^{-4}	

Table 3-10. Species-specific non-dietary fraction parameter distributions and rationale

Parameter by Model Compartment	Unit	Modeling Area	Nominal Value	Acceptable Range	Source Notes
		RM 14.7–dam	3.8×10^{-4}	1.7×10^{-7} – 4.0×10^{-4}	Weighted average of literature-based value for species within the DEP model compartment (see Appendix D; Table 3); range based on minimum to maximum values for component species representing 1% or more of the total DEP biomass. No range was available for the lipid fraction and water content parameters; thus, point estimates were used.
Lipid fraction of organism	fraction	RM 0–RM 6	0.014	0.013–0.021	
		RM 6–RM 14.7	0.021	0.013–0.021	
		RM 14.7–dam	0.021	na	
Water content fraction of organism	fraction	RM 0–RM 6	0.91	0.80–0.91	
		RM 6–RM 14.7	0.80	0.80–0.91	
		RM 14.7–dam	0.80	na	
Fraction of porewater ventilated	none	all	0.05	0.05–0.15	Respiration takes place at sediment surface; however, organisms burrow in sediment to feed on organic material, and burrowing activity entrains overlying water that dilutes sediment porewater.
Benthic Invertebrate FFs					
Weight	kg	RM 0–RM 6	1.1×10^{-5}	na	Weighted average of literature-based value for species within the FF model compartment (see Appendix D; Table 4); range based on minimum to maximum values for component species representing 1% or more of the total FF biomass. No range was available for the lipid fraction and water content parameters; thus, point estimates were used.
		RM 6–RM 14.7	5.6×10^{-5}	6.4×10^{-6} – 6.1×10^{-5}	
		RM 14.7–dam	6.0×10^{-5}	6.4×10^{-6} – 6.1×10^{-5}	
Lipid fraction of organism	fraction	RM 0–RM 6	0.023	na	
		RM 6–RM 14.7	0.013	0.013–0.023	
		RM 14.7–dam	0.013	na	
Water content fraction of organism	fraction	RM 0–RM 6	0.81	na	
		RM 6–RM 14.7	0.91	0.81–0.91	
		RM 14.7–dam	0.91	na	
Fraction of porewater ventilated	none	all	0.05	0.01–0.1	Literature-based values were available for <i>Macoma nasuta</i> , and a reported 4% of total water ventilated was porewater (Kaag et al. 1997).
Benthic Invertebrate DETs					
Weight	kg	RM 0–RM 6	4.3×10^{-5}	3.1×10^{-7} – 3.3×10^{-4}	Weighted average of literature-based value for species within the DET model compartment (see Appendix D; Table 5); range based on minimum to maximum values for component species representing 1% or more of the total DET biomass.
		RM 6–RM 14.7	6.0×10^{-6}	3.1×10^{-7} – 1.3×10^{-5}	
		RM 14.7–dam	5.6×10^{-6}	3.1×10^{-7} – 1.1×10^{-5}	
Lipid fraction of organism	fraction	RM 0–RM 6	0.014	0.0059–0.038	
		RM 6–RM 14.7	0.013	0.0059–0.038	
		RM 14.7–dam	0.0097	0.0059–0.038	
Water content fraction of organism	fraction	RM 0–RM 6	0.82	0.79–0.92	
		RM 6–RM 14.7	0.85	0.79–0.92	
		RM 14.7–dam	0.90	0.79–0.92	

Table 3-10. Species-specific non-dietary fraction parameter distributions and rationale

Parameter by Model Compartment	Unit	Modeling Area	Nominal Value	Acceptable Range	Source Notes
Fraction of porewater ventilated	none	all	0.01	0.01– 0.05	Respiration dependent on entrainment of overlying water to maintain oxygen levels; respiration of porewater minimal, but animals live in tubes and burrows within sediment and may be exposed to diluted porewater.
Benthic Invertebrate C/Os					
Weight	kg	RM 0–RM 6	3.3×10^{-5}	3.3×10^{-6} – 2.2×10^{-4}	Weighted average of literature-based value for species within C/O model compartment (see Appendix D; Table 6). Range based on minimum to maximum values for component species representing 1% or more of the total C/O biomass.
		RM 6–RM 14.7	2.4×10^{-6}	3.0×10^{-7} – 4.0×10^{-6}	
		RM 14.7–dam	2.2×10^{-6}	3.0×10^{-7} – 2.7×10^{-6}	
Lipid fraction of organism	fraction	RM 0–RM 6	0.016	0.0059–0.017	
		RM 6–RM 14.7	0.014	0.0060–0.024	
		RM 14.7–dam	0.012	0.0060–0.024	
Water content fraction of organism	fraction	RM 0–RM 6	0.73	0.73–0.85	
		RM 6–RM 14.7	0.81	0.76–0.85	
		RM 14.7–dam	0.82	0.76–0.85	
Fraction of porewater ventilated	none	all	0.05	0.01–0.05	Respiration dependent on entrainment of overlying water to maintain oxygen levels; respiration of porewater minimal because it is typically anoxic, but animals live in tubes and burrows within sediment and thus may be exposed to diluted porewater.
Filter-Feeding Fish^a					
Weight	kg	RM 0–RM 6	0.0065	0.0030–0.0099 ^b	Based on LPRSA gizzard shad data (n = 115); range of 0.022 to 0.106 kg and SE of 0.020 kg (67 to 111 mm in length), which reflect the size of fish expected to be consumed by upper-trophic-level species; juvenile (young-of-the-year). Data only available for the RM 6–RM 14.7 modeling area; these values used as surrogates for other modeling areas.
		RM 6–RM 14.7	0.0065	0.0030–0.0099 ^b	
		RM 14.7–dam	0.0065	0.0030–0.0099 ^b	
Lipid fraction of organism	fraction	RM 0–RM 6	0.022	0.015–0.029 ^b	LPRSA gizzard shad data (n = 3); range of 0.019 to 0.026 and SE of 0.0022. Data only available for the RM 6–RM 14.7 modeling area; these values used as surrogate for other modeling areas.
		RM 6–RM 14	0.022	0.015–0.029 ^b	
		RM 14.7–dam	0.022	0.015–0.029 ^b	
Water content fraction of organism	fraction	RM 0–RM 6	0.78	0.72–0.83 ^b	LPRSA gizzard shad data (n = 3); range of 0.75 to 0.81 and SE of 0.019. Data only available for the RM 6–RM 14.7 modeling area; these values used as surrogate for other modeling areas.
		RM 6–RM 14.7	0.78	0.72–0.83 ^b	
		RM 14.7–dam	0.78	0.72–0.83 ^b	
Fraction of porewater ventilated	none	all	0	na (point estimate)	Estimated based on information regarding feeding habits.

Table 3-10. Species-specific non-dietary fraction parameter distributions and rationale

Parameter by Model Compartment	Unit	Modeling Area	Nominal Value	Acceptable Range	Source Notes
Small Forage Fish^c					
Weight	kg	RM 0–RM 6	0.0045	0.0032–0.0058 ^b	LPRSA mummichog data (n = 667); range of 0.0005 to 0.016 kg and SE of 0.00043 kg (30 to 100 mm in length).
		RM 6–RM 14.7	0.0027	0.0012–0.0042 ^b	LPRSA mummichog data (n = 1,205); range of 0.0005 to 0.036 kg and SE of 0.00049 kg (25 to 159 mm in length).
		RM 14.7–dam	0.0039	0.0039 ^b	LPRSA mummichog data (n = 1); range of 0.0039 kg (25 to 121 mm in length).
Lipid fraction of organism	fraction	RM 0–RM 6	0.017	0.014–0.020 ^b	LPRSA data (n = 11); range of 0.014 to 0.024 and SE of 0.00090.
		RM 6–RM 14.7	0.025	0.019–0.031 ^b	LPRSA data (n = 13); range of 0.018 to 0.043 and SE of 0.0019.
		RM 14.7–dam	0.037	0.037 ^b	LPRSA data (n = 1); 0.037.
Water content fraction of organism	fraction	RM 0–RM 6	0.75	0.74–0.76 ^b	LPRSA data (n = 11); range of 0.74 to 0.77 and SE of 0.0032.
		RM 6–RM 14.7	0.75	0.73–0.77 ^b	LPRSA data (n = 13); range of 0.68 to 0.78 and SE of 0.0068.
		RM 14.7–dam	0.80	0.80 ^b	LPRSA data (n = 1); 0.80 .
Fraction of porewater ventilated	none	all	0.05	0.01–0.10	Estimated based on information regarding feeding habits.
Blue Crab					
Weight	kg	RM 0–RM 6	0.17	0.14–0.19 ^b	LPRSA data (n = 186); range of 0.068 to 0.35 kg and SE of 0.0085 kg (114 to 179 mm in length).
		RM 6–RM 14.7	0.14	0.12–0.15 ^b	LPRSA data (n = 98); range of 0.024 to 0.24 kg and SE of 0.0048 kg (114 to 175 mm in length).
		RM 14.7–dam	0.15	0.13–0.17 ^b	LPRSA data (n = 16); range of 0.094 to 0.22 kg and SE of 0.0064 kg (116 to 167 mm in length).
Lipid fraction of organism	fraction	RM 0–RM 6	0.012	0.010–0.014 ^b	LPRSA data (n = 19); range of 0.0072 to 0.015 and SE of 0.00057.
		RM 6–RM 14.7	0.012	0.0066–0.017 ^b	LPRSA data (n = 7); range of 0.0082 to 0.020 and SE of 0.0018.
		RM 14.7–dam	0.012	0.0066–0.017 ^b	No data; used data from RM 6–14.7 as surrogate.
Water content fraction of organism	fraction	RM 0–RM 6	0.79	0.77–0.80 ^b	LPRSA data (n = 19); range of 0.77 to 0.82 and SE of 0.0037.
		RM 6–RM 14.7	0.81	0.80–0.83 ^b	LPRSA data (n = 7); range of 0.79 to 0.83 and SE of 0.0060.
		RM 14.7–dam	0.81	0.80–0.83 ^b	No data; used data from RM 6–14.7 as surrogate.
Fraction of porewater ventilated	none	all	0.05	0–0.10	Estimated using information regarding feeding habits.
Carp					
Weight	kg	RM 6–RM 14.7	3.1	2.6–3.5 ^b	LPRSA data (n = 11); range of 2.2 to 3.9 kg and SE of 0.16 kg (524 to 610 mm in length).
		RM 14.7–dam	3.1	3.0–3.2 ^b	LPRSA data (n = 3); all three values equal to 3.1 kg and SE of 0.022 kg (596 to 610 mm in length).
Lipid fraction of organism	fraction	RM 6–RM 14.7	0.052	0.039–0.065 ^b	LPRSA data (n = 11); range of 0.028 to 0.081 and SE of 0.0043.
		RM 14.7–dam	0.064	0.036–0.092 ^b	LPRSA data (n = 3); range of 0.048 to 0.080 and SE of 0.0092.
Water content fraction of organism	fraction	RM 6–RM 14.7	0.65	0.62–0.69 ^b	LPRSA data (n = 11); range of 0.58 to 0.71 and SE of 0.012.
		RM 14.7–dam	0.70	0.68–0.72 ^b	LPRSA data (n = 3); range of 0.69 to 0.71 and SE of 0.0072.
Fraction of porewater ventilated	none	all	0.05	0.01–0.10	Estimated using information regarding feeding habits.

Table 3-10. Species-specific non-dietary fraction parameter distributions and rationale

Parameter by Model Compartment	Unit	Modeling Area	Nominal Value	Acceptable Range	Source Notes
Catfish (white and channel catfish)					
Weight	kg	RM 0–RM 6	0.95	0.52–1.4 ^b	LPRSA data (n = 6); range of 0.51 to 1.3 kg and SE of 0.14 kg (340 to 471 mm in length).
		RM 6–RM 14	0.88	0.68–1.1 ^b	LPRSA data (n = 27); range of 0.42 to 1.7 kg and SE of 0.068 kg (315 to 541 mm in length).
		RM 14.7–dam	0.95	0.65–1.3 ^b	LPRSA data (n = 12); range of 0.49 to 1.5 kg and SE of 0.10 kg (352 to 541 mm in length).
Lipid fraction of organism	fraction	RM 0–RM 6	0.044	0.021–0.067 ^b	LPRSA data (n = 6); range of 0.021 to 0.068 and SE of 0.0076.
		RM 6–RM 14.7	0.060	0.047–0.074 ^b	LPRSA data (n = 27); range of 0.017 to 0.11 and SE of 0.0045.
		RM 14.7–dam	0.066	0.050–0.082 ^b	LPRSA data (n = 12); range of 0.039 to 0.093 and SE of 0.0052.
Water content fraction of organism	fraction	RM 0–RM 6	0.74	0.70–0.79 ^b	LPRSA data (n = 6); range of 0.69 to 0.79 and SE of 0.015.
		RM 6–RM 14.7	0.74	0.72–0.75 ^b	LPRSA data (n = 27); range of 0.68 to 0.82 and SE of 0.0063.
		RM 14.7–dam	0.73	0.70–0.75 ^b	LPRSA data (n = 12); range of 0.69 to 0.76 and SE of 0.0072.
Fraction of porewater ventilated	none	all	0.05	0.01–0.10	Estimated using information regarding feeding habits.
White Perch					
Weight	kg	RM 0–RM 6	0.17	0.0039–0.33 ^b	LPRSA data (n = 29); range of 0.056 to 0.54 kg and SE of 0.054 kg (158 to 321 mm in length).
		RM 6–RM 14.7	0.094	0.032–0.16 ^b	LPRSA data (n = 27); range of 0.028 to 0.20 kg and SE of 0.021 kg (118 to 236 mm in length).
		RM 14.7–dam	0.059	0.049–0.070 ^b	LPRSA data (n = 9); range of 0.052 to 0.070 kg and SE of 0.0034 kg (159 to 175 mm in length).
Lipid fraction of organism	fraction	RM 0–RM 6	0.048	0.037–0.059 ^b	LPRSA data (n = 9); range of 0.033 to 0.066 and SE of 0.0037.
		RM 6–RM 14.7	0.043	0.016–0.070 ^b	LPRSA data (n = 8); range of 0.013 to 0.090 and SE of 0.0089.
		RM 14.7–dam	0.040	0.035–0.045 ^b	LPRSA data (n = 3); range of 0.037 to 0.043 and SE of 0.0018.
Water content fraction of organism	fraction	RM 0–RM 6	0.70	0.68–0.72 ^b	LPRSA data (n = 9); range of 0.66 to 0.73 and SE of 0.0065.
		RM 6–RM 14.7	0.71	0.68–0.73 ^b	LPRSA data (n = 8); range of 0.68 to 0.74 and SE of 0.0076.
		RM 14.7–dam	0.72	0.71–0.72 ^b	LPRSA data (n = 3); values equal to 0.72 and SE of 0.0088..
Fraction of porewater ventilated	none	all	0	na (point estimate)	Estimated using information regarding feeding habits
American Eel – Small (< 50 cm)					
Weight	kg	RM 0–RM 6	0.18	0.046–0.38 ^b	LPRSA data (n = 7); range of 0.046 to 0.29 kg and SE of 0.067 kg (287 to 508 mm in length).
		RM 6–RM 14.7	0.16	0.032–0.29 ^b	LPRSA data (n = 12); range of 0.028 to 0.29 kg and SE of 0.043 kg (264 to 481 mm in length).
		RM 14.7–dam	0.041	0.034–0.048 ^b	LPRSA data (n = 21); range of 0.028 to 0.048 kg and SE of 0.0022 kg (264 to 310 mm in length).
Lipid fraction of organism	fraction	RM 0–RM 6	0.054	0.032–0.076 ^b	LPRSA data (n = 3); range of 0.045 to 0.069 and SE of 0.0074.
		RM 6–RM 14.7	0.057	0.031–0.083 ^b	LPRSA data (n = 6); range of 0.032 to 0.082 and SE of 0.0087.
		RM 14.7–dam	0.069	0.045–0.093 ^b	LPRSA data (n = 5); range of 0.050 to 0.095 and SE of 0.0080.

Table 3-10. Species-specific non-dietary fraction parameter distributions and rationale

Parameter by Model Compartment	Unit	Modeling Area	Nominal Value	Acceptable Range	Source Notes
Water content fraction of organism	fraction	RM 0–RM 6	0.70	0.69–0.72 ^b	LPRSA data (n = 3); range of 0.69 to 0.71 and SE of 0.0052.
		RM 6–RM 14.7	0.70	0.66–0.74 ^b	LPRSA data (n = 6); range of 0.66 to 0.75 and SE of 0.014.
		RM 14.7–dam	0.68	0.65–0.71 ^b	LPRSA data (n = 5); range of 0.66 to 0.71 and SE of 0.0087.
Fraction of porewater ventilated	none	all	0	na (point estimate)	Estimated using information regarding feeding habits.
American Eel – Large (> 50 cm)					
Weight	kg	RM 0–RM 6	0.42	0.35–0.48 ^b	LPRSA data (n = 3); range of 0.38 to 0.45 kg and SE of 0.022 kg (551 to 635 mm in length).
		RM 6–RM 14.7	0.37	0.33–0.41 ^b	LPRSA data (n = 6); range of 0.32 to 0.42 kg and SE of 0.014 kg (511 to 603 mm in length).
		RM 14.7–dam	0.37	0.33–0.41 ^b	No data; used data from RM 6–14.7 as surrogate.
Lipid fraction of organism	fraction	RM 0–RM 6	0.064	0.040–0.12 ^b	LPRSA data (n = 3); range of 0.025 to 0.085 and SE of 0.020.
		RM 6–RM 14.7	0.079	0.040–0.12 ^b	LPRSA data (n = 6); range of 0.027 to 0.12 and SE of 0.013.
		RM 14.7–dam	0.079	0.040–0.12 ^b	No data; used data from RM 6–14.7 as surrogate.
Water content fraction of organism	fraction	RM 0–RM 6	0.69	0.62–0.76 ^b	LPRSA data (n = 3); range of 0.66 to 0.73 and SE of 0.023.
		RM 6–RM 14.7	0.69	0.64–0.75 ^b	LPRSA data (n = 6); range of 0.65 to 0.77 and SE of 0.018.
		RM 14.7–dam	0.69	0.64–0.75 ^b	No data; used data from RM 6–14.7 as surrogate.
Fraction of porewater ventilated	none	all	0	na (point estimate)	Estimated using information regarding feeding habits.
Bass (smallmouth and largemouth)					
Weight	kg	RM 6–RM 14.7	0.29	0.15–0.44 ^b	LPRSA data (n = 4); range of 0.14 to 0.44 kg and SE of 0.049 kg (219 to 319 mm in length).
		RM 14.7–dam	0.28	0.11–0.71 ^b	LPRSA data (n = 2); range of 0.11 to 0.42 kg and SE of 0.14 kg (190 to 307 mm in length).
Lipid fraction of organism	fraction	RM 6–RM 14.7	0.024	0.021–0.027 ^b	LPRSA data (n = 4); range of 0.021 to 0.025 and SE of 0.00096.
		RM 14.7–dam	0.026	0.016–0.037 ^b	LPRSA data (n = 2); range of 0.022 to 0.029 and SE of 0.0035.
Water content fraction of organism	fraction	RM 6–RM 14.7	0.75	0.74–0.76 ^b	LPRSA data (n = 4); range of 0.74 to 0.76 and SE of 0.0040.
		RM 14.7–dam	0.74	0.71–0.76 ^b	LPRSA data (n = 2); range of 0.73 to 0.75 and SE of 0.0085.
Fraction of porewater ventilated	none	all	0	na (point estimate)	Estimated using information regarding feeding habits.

^a Examples of filter-feeding fish include young-of-the-year Atlantic menhaden and small gizzard shad.

^b Acceptable range is equal to the range of the mean +/- three times the SE of the raw data, which defines the standard deviation of the distribution around the mean value. When necessary, ranges were truncated at the minimum value (i.e., values were not allowed to be negative).

^c Examples of small forage fish include mummichog, shiners, and tessellated darter.

AE – absorption efficiency

C/O – benthic invertebrate carnivore/omnivore

DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

na – not applicable

NLOC – non-lipid organic carbon

NLOM – non-lipid organic matter

RM – river mile

SE – standard error

tetraCB – tetrachlorobiphenyl

Windward – Windward Environmental LLC

Tables 3-11 and 3-12 (a to m) provide the dietary parameter assumptions for the LPRSA bioaccumulation model. Particulates/detritus (either as near-bottom or water column particulates/detritus) were modeled separately from sediment solids for dietary items in order to better represent exposure for organisms that feed on settling or newly settled organic matter, rather than bulk sediment (see Section 3.2). The proportion of each prey item in the diet for each model compartment was based on LPRSA-specific data (including relative biomass for benthic invertebrates and relative abundance for small fish) and a review of general and regional scientific literature on dietary preferences.

The rationale for the selection of the prey items¹⁴ is summarized in Tables 3-12a through 3-12m. Prey portions of benthic invertebrates and small fish differ by reach based on the feeding preferences of modeled species and information regarding abundance (see Appendices D and E for information regarding benthic invertebrate and small fish abundance, respectively).

A best estimate nominal value for each potential prey item (e.g., zooplankton, filter-feeding fish, and DEPs) was selected. There is uncertainty and variability in the assigned percentages, especially for fish, because of their opportunistic feeding behavior. In reality, it is likely that fish diets vary considerably depending on prey availability. Thus, the diets of fish can be influenced by season and location.

¹⁴ Crab and larger fish (i.e., carp, catfish, white perch, large eel, and bass) are not used as diet items in the model.

Table 3-11. Overview of species-specific dietary percentages

Model Compartment	Dietary Percentages (nominal values)						
	Sediment Solids	Particulates/Detritus		Phytoplankton/ Algae	Zooplankton	Benthic Invertebrates	Small Fish
		Near- bottom/Fluff	Water Column				
Zooplankton	-	-	-	100% ^a	-	-	-
DEP ^b	23–89%	10–43%	-	0–17%	0–17%	-	-
FF ^b	5–15%	0–19%	-	33–47.5%	33–47.5%	-	-
DET ^b	13–28%	64–74%	-	3.5–8%	3.5–8%	0–2%	-
C/O ^b	5–8%	27–30%	-	0%	0%	62–68%	-
Filter-feeding fish	-	-	50%	25%	25%	-	-
Small forage fish	1%	15%	-	15%	4%	65%	-
American eel – small (< 50 cm)	2%	3%	-	-	-	85%	10%
Blue crab	2%	1%	-	-	-	83%	14%
Common carp	15%	25%	-	5%	-	54%	1%
Catfish	5%	10%	-	2%	-	43%	40%
White perch	-	5%	-	2%	3%	75%	15%
American eel – large (> 50 cm)	2%	3%	-	-	-	55%	40%
Bass (smallmouth/ largemouth)	-	-	-	-	-	20%	80%

Note: Rationale for these fractions and details regarding the breakdown within the benthic invertebrate and small fish categories is provided in Tables 3-12a through 3-12m and is discussed further in Appendix D (for benthic invertebrates) and Appendix E (for blue crab and fish).

- ^a It was assumed that the portion of carnivorous zooplankton in the LPRSA compared with the portion of planktivores is negligible.
- ^b Ranges for benthic invertebrate model compartments are based on best estimates in the three modeling areas, which reflect the different assemblages of benthic invertebrates in these areas.

C/O – benthic invertebrate carnivore/omnivore
DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore
FF – benthic invertebrate filter feeder
LPRSA – Lower Passaic River Study Area

Table 3-12a. Diet distributions and rationale for benthic invertebrate DEPs

Prey Items	Nominal Value and Range (%)		
	RM 0–RM 6	RM 6–RM 14.7	RM 14.7–Dundee Dam
Sediment solids	23 (0–40)	89 (70–100)	84 (60–100)
Particulates/detritus (near-bottom/fluff layer)	43 (25–75)	10 (0–30)	16 (0–40)
Phytoplankton/algae	17 (0–30)	0.5 (0–5)	0 (0–5)
Zooplankton	17 (0–30)	0.5 (0–5)	0 (0–5)

Rationale and Source (see Appendix D for details):

- **Species** – Model compartment includes benthic invertebrates whose primary feeding strategy involves intentionally ingesting sediment in order to digest organic material (e.g., buried detritus and bacteria). Examples include various oligochaete/polychaete worms, clams (e.g., *Macoma* spp), and amphipod crustaceans.
- **Overview and feeding plasticity** – Although DEPs consume primarily sediment solids, it is common for invertebrates to utilize alternate feeding strategies (an adaptation often referred to as feeding plasticity). As described in detail in Appendix D, diet fractions and ranges within each LPRSA modeling area were developed by considering the feeding habits of the DEPs present in the LPRSA benthic community in that area.
- **Differences across modeling areas** – Differences in feeding strategies across modeling areas were based on the variability of the DEP species that were present in each area in the LPRSA. For example, *Macoma* spp. made up the majority (98%) of the biomass for the DEP group from RM 0 to RM 6, whereas they were 10% or less of the biomass for the other two modeling areas. The large difference between the diet for the RM 0 to RM 6 modeling segment and the other two segments occurs because although *Macoma* spp. are classified as DEPs, they frequently feed as either a DET or FF (see Appendix D).

DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

RM – river mile

Table 3-12b. Diet distributions and rationale for benthic invertebrate FFs

Prey Items	Nominal Value and Range (%)		
	RM 0–RM 6	RM 6–RM 14.7	RM 14.7–Dundee Dam
Sediment solids	5 (0–20)	14 (0–30)	15 (0–30)
Particulates/detritus (near-bottom/fluff layer)	0 (0–5)	18 (0–40)	19 (0–40)
Phytoplankton/algae	47.5 (25–75)	34 (10–50)	33 (10–50)
Zooplankton	47.5 (25–75)	34 (10–50)	33 (10–50)
Benthic invertebrates	0 (na)	0 (na)	0 (na)

Rationale and Source (see Appendix D for details):

- **Species** – Model compartment includes benthic invertebrates whose primary feeding strategy involves passively collecting suspended material (e.g., through the use of polychaete mucus nets) or actively pumping particulates past filtering appendages (e.g., through the use of siphons in bivalves or setae in small crustaceans). Examples include polychaete worms, bivalves (oysters and clams), crustaceans (e.g., barnacles, mysids, and shrimp), and insects (e.g., caddisflies and midges).
- **Overview and feeding plasticity** – Although FFs consume primarily material from the water column (represented by phytoplankton and zooplankton in the bioaccumulation model), it is common for invertebrates to utilize alternate feeding strategies (an adaptation often referred to as feeding plasticity). As is described in detail in Appendix D, diet fractions and ranges within each LPRSA area were developed by considering the feeding habits of the FFs present within the LPRSA benthic community in that area.
- **Benthic invertebrates** – Based on the review of feeding habits, no consumption of other invertebrate species is anticipated.
- **Differences across modeling areas** – Differences in feeding strategies across modeling areas were based on the variability of the FF species that were present in each area in the LPRSA.

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

na – not applicable

RM – river mile

Table 3-12c. Diet distributions and rationale for benthic invertebrate DETs

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	28 (5–50)	-	13 (5–30)	-	14 (5–30)	-
Particulates/detritus (near-bottom/fluff layer)	64 (50–95)	-	74 (20–95)	-	70 (20–95)	-
Phytoplankton/algae	3.5 (0–10)	-	5.5 (0–25)	-	8 (0–25)	-
Zooplankton	3.5 (0–10)	-	5.5 (0–25)	-	8 (0–25)	-
Benthic invertebrates	1 (0–10)	-	2 (0–10)	-	0 (0–10)	-
DEPs	1 (0–9)	70 (50–90)	1 (0–7)	52 (30 – 70)	0 (0–7)	45 (15–65)
FFs	0 (0–5)	30 (10–50)	1 (0–7)	48 (30 – 70)	0 (0–9)	55 (35–85)

Rationale and Source (see Appendix D for details):

- **Species** – Model compartment includes benthic invertebrates whose primary feeding strategy involves the consumption of particulate/detritus (although the feeding strategies may differ). Examples include oligochaete/polychaete worms, clams, midges, beetles, amphipods, and insects.
- **Overview and feeding plasticity** – Although based on DET feeding habits, particulates/detritus on the river bottom (including dead and decaying plankton and plant material) are assumed to constitute the majority of the diet for DETs, it is common for invertebrates to utilize alternate feeding strategies (an adaptation often referred to as feeding plasticity). As described in detail in Appendix D, diet fractions and ranges within each LPRSA area were developed by considering the feeding habits of the FFs present within the LPRSA. Thus, some consumption of sediment solids, phytoplankton/zooplankton, and other invertebrates is anticipated.
- **Benthic invertebrates** – Based on the review of feeding habits, only a small fraction of other invertebrates are anticipated to be consumed. The consumption of other invertebrates is assumed to occur proportionally based on the relative biomass for each modeling area (value development columns and Appendix D).
- **Differences across modeling areas** – Differences in feeding strategies across modeling areas were based on the variability of the DET species that were present within each area in the LPRSA.

DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

RM – river mile

Table 3-12d. Diet distributions and rationale for benthic invertebrate C/Os

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7– Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	5 (0–20)	-	8 (0–20)	-	8 (0–20)	-
Particulates/detritus (near-bottom/fluff layer)	27 (10–45)	-	30 (0–30)	-	29 (0–30)	-
Phytoplankton/algae	0 (0–5)	-	0 (0–5)	-	0 (0–5)	-
Zooplankton	0 (0–5)	-	0 (0–5)	-	0 (0–5)	-
Benthic invertebrates	68 (30–90)	-	62 (30–90)	-	63 (30–90)	-
DEPs	37 (10–66)	54 (33–73)	18 (6–36)	29 (20–40)	25 (7–48)	39 (22–53)
FFs	15 (1–40)	23 (3–44)	20 (2–50)	32 (6–55)	29 (4–60)	46 (12–67)
DETs	16 (16–23)	24 (21–26)	24 (5–50)	39 (18–55)	9 (2–41)	15 (5–46)

Rationale and Source (see Appendix D for details):

- **Species** – Model compartment includes benthic invertebrates whose primary feeding strategy involves the consumption of other benthic organisms but that may also obtain a fraction of their diet from detritus, sediment, or other materials. Examples of C/Os include turbellarians, nematodes, leeches, larger insects, and decapods (e.g., crayfish and shrimp).
- **Overview and feeding plasticity** – Although C/Os are expected to primarily consume other benthic invertebrates, it is common for invertebrates to utilize alternate feeding strategies (an adaptation often referred to as feeding plasticity). As described in detail in Appendix D, diet fractions and ranges within each LPRSA area were developed by considering the feeding habits of the C/Os present within the LPRSA. Thus, some consumption of sediment solids and near-bottom particulates is anticipated.
- **Benthic invertebrates** – C/Os are assumed to consume other benthic invertebrates proportional to the relative biomass of benthic invertebrates in the LPRSA by modeling area (see value development columns and Appendix D).
- **Differences across modeling areas** – Differences in feeding strategies across modeling areas were based on the variability of the C/O species that were present within each area in the LPRSA.

C/O – benthic invertebrate carnivore/omnivore

DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

RM – river mile

Table 3-12e. Diet distributions and rationale for small filter-feeding fish

Prey Items	Nominal Value and Range (%)		
	RM 0–RM 6	RM 6–RM 14.7	RM 14.7–Dundee Dam
Sediment solids	0 (na)	0 (na)	0 (na)
Particulates/detritus (water-column)	50 (40–80)	50 (40–80)	50 (40–80)
Phytoplankton/algae	25 (0–40)	25 (0–40)	25 (0–40)
Zooplankton	25 (0–30)	25 (0–30)	25 (0–30)

Rationale and Source (see Appendix E for details):

- **Species** – This model compartment represents small filter-feeding fish such as Atlantic menhaden, gizzard shad, and various species of silversides.
- **Overview** – The diet for filter-feeding fish is based on that of Atlantic menhaden (one of the species in this compartment collected most frequently in the LPRSA), which are opportunistic filter feeders as juveniles and adults, consuming zooplankton, phytoplankton, and diatom chains depending on the availability of prey items. The majority of prey is identified as “amorphous material” and is represented by particulates/detritus. If phytoplankton abundance is limited, menhaden may consume more detritus. In addition, the portion of zooplankton in the diet decreases as fish move from open waters to marshes (Rogers and van den Avyle 1989; Jeffries 1975). Thus, particulates/detritus (from the water column) were estimated to be one-half of their diet, with phytoplankton/algae and zooplankton making up the remainder of the diet based on general portion estimates provided by FishBase (2014).
- **Sediment** – Based on the feeding habits of filter-feeding fish (i.e., that they live and feed in the water column), the ingestion of sediment solids is not expected.
- **Differences across modeling areas** – No differences were incorporated into the diets by river segment due to a lack of site-specific data. Although some information suggests that the diet may include lower amounts of zooplankton with increased distance from the ocean, insufficient information was available to know whether this occurs in the LPRSA.

na – not applicable

RM – river mile

LPRSA – Lower Passaic River Study Area

Table 3-12f. Diet distributions and rationale for small forage fish

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	1 (0–3)	-	1 (0–3)	-	1 (0–3)	-
Particulates/detritus (near-bottom/fluff layer)	15 (0–30)	-	15 (0–30)	-	15 (0–30)	-
Phytoplankton/algae	15 (0–30)	-	15 (0–30)	-	15 (0–30)	-
Zooplankton	4 (0–10)	-	4 (0–10)	-	4 (0–10)	-
Benthic invertebrates	65 (20–100)	-	65 (20–100)	-	65 (20–100)	-
DEPs	35 (7–73)	54 (33–73)	16 (3–34)	25 (17–34)	23 (3–66)	36 (16–66)
FFs	14 (1–44)	22 (3–44)	18 (2–53)	27 (12–53)	27 (6–66)	42 (28–66)
DETs	15 (4–26)	23 (21–26)	22 (3–43)	34 (15–43)	8 (1–25)	12 (3–25)
C/Os	1 (0–2)	1 (1–2)	9 (1–20)	14 (7–20)	7 (0–27)	10 (1–27)

Rationale and Source (see Appendix E for details):

- **Species** – This model compartment represents a variety of small benthic-feeding forage fish, including mummichog, killifish, pumpkinseed, bluegill, other sunfish, darters, and various species of shiners.
- **General** – The diet for small forage fish is based on that of mummichog (the small forage fish collected the most frequently during LPRSA sampling and collected throughout the LPRSA), which feed primarily on small crustaceans (i.e., amphipods, tanaids, copepods, and ostracods), polychaetes, insects (adult and larvae), detritus, and algae (Abraham 1985; Allen et al. 1994; James-Pirri et al. 2001; Kneib 1986; Currin et al. 2003). Benthic invertebrates are assumed to compose the majority of the diet, with detritus, algae, and zooplankton each making up a smaller portion of the diet; actual dietary portions are likely a factor of availability in the LPRSA.
- **Sediment** – Studies have reported the presence of detritus in mummichog stomachs but not the specific consumption of sediment (see Appendix E). However, mummichog longer than 2.5 cm, which were present in the LPRSA, consume some near-bottom detritus and likely to incidentally ingest a small portion of sediment solids while feeding.
- **Benthic invertebrates** – Small forage fish are assumed to consume specific types of small benthic invertebrates in proportion to the relative biomass of these invertebrates in the LPRSA by modeling area (see value development columns and Appendix D). The numbers represent the relative biomass for each modeling area (sum of shaded rows for benthic invertebrates is equal to 100%). To account for the fact that LPRSA benthic invertebrate biomass varies by season and location, the nominal value represents an average biomass, while the calibration range reflects the range across seasons.
- **Differences across modeling areas** – The fractions of the specific benthic invertebrate prey groups were varied by river segment based on the variability of benthic invertebrate biomass in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore

DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

RM – river mile

Table 3-12g. Diet distributions and rationale for small American eel

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	2 (0–5)	-	2 (0–5)	-	2 (0–5)	-
Particulates/detritus (near-bottom/fluff layer)	3 (0–5)	-	3 (0–5)	-	3 (0–5)	-
Benthic invertebrates	85 (50–100)	-	85 (50–100)	-	85 (50–100)	-
DEPs	46 (17–73)	54 (33–73)	21 (9–34)	25 (17–34)	31 (8–66)	36 (16–66)
DETs	19 (2–44)	22 (3–44)	23 (6–53)	27 (12–53)	36 (14–66)	42 (28–66)
FFs	20 (11–26)	23 (21–26)	29 (8–43)	34 (15–43)	10 (2–25)	12 (3–25)
C/Os	1 (1–2)	1 (1–2)	12 (4–20)	14 (7–20)	9 (1–27)	10 (1–27)
Small fish	10 (0–25)	-	10 (0–25)	-	10 (0–25)	-
Filter-feeding fish	4 (0–25)	40 (16–99)	2 (0–15)	22 (10–60)	0 (0–1)	0 (0–5)
Small forage fish	6 (0–21)	60 (1–84)	8 (0–23)	78 (40–90)	10 (0–25)	100 (95–100)

Rationale and Source (see Appendix E for details):

- **Species** – This model compartment represents young-of-the-year and juvenile American eel (i.e., eel < 50 cm in length).
- **Overview** – The diet of the American eel is diverse, consisting of crabs, crayfish, bivalves, polychaetes, insects, gastropods, and fish (Ogden 1970; Lookabaugh and Angermeier 1992; Wenner and Musick 1975). Smaller American eel consume primarily aquatic insects and other benthic invertebrates; as American eel grow, fish and crustaceans (i.e., crayfish or crab) become more important components of their diet (Lookabaugh and Angermeier 1992; Ogden 1970). Selected prey portions are based on smaller eel (see Appendix E for details).
- **Sediment** – Data on sediment consumption were not available, but a small amount of sediment and particulate/detritus ingestion was included in the diet based on the benthic feeding habits of eel.
- **Benthic invertebrates** – Ogden (1970) reported that the size of invertebrates found in eel stomachs increased with increasing eel size. Within each size class, organisms were generally present in proportions related to those found in bottom sediment. Therefore, smaller eel modeled in this compartment were assumed to consume specific types of benthic invertebrates in proportion to the relative biomass of these invertebrates in the LPRSA by modeling area (see value development columns and Appendix D). These groups account for the varying benthic invertebrate prey (e.g., crustaceans and smaller invertebrates; see Table 3-1) that smaller American eel are expected to consume based on the prey's site-specific availability. To account for the fact that LPRSA benthic invertebrate biomass varies by season and location, the nominal value represents an average biomass, while the calibration range reflects the range across seasons.
- **Small fish** – Diet fractions are based on available information regarding the abundance of small fish in the LPRSA by modeling area (see value development columns; Appendix E, Table 3). Because of the mechanistic limitations of the bioaccumulation model, modeled species/groups can only consume species/groups that are of lower trophic levels (i.e., they cannot eat other members of their own group/species or those higher on the food chain). Thus, the percent of the diet attributed to small American eel in Appendix E were proportionally distributed to small filter-feeding fish and small forage fish. Small American eel are primarily bottom feeders (Ogden 1970); therefore, no adjustments were made to the small fish abundance-based percentages, which already weight the diets toward the consumption of small benthic fish. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal values represent an average abundance, while the calibration range reflects the range across river miles within a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomasses and small fish abundance in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore
 DEP – benthic invertebrate deposit feeder
 DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder
 LPRSA – Lower Passaic River Study Area
 RM – river mile

Table 3-12h. Diet distributions and rationale for blue crab

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	2 (0–5)	-	2 (0–5)	-	2 (0–5)	-
Particulates/detritus (near-bottom/fluff layer)	1 (0–5)	-	1 (0–5)	-	1 (0–5)	-
Benthic invertebrates	83 (60–90)	-	83 (60–90)	-	83 (60–90)	-
DEPs	45 (20–66)	54 (33–73)	21 (10–31)	25 (17–34)	30 (10–59)	36 (16–66)
FFs	18 (2–40)	22 (3–44)	22 (7–48)	27 (12–53)	35 (17–59)	42 (28–66)
DETs	19 (13–23)	23 (21–26)	28 (9–39)	34 (15–43)	10 (2–23)	12 (3–25)
C/Os	1 (1–2)	1 (1–2)	12 (4–18)	14 (7–20)	8 (1–24)	10 (1–27)
Small fish	14 (5–25)	-	14 (5–25)	-	14 (5–25)	-
Filter-feeding fish	5 (1–25)	39 (16–98)	3 (0–15)	21 (0–60)	0 (0–1)	0 (0–5)
Small forage fish	8 (0–21)	59 (1–83)	10 (2–16)	71 (38–62)	7 (2–16)	51 (41–62)
Small American eel	0 (0–2)	2 (1–6)	1 (0–8)	8 (0–31)	7 (2–15)	49 (38–59)

Rationale and Source (see Appendix E for details):

- **Species** – This model compartment represents adult blue crab.
- **Overview** – Blue crab are opportunistic feeders whose diet varies depending on their size and prey availability. The blue crab diet consists primarily of mollusks and crustaceans (including other blue crab); small fish make up a smaller portion of the diet. The dietary portions were primarily based on a Chesapeake Bay estuary study of blue crabs averaging 13 cm in width (Hines et al. 1990), and qualitatively on studies from northern Florida (Laughlin 1982) and Raritan Bay (Stehlik et al. 1998), as described in Appendix E.
- **Sediment** – The ingestion of sediment, particulates, and/or detritus was reported to be a minimal component of the blue crab diet in the available literature studies (Laughlin 1982; Stehlik et al. 1998; Hines et al. 1990).
- **Benthic invertebrates** – Blue crab are assumed to consume specific types of small benthic invertebrates in proportion to the relative biomass of these invertebrates in the LPRSA by modeling area (see value development columns and Appendix D). To account for the fact that LPRSA benthic invertebrate biomass varies by season and location, the nominal value represents an average biomass, while the calibration range reflects the range across seasons.
- **Small fish** – Diet fractions are based on available information regarding the abundance of small fish in the LPRSA by modeling area (value development columns and Appendix E). Blue crab are primarily bottom feeders based on their life history; therefore, no adjustments were made to the small fish abundance-based percentages, which already weight the diets toward the consumption of small benthic fish. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal value represents an average abundance, while the calibration range reflects the range across river miles within a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomasses and small fish abundance in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore

DEP – benthic invertebrate deposit feeder

DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area

RM – river mile

Table 3-12i. Diet distributions and rationale for carp

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	na	-	15 (5–25)	-	15 (5–25)	-
Particulates/detritus (near-bottom/fluff layer)	na	-	25 (10–40)	-	25 (10–40)	-
Phytoplankton/algae	na	-	5 (0–10)	-	5 (0–10)	-
Benthic invertebrates	na	-	54 (25–75)	-	54 (25–75)	-
DEPs	na	-	14 (4–26)	25 (17–34)	19 (4–50)	36 (16–66)
FFs	na	-	15 (3–40)	27 (12–53)	23 (7–50)	42 (28–66)
DETs	na	-	18 (4–32)	34 (15–43)	6 (1–19)	12 (3–25)
C/Os	na	-	8 (2–15)	14 (7–20)	5 (0–20)	10 (1–27)
Small fish	na	-	1 (0–5)	-	1 (0–5)	-
Filter-feeding fish	na	-	0 (0–3)	21 (0–60)	0 (0–0.3)	0 (0–5)
Small forage fish	na	-	1 (0–3)	71 (38–62)	1 (0–3)	51 (41–62)
Small American eel	na	-	0 (0–2)	8 (0–31)	0 (0–3)	49 (38–59)

Rationale and Source (see Appendix E for details):

- **Species** – Compartment includes adult common carp.
- **General** – Carp are highly opportunistic feeders and have a variable diet. Detritus, algae, plants, and small benthic invertebrates make up the majority of the carp diet; carp may also consume insects, small fish, and plankton (Maryland DNR 2007; Garcia-Berthou 2001; USGS 2010; Walburg and Nelson 1966). Benthic invertebrates are expected to compose the greatest portion of the carp diet.
- **Sediment** – Studies have reported the presence of detritus in carp stomachs (indicating some incidental ingestion of sediment) but did not quantify sediment consumption (Campos 2005; Walburg and Nelson 1966). Based on carp feeding habits, sediment solids and particulates/detritus are anticipated to be an important component of the carp diet.
- **Benthic invertebrates** – Carp are assumed to consume specific types of small benthic invertebrates in proportion to the relative biomass of these invertebrates in the LPRSA by modeling area (see value development columns and Appendix D). To account for the fact that LPRSA benthic invertebrate biomass varies by season and location, the nominal value represents an average biomass, while the calibration range reflects the range across seasons.
- **Small fish** – Diet fractions are based on the available information regarding abundance of small fish in the LPRSA by modeling area (see value development columns and Appendix E). Carp are primarily bottom feeders; therefore, no adjustments were made to the abundance-based small fish percentages, which already weight the diets toward the consumption of small benthic fish. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal value represents an average abundance, while the calibration range reflects the range across river miles within a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomasses and small fish abundance in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore
 DEP – benthic invertebrate deposit feeder
 DET – benthic invertebrate detritivore
 FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area
 na – not applicable
 RM – river mile

Table 3-12j. Diet distributions and rationale for catfish

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	5 (0–10)	-	5 (0–10)	-	5 (0–10)	-
Particulates/detritus (near-bottom/fluff layer)	10 (5–20)	-	10 (5–20)	-	10 (5–20)	-
Phytoplankton/algae	2 (0–5)	-	2 (0–5)	-	2 (0–5)	-
Benthic invertebrates	43 (20–60)	-	43 (20–60)	-	43 (20–60)	-
DEPs	23 (7–44)	54 (33–73)	11 (3–20)	25 (17–34)	16 (3–40)	36 (16–66)
FFs	9 (1–26)	22 (3–44)	12 (2–32)	27 (12–53)	18 (6–40)	42 (28–66)
DETs	10 (4–16)	23 (21–26)	15 (3–26)	34 (15–43)	5 (1–15)	12 (3–25)
C/Os	0 (0–1)	1 (1–2)	6 (1–12)	14 (7–20)	4 (0–16)	10 (1–27)
Small fish	40 (20–60)	-	40 (20–60)	-	40 (20–60)	-
Filter-feeding fish	16 (3–59)	39 (16–98)	8 (0–36)	21 (0–60)	0 (0–3)	0 (0–5)
Small forage fish	24 (0–50)	59 (1–83)	28 (8–37)	71 (38–62)	20 (8–37)	51 (41–62)
Small American eel	1 (0–4)	2 (1–6)	3 (0–19)	8 (0–31)	20 (8–35)	49 (38–59)

Rationale and Source (see Appendix E for details):

- **Species** – This model compartment represents adult channel and white catfish.
- **General** – Both channel and white catfish are opportunistic benthic feeders that prey on available invertebrates and small fish (California Fish Website 2013b; FishBase 2014). Common dietary items of adult white catfish include invertebrates (e.g., amphipods, crayfish, shrimp, and small clams), small fish, and detritus, with small fish and benthic invertebrates likely composing the majority of the adult diet (Turner 1966b; FishBase 2014). Adult channel catfish have been found to prey primarily on insects, detritus, crayfish, and small fish (NJDEP 2001b; Wellborn 1988; California Fish Website 2013a). Phytoplankton/algae consumption in the LPRSA is assumed to be minimal due to its limited presence relative to other available prey items.
- **Sediment** – A small portion of sediment solids and particulate/detritus ingestion was included based on the benthic feeding behavior of catfish species.
- **Benthic invertebrates** – Catfish are assumed to consume specific types of small benthic invertebrates in proportion to the relative biomass of these invertebrates in the LPRSA by modeling area (see value development columns and Appendix D). These groups account for the varying benthic invertebrate prey (e.g., decapods, shrimp, and amphipods; see Table 3-1) that catfish are expected to consume based on the prey's site-specific availability. To account for the fact that LPRSA benthic invertebrate biomass varies by season and location, the nominal value represents an average biomass, while the calibration range reflects the range across seasons. Although the available literature suggests that catfish may consume greater percentages of some invertebrates, any modification of diet percentages is uncertain due to the opportunistic nature of catfish feeding habits and the variety of species within each benthic invertebrate group (see Table 3-1).
- **Small fish** – Diet fractions are based on the abundance of small fish in the LPRSA (see value development columns and Appendix E). Catfish are primarily bottom feeders but are also known to swim in the water column to feed on pelagic fish (California Fish Website 2013b; Wellborn 1988; FishBase 2014); therefore, no adjustments were made to the abundance-based small fish percentages because while small benthic fish make up the highest percent based on abundance, fish present in the water column (i.e., filter-feeding fish) also make up some portion of the abundance in the lower portions of the LPRSA. The nominal value represents an average abundance, while the calibration range reflects the range across river miles within a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomasses and small fish abundance in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore
 DEP – benthic invertebrate deposit feeder
 DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder
 LPRSA – Lower Passaic River Study Area
 RM – river mile

Table 3-12k. Diet distributions and rationale for white perch

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	0 (na)	-	0 (na)	-	0 (na)	-
Particulates/detritus (near-bottom/fluff layer)	5 (0–20)	-	5 (0–20)	-	5 (0–20)	-
Phytoplankton/algae	2 (0–20)	-	2 (0–20)	-	2 (0–20)	-
Zooplankton	3 (0–20)	-	3 (0–20)	-	3 (0–20)	-
Benthic invertebrates	75 (0–100)	-	75 (0–100)	-	75 (0–100)	-
DEPs	41 (0–73)	54 (33–73)	19 (0–34)	25 (17–34)	27 (0–66)	36 (16–66)
FFs	17 (0–44)	22 (3–44)	20 (0–53)	27 (12–53)	32 (0–66)	42 (28–66)
DETs	17 (0–26)	23 (21–26)	26 (0–43)	34 (15–43)	9 (0–25)	12 (3–25)
C/Os	1 (0–2)	1 (1–2)	11 (0–20)	14 (7–20)	8 (0–27)	10 (1–27)
Small fish	15 (0–90)	-	15 (0–90)	-	15 (0–90)	-
Filter-feeding fish	6 (0–88)	39 (16–98)	3 (0–54)	21 (0–60)	0 (0–5)	0 (0–5)
Small forage fish	9 (0–75)	59 (1–83)	11 (0–56)	71 (38–62)	8 (0–56)	51 (41–62)
Small American eel	0 (0–5)	2 (1–6)	1 (0–28)	8 (0–31)	7 (0–53)	49 (38–59)

Rationale and Source (see Appendix E for details):

- **Species** – Compartment includes mature white perch.
- **General** – The diet selected for the LPRSA is based primarily on regional data from the Hudson and Hackensack Rivers in New York and New Jersey; the data indicated that the majority of the perch diet is composed of benthic invertebrates (primarily amphipods, shrimp, and copepods), followed by a small portion of small fish (Bath and O'Connor 1985; Weis 2005; TAMS 1999). The diet also includes small amounts of detritus, phytoplankton, and zooplankton based on information from other studies that have suggested that perch may consume small amounts of these items when they are available and/or incidentally while feeding (McGrath 2005; Schaeffer and Margraf 1986; Bath and O'Connor 1985; Weis 2005; Weisberg and Janicki 1990). The selected ranges are intended to reflect the opportunistic foraging habits of white perch.
- **Sediment** – Studies did not report the specific consumption of sediment; a small amount of particulate/detritus ingestion was included based on the benthic feeding habits of white perch, but the ingestion of sediment solids is assumed to be negligible.
- **Benthic invertebrates** – White perch are assumed to consume specific types of small benthic invertebrates in proportion to the relative biomass of these invertebrates in the LPRSA by modeling area (see value development columns and Appendix D). These groups account for the varying benthic invertebrate prey (e.g., crustaceans, including amphipods and shrimp; see Table 3-1) that white perch are expected to consume based on the prey's site-specific availability. To account for the fact that LPRSA benthic invertebrate biomass varies by season and location, the nominal value represents an average biomass, while the calibration range reflects the range across seasons.
- **Small fish** – Diet fractions are based on the abundance of small fish in the LPRSA (see value development columns and Appendix E) because of the opportunistic feeding habits of white perch. White perch are primarily bottom feeders but they also feed in the water column; therefore, no adjustments were made to the abundance-based small fish percentages because while the small benthic fish make up the highest percent based on abundance, fish present in the water column (i.e., filter-feeding fish) also make up some portion of the abundance in the lower portions of the LPRSA. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal value represents an average abundance, while the calibration range reflects the range across river miles within a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomasses and small fish abundance in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore
 DEP – benthic invertebrate deposit feeder
 DET – benthic invertebrate detritivore
 FF – benthic invertebrate filter feeder

LPRSA – Lower Passaic River Study Area
 na – not applicable
 RM – river mile

Table 3-12I. Diet distributions and rationale for large American eel

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	2 (0–5)	-	2 (0–5)	-	2 (0–5)	-
Particulates/detritus (near-bottom/fluff layer)	3 (0–5)	-	3 (0–5)	-	3 (0–5)	-
Benthic invertebrates	55 (20–80)	-	55 (20–80)	-	55 (20–80)	-
DEPs	22 (4–58)	40 (20–73)	8 (2–27)	15 (10–34)	14 (3–53)	25 (16–66)
FFs	8 (1–35)	15 (3–44)	8 (2–42)	15 (10–53)	17 (4–53)	30 (20–66)
DETs	8 (1–21)	15 (5–26)	14 (3–34)	25 (15–43)	3 (1–20)	5 (3–25)
C/Os	17 (0–40)	30 (1–50)	25 (1–40)	45 (7–50)	22 (0–44)	40 (1–55)
Small fish	40 (0–90)	-	40 (0–90)	-	40 (0–90)	-
Filter-feeding fish	16 (0–88)	39 (16–98)	8 (0–54)	21 (0–60)	0 (0–5)	0 (0–5)
Small forage fish	24 (0–75)	59 (1–83)	28 (0–56)	71 (38–62)	20 (0–56)	51 (41–62)
Small American eel	1 (0–5)	2 (1–6)	3 (0–28)	8 (0–31)	20 (0–53)	49 (38–59)

Rationale and Source (see Appendix E for details):

- **Species** – Compartment includes adult American eel (> 50 cm in length).
- **General** – The diet of the American eel is diverse, consisting of crabs, crayfish, bivalves, polychaetes, insects, gastropods, and fish (Ogden 1970; Lookabaugh and Angermeier 1992; Wenner and Musick 1975). As American eel grow, fish and crustaceans (i.e., crayfish or crab) become more important components of their diet than do aquatic insects and other benthic invertebrates (Lookabaugh and Angermeier 1992; Ogden 1970). Selected prey portions are based on larger fish representing upper-trophic-level feeders; prey portions for American eel > 50 cm were evaluated (see Appendix E for additional details).
- **Sediment** – Data on sediment consumption were not available, but a small amount of sediment and particulate/detritus ingestion was included based on the benthic feeding habits of eel.
- **Benthic invertebrates** – The diet percentages of benthic invertebrates are based both on the abundance of benthic invertebrates and the feeding habits of eel (i.e., preferential feeding on certain types of larger invertebrates rather than eating all invertebrates in equal amounts relative to their abundances). Ogden (1970) reported that the size of invertebrates found in eel stomachs increased with increasing eel size. Within each size class, organisms were generally present in proportions related to those found in bottom sediment. Based on this information, eel were assumed to consume more C/Os (e.g., decapods such as crayfish and small crabs) than would be indicated by biomass percentages alone (i.e., because biomass percentages generally did not account for larger decapods such as blue crabs [Table 3-1]). The remaining benthic invertebrate fractions (for DEPs, FFs, and DETs) were assigned based on the relative biomasses of these organisms in each modeling area (see value development columns).
- **Small fish** – Diet fractions are based on the available information regarding abundance of small fish in the LPRSA (see value development columns and Appendix E) because of the opportunistic feeding habits of American eel. American eel are primarily bottom feeders (Ogden 1970); therefore, no adjustments were made to the abundance-based small fish percentages, which already weight the diets toward the consumption of small benthic fish. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal value represents an average abundance, while the calibration range reflects the range across river miles within a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomasses and small fish abundance in different areas of the LPRSA.

C/O – benthic invertebrate carnivore/omnivore
 DEP – benthic invertebrate deposit feeder
 DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder
 LPRSA – Lower Passaic River Study Area
 RM – river mile

Table 3-12m. Diet distributions and rationale for bass

Prey Items	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development	Nominal Value and Range (%)	Value Development
Sediment solids	na	-	0 (na)	-	0 (na)	-
Particulates/detritus (near-bottom/fluff layer)	na	-	0 (na)	-	0 (na)	-
Benthic invertebrates	na	-	20 (0–80)	-	20 (0–80)	-
DEPs	na	-	3 (0–27)	15 (10–34)	5 (0–53)	25 (16–66)
DETs	na	-	3 (0–42)	15 (10–53)	6 (0–53)	30 (20–66)
FFs	na	-	5 (0–34)	25 (15–43)	1 (0–20)	5 (3–25)
C/Os	na	-	9 (0–40)	45 (7–50)	8 (0–44)	40 (1–55)
Small fish	na	-	80 (20–100)	-	80 (20–100)	-
Filter-feeding fish	na	-	17 (0–60)	21 (0–60)	0 (0–5)	0 (0–5)
Small forage fish	na	-	57 (8–62)	71 (38–62)	41 (8–62)	51 (41–62)
Small American eel	na	-	6 (0–31)	8 (0–31)	39 (8–59)	49 (38–59)

Rationale and Source (see Appendix E for details):

- **Species** – Compartment includes both smallmouth and largemouth bass.
- **Overview** – Both smallmouth and largemouth bass are considered to be opportunistic predators that will generally consume prey relative to their abundance in the environment. Smallmouth bass consume primarily fish and crayfish; other, smaller components of their diet may include insects, other crustaceans, mollusks, and worms (George and Hadley 1979; Turner 1966a; Wydoski and Whitney 1979). Adult largemouth bass are predominately piscivorous and eat a variety of small fish (e.g., bluegills, minnows, perch, and shiners) but are also opportunistic and will eat crayfish, frogs, insects, snakes, and even small mammals and birds that enter the water (Scott and Crossman 1973). A Hudson River study found that 75 to 90% of the largemouth bass diet consisted of fish, and 10 to 25% consisted of various invertebrates, including crayfish (TAMS and Menzie-Cura 2000). The invertebrates most commonly observed in the gut contents of largemouth bass included amphipods, isopods, cladocerans, copepods, ostracods, and some chironomid larvae (TAMS and Menzie-Cura 2000).
- **Sediment** – Bass spend most of their time in the pelagic zone, so their ingestion of sediment solids and particulates/detritus is assumed to be negligible.
- **Benthic invertebrates** – The diet percentages of benthic invertebrates are based both on the abundance of benthic invertebrates and the feeding habits of bass (i.e., preferential feeding on certain types of larger invertebrates rather than eating all invertebrates in equal amounts relative to their abundance). Because bass are assumed to preferentially consume crayfish and other decapods (such as small crabs), a greater portion of C/Os was assigned to bass than would be indicated by biomass percentages alone (i.e., because biomass percentages generally did not account for larger decapods such as blue crabs [Table 3-1]). The remaining benthic invertebrate fractions (for DEPs, FFs, and DETs) were assigned based on the relative biomasses of these organisms in each modeling area (see value development columns).
- **Small fish** – Diet fractions are based on the available information regarding abundance of small fish in the LPRSA (see value development columns and Appendix E) because of the opportunistic feeding habits of bass. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal value represents an average abundance, while the calibration range reflects the range across river miles in a given area.
- **Differences across modeling areas** – The proportions of benthic invertebrates and small fish in the diet were varied by modeling area based on the variability of benthic invertebrate biomass and small fish abundance in different areas of the LPRSA. To account for the fact that LPRSA small fish abundance varies by season and location, the nominal value represents an average abundance, while the calibration range reflects the range across seasons.

C/O – benthic invertebrate carnivore/omnivore
 DEP – benthic invertebrate deposit feeder
 DET – benthic invertebrate detritivore

FF – benthic invertebrate filter feeder
 LPRSA – Lower Passaic River Study Area
 na – not applicable
 RM – river mile

If a species evaluated in the LPRSA BERA (Windward 2019b) was included in the bioaccumulation model, the diet used in the bioaccumulation model was developed to be consistent with that used for the BERA. However, the way in which these diets were applied in the BERA and the bioaccumulation model might differ:

- ◆ Estimated fish diets in the bioaccumulation model are not limited to those prey types that have LPRSA empirical chemistry data. The model includes a wider range of potential prey items and specific invertebrate compartments, whereas the BERA (Windward 2019b) fish diets are based on only prey items for which LPRSA empirical concentration data were available.
- ◆ As was done in the BERA (Windward 2019b), the bioaccumulation model uses point estimates as the starting point for prey portions. However, a range of diet fraction values were also considered in the bioaccumulation model. This allows for the refinement of diets as part of the calibration process.
- ◆ Sediment was included in the diets for both the bioaccumulation model and the BERA, although the way that exposure to sediment was accounted for was different in each. For the bioaccumulation model, two types of sediment (sediment solids and particulate/detritus) were included as components of the diet. For the BERA (Windward 2019b), exposure to sediment (sediment solids) was assumed to occur as incidental ingestion only (i.e., it was evaluated separately from the diet). Thus, the differences between the bioaccumulation model dietary percentage values and those used in the BERA reflect the differences in how sediment ingestion was treated.

These differences do not indicate inconsistency between the BERA (Windward 2019b) and the bioaccumulation model. Rather they reflect the different purposes, model specificities, and applications of these two RI/FS tools. Details on the differences between the LPRSA BERA (Windward 2019b) and bioaccumulation model diets are presented in Appendix E.

3.3.4 Empirical fish and crab tissue data used for model calibration

The bioaccumulation model calibration used the whole-body fish and crab tissue data collected from the LPRSA in 2009/2010, which were the most recent data at the time of model calibration (Tables 3-13 and 3-14).¹⁵ Appendix E provides additional information regarding the samples included in the model calibration dataset. The complete calibration dataset and maps showing the catch locations for each model compartment are presented in Appendix F. Two carp samples collected between RM 4 and RM 5 and one catfish sample collected near RM 2 were included in the calibration dataset despite being collected outside the modeling areas for those species (see Section 3.2.5). These samples were included because the fish likely spent most of their time in the modeling area and moved further downstream with a freshwater excursion (e.g., during an ebb tide). The effect of the exclusion vs. inclusion of these samples was found to be insignificant with regard to the calibration. The model was not calibrated for plankton/algae, zooplankton, or benthic invertebrates.

¹⁵ The current conditions biota dataset (which includes data collected in 2019 and 2021 [rather than in 2019 and 2020, because of delays due to the COVID-19 pandemic]), along with updated CFT model output, will be used as part of the model validation and/or refinement process that will occur as part of the adaptive management approach for the Upper 9-Mile IR (see Section 6).

Table 3-13. Numbers of tissue samples used in model calibration

LPRSA Sampling Area	Number of Whole-body Samples																	
	Small Filter-feeding Fish		Small Forage Fish		American Eel (< 50 cm)		Blue Crab		Common Carp		White Perch		Catfish ^a		American Eel (> 50 cm)		Bass ^b	
	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I	C	I
RM 0 to RM 2 (Reach 1)	-	-	2	-	1	-	8	-	-	-	-	2	-	-	-	1	-	-
RM 2 to RM 4 (Reach 2)	-	-	6	-	1	-	6	-	-	-	-	1	-	1	-	-	-	-
RM 4 to RM 6 (Reach 3)	-	-	3	-	-	1	4	-	-	2 ^c	6	-	-	4	-	2	-	-
RM 6 to RM 8 (Reach 4)	1	-	5	-	-	-	4	-	-	2	2	-	-	1	-	4	1	-
RM 8 to RM 10 (Reach 5)	-	-	4	-	1	-	2	-	-	2	3	-	-	3	-	2	2	1
RM 10 to RM 12 (Reach 6)	1	-	2	-	-	2	5 ^d	-	-	2	-	1	-	7	-	-	-	-
RM 12 to RM 14 (Reach 7)	1	-	-	-	-	1	6 ^d	-	-	2	1	1	-	4	-	-	-	-
RM 14 to RM 17.4 (Reach 8)	-	-	3	-	5	-	6 ^d	-	-	2	3	-	-	10	-	-	1	1
Count of Samples by Modeling Area^e																		
Area 1: RM 0 to RM 6	0		11		3		19		na		9		6		3		na	
Area 2: RM 6 to RM 14.7	3		13		6		19		11		8		27		6		4	
Area 3: RM 14.7 to Dundee Dam	0		1		5		6		3		3		12		0		2	

^a Includes white catfish and channel catfish.

^b Includes smallmouth and largemouth bass.

^c Two individual carp samples were collected outside of the modeling areas identified for carp (see Section 3.2.5). These samples, which were collected between RM 5 and RM 6, were included in the calibration dataset because the majority of exposure for these fish is expected to have occurred within the modeling area.

^d Crab tissue concentrations in these reaches were calculated based on muscle/hepatopancreas data (see Appendix E for details).

^e Fish and crab tissue samples were assigned species-specific boundary rules and, in some cases, were assigned to more than one river segment based on the size of their typical foraging area (see Appendix E for specific rules and details).

C – composite fish sample

I – individual fish sample

LPRSA – Lower Passaic River

na – not applicable (not modeled in this area)

RM – river mile

Table 3-14. Summary of empirical fish and crab concentrations for model calibration

Model Compartment	Modeling Area	No. of Samples	Concentration in Whole-body Tissue ^a					
			2,3,7,8-TCDD (ng/kg ww)		TetraCB (µg/kg ww)		1,2,3,4,6,7,8-HpCDF (ng/kg ww)	
			Mean	Range	Mean	Range	Mean	Range
Small filter-feeding fish	RM 0 to RM 6	0	no data	no data	no data	no data	no data	no data
	RM 6 to RM 14.7	3	30	11–44	120	69–140	9.1	5.4–15
	RM 14.7 to dam	0	no data	no data	no data	no data	no data	no data
Small forage fish	RM 0 to RM 6	11	25	11–54	91	51–190	1.6	0.65–4.4
	RM 6 to RM 14.7	13	48	2.4–100	150	75–250	5.1	0.32–12
	RM 14.7 to dam	1	16	16	120	120	3.6	3.6
American eel (< 50 cm)	RM 0 to RM 6	3	28	26–30	280	240–370	2.5	2.2–2.7
	RM 6 to RM 14.7	6	13	0.54–30	170	31–370	1.1	0.36–2.6
	RM 14.7 to dam	5	0.57	0.21–1.4	100	53–170	0.88	0.41–1.3
Blue crab ^b	RM 0 to RM 6	19	49	24–74	59	28–82	4.4	2.4–5.8
	RM 6 to RM 14.7	19	43	11–86	46	19–75	2.4	1.2–9.8
	RM 14.7 to dam	6	22	17–33	33	30–40	1.3	1.1–1.5
Carp ^c	RM 0 to RM 6	na	na	na	na	na	na	na
	RM 6 to RM 14.7	11 ^d	440	5.2–1,400	1,100	230–2,100	8.6	1.7–18
	RM 14.7 to dam	3	27	5.2–46	330	230–430	2.6	1.5–4.7
Catfish (includes channel and white catfish)	RM 0 to RM 6	6	230	120–410	560	340–950	5.1	1.3–2.1
	RM 6 to RM 14.7	27	120	20–330	340	69–1,100	1.0	0.44–2.2
	RM 14.7 to dam	12	100	22–310	310	110–730	0.96	0.48–2.9
White perch	RM 0 to RM 6	9	140	73–180	550	260–850	1.3	0.69–1.7
	RM 6 to RM 14.7	8	150	18–250	480	61–830	1.1	0.21–1.8
	RM 14.7 to dam	3	35	20–62	210	160–240	0.52	0.46–0.57
American eel (> 50 cm)	RM 0 to RM 6	3	17	5.7–25	260	160–360	1.5	0.46–2.4
	RM 6 to RM 14.7	6	31	14–47	210	62–450	1.4	0.84–2.4
	RM 14.7 to dam	0	no data	no data	no data	no data	no data	no data

Model Compartment	Modeling Area	No. of Samples	Concentration in Whole-body Tissue ^a					
			2,3,7,8-TCDD (ng/kg ww)		TetraCB (µg/kg ww)		1,2,3,4,6,7,8-HpCDF (ng/kg ww)	
			Mean	Range	Mean	Range	Mean	Range
Bass (includes smallmouth and largemouth bass)	RM 0 to RM 6	na	na	na	na	na	na	na
	RM 6 to RM 14.7	4	88	32–180	250	130–430	0.43	0.31–0.52
	RM 14.7 to dam	2	4.2	0.43–8.0	350	110–590	0.39	0.33–0.45

Note: See Appendix F for the complete empirical whole-body tissue dataset used for model calibration and maps showing sample locations.

- ^a Based only on detected concentrations (i.e., all samples in the dataset had detected concentrations), except for American eel and 2,3,7,8-TCDD.
- ^b Whole-body concentrations in blue crab collected above RM 10 were calculated based on muscle/hepatopancreas data (see Appendix E for details).
- ^c Carp and bass were not included in the RM 0 to RM 6 modeling area, as described in Section 3.2.5.
- ^d Two carp samples collected between RM 5 and RM 6 were included in the calibration dataset for RM 6 to RM 14.7 because, although they were collected outside of the modeling area identified for carp, the majority of the exposure for these fish is expected to have occurred within the modeling area.

HpCDF -- heptachlorodibenzofuran

RM – river mile

tetraCB – tetrachlorobiphenyl

na – not applicable

TCDD – tetrachlorodibenzo-*p*-dioxin

ww – wet weight

4 Model Calibration and Results

This section discusses the methods for model calibration as well as the calibration results.

4.1 CALIBRATION METHODS

The model was evaluated using the metrics described in Section 4.1.1. These metrics were used to evaluate and improve model performance through the calibration approach described in Section 4.1.2.

4.1.1 Model performance metrics

The performance of the bioaccumulation model was evaluated using two primary metrics: first, a graphical comparison of modeled whole-body concentrations to the range of empirical whole-body tissue data, and second, the species predictive accuracy factor (SPAF). Finally, a third metric was used to evaluate the benthic invertebrate model predictions by calculating a modeled BSAF and comparing that value with BSAFs from literature.

4.1.1.1 *Metric 1 – Graphical evaluation of results*

A graphical evaluation of the model-predicted tissue concentrations compared with empirical whole-body fish tissue concentration data for both the steady-state and dynamic models was one of the metrics used to evaluate model performance. The goal for model performance was good comparability between the empirical data and model-predicted results.

This evaluation of model predictions allowed for the consideration of spatial and temporal variability in the empirical tissue dataset. It also provided confidence that the model was able to reasonably predict mean tissue concentrations, while acknowledging uncertainty about how well model assumptions regarding exposure conditions in the river match the true exposure conditions experienced by the fish that were sampled. Furthermore, this metric allowed for the acknowledgement that tissue concentrations in some species are highly variable, making average concentrations more uncertain.

4.1.1.2 *Metric 2 – SPAF*

A SPAF, which compares model-predicted concentrations with average empirical concentrations, was used to characterize how closely the model predicts average chemical concentrations in tissue samples for each species and modeling area. The calculation of the SPAF depends on whether the concentrations predicted by the bioaccumulation model are greater or less than the average empirical (i.e., measured) concentrations. If the model is over-predicting (i.e., the predicted tissue chemical concentration is greater than the empirical average for the specified tissue type), then

the SPAF is calculated by dividing the predicted value by the empirical value. If the model is under-predicting, the SPAF is calculated by dividing the empirical value by the predicted value. Thus, the SPAF is always greater than or equal to 1 (Equation 1). To indicate whether the model was over- or under-predicting relative to the empirical average concentration, SPAFs were labeled with a plus (+) or minus (-), respectively.

$$SPAF = MAX \left(\frac{C_{predicted}}{C_{empirical}}, \frac{C_{empirical}}{C_{predicted}} \right) \quad \text{Equation 1}$$

Where:

SPAF = species predictive accuracy factor
 $C_{predicted}$ = predicted tissue concentration
 $C_{empirical}$ = empirical tissue concentration

By definition, a SPAF of 1 indicates that the model is predicting the exact average of the empirical data. The goals for bioaccumulation model performance are:

- ◆ SPAF of < 3 for priority calibration targets¹⁶ (see Section 4.1.2.1)
- ◆ Combination of over- and under-prediction across species for each chemical (i.e., for a given chemical, some target species concentrations are over-predicted and some are under-predicted)

4.1.1.3 Metric 3 – Invertebrate BSAFs

No appropriate field-collected benthic invertebrate data were available for the LPRSA against which to compare model predictions. In addition, the laboratory bioaccumulation data available for the LPRSA were not considered a reliable metric against which model predictions should be compared, because the resulting bioaccumulation tissue concentrations were not reflective of *in situ* exposure.

Due to the lack of site-specific data against which model results could be compared, BSAFs were calculated to evaluate whether model predictions were reasonable for the benthic invertebrate model compartments. While BSAFs are uncertain and are not recommended as an approach for estimating tissue concentrations, comparing model-predicted BSAFs with literature BSAFs is useful for understanding whether the model is providing a reasonable estimate for benthic invertebrates. The model performance goal for this metric was for the model-calculated BSAFs to be close to or within the range of the literature BSAFs.

¹⁶ As part of the significant changes that CPG made between 2015 and 2021 to various aspects of the model under USEPA's oversight, the SPAF goal evolved from < 2 to < 3. This change occurred to acknowledge the wide range of variability in the empirical tissue data, and to ensure that the model was not overly constrained.

For a given invertebrate group and modeling area, model-predicted BSAFs (expressed as tissue concentration [mg/kg-lipid] divided by sediment concentration [mg/kg-organic carbon (OC)]) were calculated as follows:

$$BSAF = \frac{(C_{\text{tissue-predicted}} / F_{\text{lipids}})}{(C_{\text{sediment}} / F_{\text{OC}})} \quad \text{Equation 2}$$

where:

BSAF	=	biota-sediment accumulation factor
$C_{\text{tissue-predicted}}$	=	model-predicted concentration in tissue
F_{lipid}	=	lipid content of tissue (fraction)
C_{sediment}	=	concentration in sediment
F_{OC}	=	organic carbon content of sediment (fraction)

For each of the three modeled chemicals (2,3,7,8-TCDD, tetraCB, and 1,2,3,4,6,7,8-HpCDF), the ranges of literature BSAFs were developed using two comprehensive BSAF databases:

- ◆ **USEPA's BSAF database** – USEPA's database is a compilation of paired sediment and tissue data for organic chemicals from 20 study areas (mostly Superfund sites).
- ◆ **US Army Corps of Engineers' (USACE's) BSAF database** (USACE 2017) – USACE maintains a database of BSAFs based on paired sediment and tissue data from peer-reviewed literature and US government agency reports.

Sediment data used to derive the invertebrate BSAFs used as model calibration targets include concentrations that span several orders of magnitude. These ranges of sediment concentrations encompass those used to calibrate the bioaccumulation model (Table 3-6).

4.1.2 Calibration approach

This section describes the approach used to calibrate the bioaccumulation model. Model calibration focused on 2,3,7,8-TCDD and tetraCB; 1,2,3,4,6,7,8-HpCDF was then used to help confirm that the model had been well calibrated.

4.1.2.1 Step 1 – Identify calibration targets

Before beginning the calibration of the bioaccumulation model, priority calibration targets were developed in collaboration with USEPA. The selection of these calibration targets considered 1) the relative abundance of data available for each species in the modeling area, 2) the importance of the RM 6 to RM 14.7 area from a remediation perspective, and 3) a potential calibration target's status as a species of interest as identified by the LPRSA BHHRA (AECOM 2017) (i.e., blue crab, common carp, white perch, catfish [both white catfish and channel catfish], American eel, and freshwater bass). Because the RM 14.7 to Dundee Dam modeling area is small relative to the

typical foraging areas for most species, and because of the limited number of samples available in this area, no calibration targets were selected in this area. The 10 species-area pairs identified as priority calibration targets are shown in Table 4-1. Uncertainty associated with the representativeness of the calibration dataset is discussed in Section 5.1.

Table 4-1. Priority calibration targets developed in collaboration with USEPA

Model Compartment	RM 0–RM 6		RM 6–RM 14.7		RM 14.7–Dundee Dam	
	Count of Samples	Priority Calibration Target?	Count of Samples	Priority Calibration Target?	Count of Samples	Priority Calibration Target?
Small filter feeding fish	0	no	3	no	0	no
Small forage fish	11	no	13	yes	1	no
Small American eel	3	no	6	yes	5	no
Blue crab	19	yes	21	yes	4	no
Carp	na	no	11	yes	3	no
Catfish	6	no	27	yes	12	no
White perch	9	yes	8	yes	3	no
Large American eel	3	no	6	yes	0	no
Bass	na	no	4	yes	2	no

Note – green shading indicates selection as a priority calibration target.

RM – river mile

USEPA – US Environmental Protection Agency

4.1.2.2 Step 2 – Enter nominal values and identify most sensitive parameters

The next step in model calibration was to identify the parameters to which the model was most sensitive. Nominal values for all parameters (as shown in Section 3.3) were entered into the model. These included chemical-specific values, area-specific values from the CFT model, and various general and species-specific parameters. Once that process was complete, the model was run using minimum and maximum values as a first step in identifying the parameters to which the model was most sensitive (see tornado plots in Appendix G). The selection of the most sensitive parameters was based on a qualitative review of the tornado plots presented in Appendix G and an understanding of model function. In addition, the impact of changes to various model parameters was evaluated and discussed with USEPA as part of the process for identifying key sensitive parameters. These sensitive parameters included the following:

- ◆ Water temperature for all modeling areas
- ◆ Select parameters specific to benthic invertebrates (dietary absorption efficiency [AE] for all feeding groups, weight of DEPs, and diet of DEPs)
- ◆ Chemical-specific parameters, including the K_{OW} , E_D , and K_M , that influence the uptake of contaminants in the food web.

4.1.2.3 Step 3 – Preliminary calibration

To maintain consistency between models, the K_{ow} values used for the LPRSA bioaccumulation model were the same as those used for the CFT model; thus, no further calibration was necessary for that parameter. For the other sensitive parameters identified in Step 2, values were incrementally adjusted while simultaneously observing changes to model performance across all three modeling areas (i.e., RM 0 to RM 6, RM 6 to RM 14.7, and RM 14.7 to RM 17.4). Changes to overall model performance, and more specifically to model performance for the priority calibration targets, were considered. Changes to the sensitive parameter values also involved consideration of whether the adjusted values were realistic (e.g., use of extreme values at either end of the distribution was generally avoided).

Several possible calibrations were evaluated for 2,3,7,8-TCDD, tetraCB, and 1,2,3,4,6,7,8-HpCDF, using both the steady-state and dynamic bioaccumulation models. USEPA and CPG engaged in a collaborative process to discuss the possible options and ensure that all parties concurred with the selected calibration. All three calibration metrics described in Section 4.1.1 were considered during this calibration process.

4.1.2.4 Step 4 – Selection of final calibration

After comparing the three preliminary calibrations, CPG and USEPA agreed on the best-performing calibration across the various chemicals, areas, and species. Final adjustments to this calibration were then considered based on a review of the selected parameters for the other potential calibrations. After the final adjustments had been made, the model was considered calibrated.

4.2 CALIBRATED MODEL RESULTS

This section presents the calibrated parameter values and the model calibration results for 2,3,7,8-TCDD, tetraCB, and 1,2,3,4,6,7,8-HpCDF relative to the performance metrics outlined in Section 4.1.1.

4.2.1 Calibrated parameter values

As described in Section 4.1.2, most parameters were left at their nominal values. The parameters for which values were altered during calibration are summarized in Table 4-2, along with discussion of the confidence in the calibrated values relative to that of the nominal value and/or range of the distribution.

Table 4-2. Summary of calibrated parameters

Parameter	Unit	Distribution		Calibrated Value	Discussion of Calibrated Value
		Nominal Value	Acceptable Range		
General Parameters					
Water temperature (all modeling areas)	°C	13	0–28	22	Temperature for all areas was adjusted to match time period during which the majority of the fish were collected (i.e., Aug./Sept. 2009). Based on site-wide data, the average temperature for those two months was 22°C; this value improved model performance and thus, as discussed with USEPA, was used as the calibrated value.
Dietary AEs for benthic invertebrates (NLOC, NLOM)	none	0.75	0.15–0.96	0.40	There is a high level of uncertainty in actual dietary AE values for invertebrates. Windward contacted Dr. Frank Gobas to discuss dietary AEs of NLOM and NLOC for invertebrates. Dr. Gobas indicated that invertebrate dietary AEs are expected to be less than those for fish (particularly pelagic fish) (Gobas 2014). The dietary NLOM and NLOC AEs for fish were estimated to be in the range of 0.50 to 0.65 (based on rainbow trout tetraCB data from Nichols et al. (2001), as cited in Arnot and Gobas (2004)), so a value below this range is likely to be a reasonable calibrated value. The calibrated value of 0.4 was selected based on model performance and is consistent with the expectation that the value is somewhat less for invertebrates than for fish. In addition, this value falls near the center of the range developed based on the available invertebrate data.
Weight of DEPs (RM 6–RM 14.7)	kg	3.6×10^{-5}	1.2×10^{-7} – 4.0×10^{-4}	1×10^{-6}	Decreasing the weight for DEPs to better match the weight of the majority (based on abundance rather than biomass) of invertebrates in this group and area improved model performance (nominal value skewed high by presence of single larger species).
Diet of DEPs in RM 6–RM14.7	%	sed = 89% fluff = 10%	sed = 70-100% fluff = 0-30%	sed = 70% fluff = 25%	Model performance was improved by reducing the portion of bedded sediment in the diet of DEPs in these two modeling areas (no changes were needed for the RM 0–RM 6 modeling area). For RM 6–RM 14.7, the remaining 5% of the calibrated diet was split equally between phytoplankton and zooplankton.
Diet of DEPs in RM 14.7–Dundee Dam	%	sed = 84% fluff = 16%	sed = 60-100% fluff = 0-40%	sed = 70% fluff = 30%	
2,3,7,8-TCDD-specific Parameters					
Log K _{ow}	kg/L	6.38	5.38–8.93	6.65	The calibrated value was the same as that used in the CFT model.
E _D	fraction	0.49	0.10–0.76	0.2	Calibrated value was selected based on model performance.

Parameter	Unit	Distribution		Calibrated Value	Discussion of Calibrated Value
		Nominal Value	Acceptable Range		
K _M – benthic invertebrates	1/day	0.013	0.002–0.082	0.02	Calibrated values were selected based on model performance for each species, as well as a review of the data (and associated level of uncertainty) used to develop the K _M distributions (Appendix C).
K _M – small fish	1/day	0.013	0.002–0.082	0.005	
K _M – carp	1/day	0.003	0.0004–0.013	0.0004 (min.)	
K _M – blue crab	1/day	0.006	0.0005–0.045	0.0005 (min.)	
K _M – American eel	1/day	0.006	0.0005–0.045	0.006	
K _M – other fish	1/day	0.006	0.0005 – 0.045	0.0005 (min.)	
TetraCB-specific Parameters					
Log K _{OW}	kg/L	6.00	5.38–6.65	6.00	The calibrated value was the same as that used in the CFT model.
E _D	fraction	0.57	0.34–0.83	0.7	Calibrated value was selected based on model performance.
K _M – blue crab	1/day	0.002	0.0004–0.014	0.0004 (min.)	Calibrated values were selected based on model performance for each species, as well as a review of the data (and associated level of uncertainty) used to develop the K _M distributions (Appendix C).
K _M – American eel	1/day	0.002	0.0004–0.014	0.0004 (min.)	
1,2,3,4,6,7,8-HpCDF-specific Parameters					
Log K _{OW}	kg/L	8.03	7.37–9.25	8.67	The calibrated value was the same as that used in the CFT model.
E _D	fraction	0.05	0.001–0.31	0.05	Calibrated was value selected based on model performance.
K _M – benthic invertebrates	1/day	0.086	0.031–0.24	0.15	Calibrated value was selected based on model performance for each species, as well as a review of the data (and associated level of uncertainty) used to develop the K _M distributions (Appendix C).
K _M – small fish	1/day	0.086	0.031–0.24	0.05	
K _M – blue crab	1/day	0.036	0.007–0.13	0.01	
K _M – carp	1/day	0.036	0.007–0.13	0.02	
K _M – American eel	1/day	0.036	0.007–0.13	0.02	
K _M – other fish	1/day	0.036	0.007 – 0.13	0.02	

Note: Parameters not included in this table were not calibrated (i.e., they were not modified from the nominal values outlined in Section 3.3). Details regarding the rationale for the distributions presented here can be found in Section 3.3.

AE – absorption efficiency
CFT – contaminant fate and transport
DEP – benthic invertebrate deposit feeder
E_D – dietary chemical transfer efficiency
HpCDF -- heptachlorodibenzofuran

K_M – metabolic biotransformation rate constant
K_{OW} – octanol-water partition coefficient
NLOC – non-lipid organic carbon
NLOM – non-lipid organic matter

RM – river mile
TCDD – tetrachlorodibenzo-*p*-dioxin
tetraCB – tetrachlorobiphenyl
USEPA – US Environmental Protection Agency
Windward – Windward Environmental LLC

4.2.2 Model performance

Once the model had been calibrated, the model's performance was evaluated using the three metrics described in Section 4.1.1. As discussed, model calibration focused on improving model performance for the priority calibration targets (Table 4-1), while also improving overall model performance (i.e., model performance for all species/modeling areas). The calibrated model performance was determined to be acceptable for all three metrics, with performance goals met for most chemicals and species (Table 4-3). For each of the metrics used to evaluate model performance and summarized in Table 4-3, more detailed model results are presented as follows:

- ◆ Metric 1 (graphical evaluation) results are presented in Figures 4-1 to 4-3; additional figures can be found in Appendix G.
- ◆ Metric 2 (SPAFs) results are presented in Table 4-4.
- ◆ Metric 3 (benthic invertebrate BSAFs) results are presented in Table 4-5.

Table 4-3. Model performance overview

Chemical	Overview of Model Performance		
	Metric 1 – Graphical Evaluation	Metric 2 – SPAFs	Metric 3 – Invertebrate BSAFs
<i>Calibration performance goal</i>	<i>good comparability between empirical and predicted results</i>	<i>SPAF of < 3 for priority calibration targets</i> <i>mix of over- and under-predictions</i>	<i>model-calculated BSAFs close to or within range of literature values</i>
2,3,7,8-TCDD	Performance goals were met (mix of over-and under-predictions, good comparability between model predictions and empirical data).	Performance goals were met, with the exception of SPAFs for two priority targets that were > 3 (small forage fish and small American eel); average SPAF of 2.2 for priority targets; range of -1.5 to 4.8.	Performance goal was met (all model-calculated BSAFs within literature range).
TetraCB	Performance goals were met (mix of over-and under-predictions, good comparability between model predictions and empirical data).	Performance goals were met; average SPAF of 1.8 for priority targets; range of -2.7 to 2.0.	Performance goal met (all model-calculated BSAFs within literature range).
1,2,3,4,6,7,8-HpCDF	Performance goals met (mix of over-and under-predictions, good comparability between model predictions and empirical data).	Performance goals met; average SPAF of 1.7 for priority targets; range of -2.2 to 2.7.	Performance goal met for all but one BSAF (11 of 12 model-calculated BSAFs within literature range).

BSAF – biota sediment accumulation factor
 HpCDF – heptachlorodibenzofuran
 SPAF – species predictive accuracy factor

TCDD – tetrachlorodibenzo-*p*-dioxin
 tetraCB – tetrachlorobiphenyl

Key takeaways with regard to the calibrated model performance include:

- ◆ Across all chemicals, species, and areas, there is a mix of over- and under-predictions from the model, which provides support for the conclusion that the model is performing within acceptable performance metrics.
- ◆ Model performance is good (SPAFs < 3) for all priority calibration targets, with three exceptions:
 - ◆ The model over-predicted concentrations of 2,3,7,8-TCDD in small forage fish and small American eel in the RM 6 to RM 14.7 modeling area. For species such as these with small foraging areas, the variability in individual exposure levels is higher than that for fish with larger exposure areas, so SPAFs should be expected to be somewhat higher. The model performed well for these species for most other areas/chemicals (both priority targets and otherwise).
 - ◆ For species with larger home ranges (e.g., blue crab, carp, catfish, and white perch), it is sometimes necessary to consider whether it might be more appropriate to evaluate model predictions as an average across areas, because individuals are exposed to conditions in multiple modeling areas. For example, the model under-predicted concentrations of tetraCB in white perch in the RM 0 to RM 6 modeling area. White perch are known to have a relatively large foraging area/home range, which may mean that they range above RM 6, exposing them to higher tetraCB concentrations than occur in the RM 0 to RM 6 modeling area.
- ◆ As expected based on low sediment concentrations, model performance for the RM 14.7 to Dundee Dam modeling area was poor for 2,3,7,8-TCDD. This is discussed further in Section 4.3.1.
- ◆ For some species, such as blue crab, the empirical data are relatively similar throughout the LPRSA, indicating that individuals of these species may use multiple modeling areas and/or areas outside of the LPRSA. Consequently, the model under-predicts concentrations for both the RM 0 to RM 6 and RM 14.7 to Dundee Dam modeling areas, but it over-predicts for the RM 6 to RM 14.7 modeling area. Thus, for species such as blue crab, evaluating model results across the entire river (i.e., averaged across all three modeling areas) may more accurately reflect exposure for blue crab.

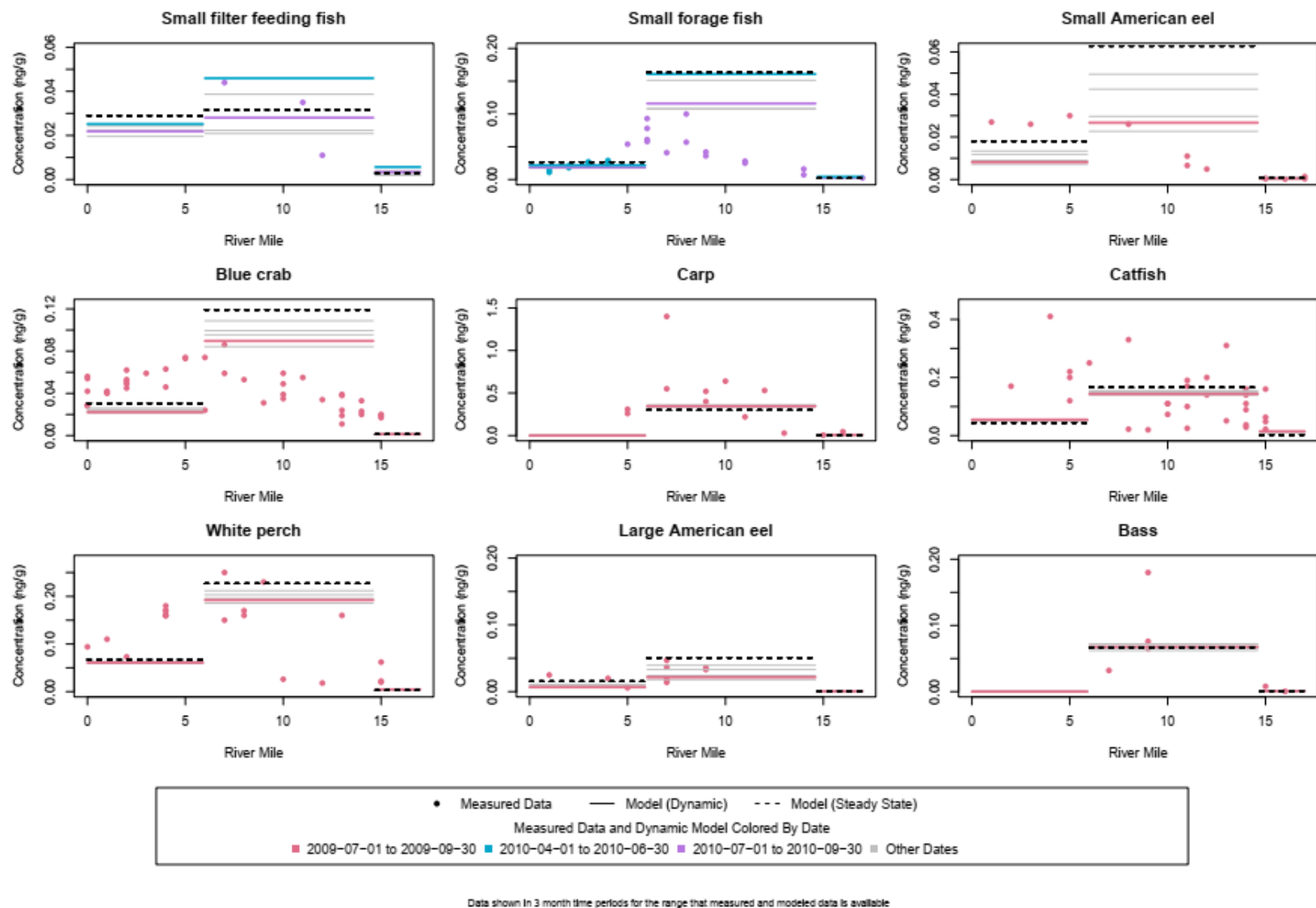
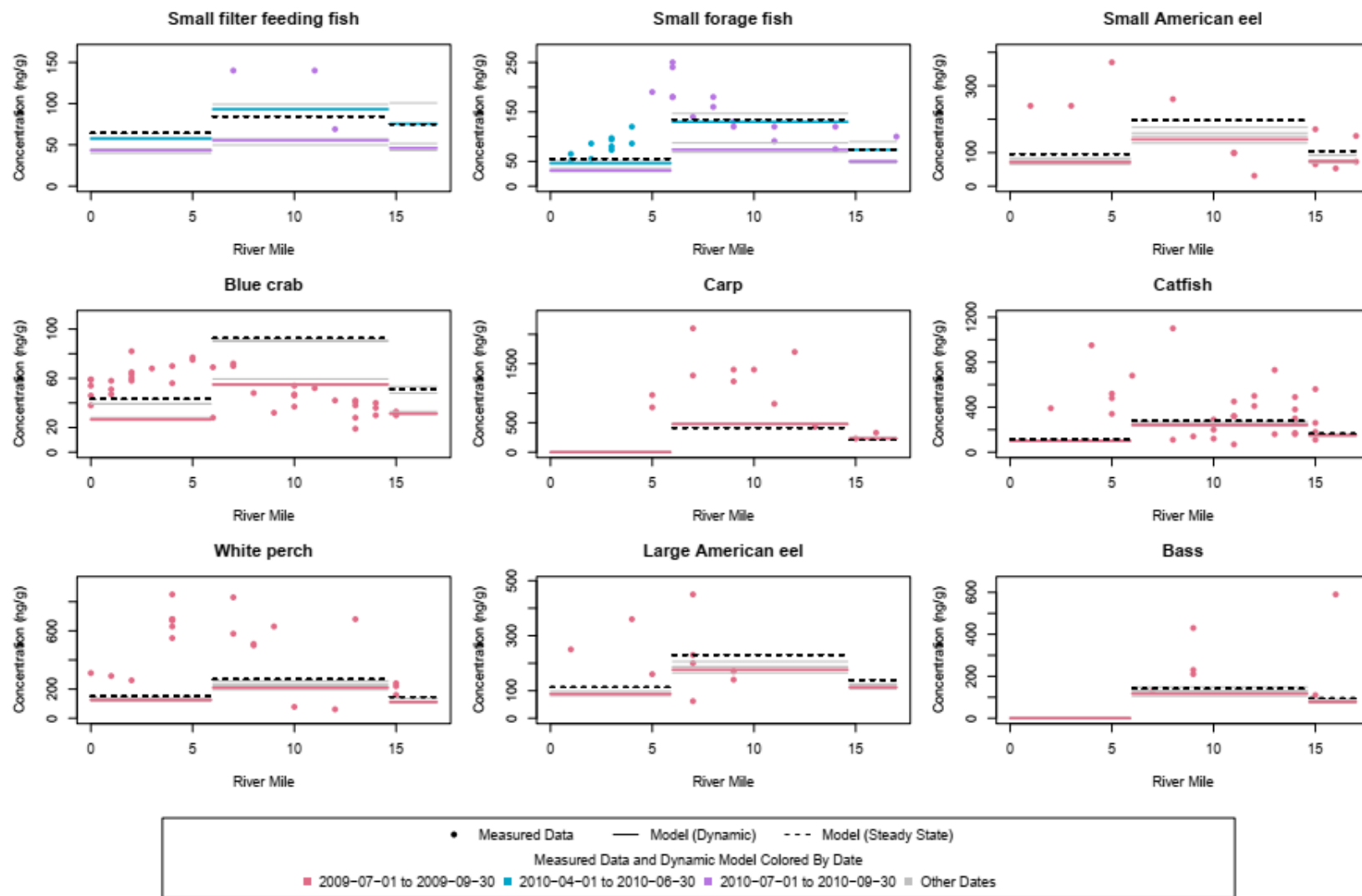


Figure 4-1. Calibrated model performance for 2,3,7,8-TCDD (metric 1)



Data shown in 3 month time periods for the range that measured and modeled data is available

Figure 4-2. Calibrated model performance for tetraCB (metric 1)

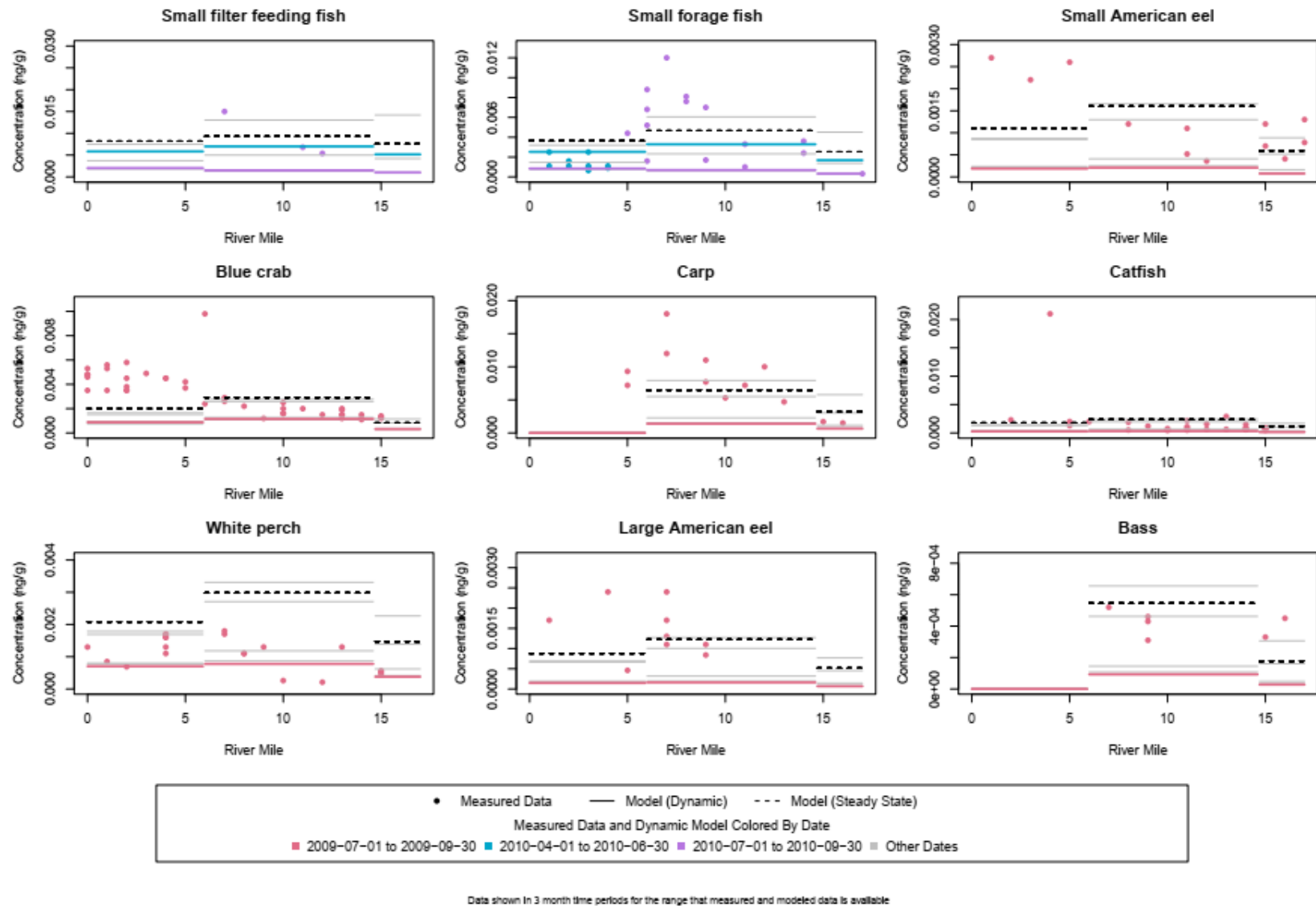


Figure 4-3. Calibrated model performance for 1,2,3,4,6,7,8-HpCDF (metric 1)

Table 4-4. SPAFs for calibrated model (metric 2)

Species	SPAFs for 2,3,7,8-TCDD			SPAFs for TetraCB			SPAFs for 1,2,3,4,6,7,8-HpCDF		
	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam
Small filter feeding fish	-	1.1	-	-	-1.4	-	-	1.0	-
Small forage fish	1.1	<u>3.4</u>	-7.6	-1.6	<u>-1.1</u>	-1.6	2.3	<u>-1.1</u>	-1.4
Small American eel	-1.6	<u>4.8</u>	1.2	-2.9	<u>1.2</u>	1.0	-2.3	<u>1.5</u>	-1.5
Blue crab	<u>-1.6</u>	<u>2.8</u>	-17.4	<u>-1.4</u>	<u>2.0</u>	1.6	<u>-2.2</u>	<u>1.3</u>	-1.6
Carp	-	<u>-1.5</u>	-6.7	-	<u>-2.7</u>	-1.6	-	<u>-1.3</u>	1.2
Catfish	-5.2	<u>1.4</u>	-47.1	-4.9	<u>-1.2</u>	-1.9	-2.8	<u>2.4</u>	1.2
White perch	<u>-2.1</u>	<u>1.5</u>	-11.1	<u>-3.6</u>	<u>-1.8</u>	-1.4	<u>1.6</u>	<u>2.7</u>	2.8
Large American eel	-1.1	<u>1.6</u>	-	-2.3	<u>1.1</u>	-	-1.7	<u>-1.1</u>	-
Bass	-	<u>-1.3</u>	-5.1	-	<u>-1.8</u>	-3.7	-	<u>1.4</u>	-2.2
Average (all)^a	2.1	2.2	13.7	2.8	1.6	1.8	2.1	1.5	1.7
Average (priority)^a	2.2			1.8			1.7		

Note: SPAFs for priority calibration targets are underlined and shown in bold.

^a Average SPAFs are calculated using absolute values (i.e., the lowest possible average SPAF is 1.0).

HpCDF – heptachlorodibenzofuran

SPAF – species predictive accuracy factor

tetraCB – tetrachlorobiphenyl

RM – river mile

TCDD – tetrachlorodibenzo-*p*-dioxin

Table 4-5. Evaluation of model performance for benthic invertebrates (metric 3)

Species Group	2,3,7,8-TCDD			TetraCB			1,2,3,4,6,7,8-HpCDF		
	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam	RM 0– RM 6	RM 6– RM 14.7	RM 14.7– Dundee Dam
BSAFs calculated using model-predicted tissue concentrations from the LPRSA bioaccumulation model									
Benthic invertebrate DEPs	0.9	0.9	2.4	1.5	1.0	1.6	0.2	0.3	0.2
Benthic invertebrate FFs	0.2	0.3	1.6	0.6	0.5	0.8	0.09	0.1	0.3
Benthic invertebrate DETs	1.1	0.3	3.6	1.8	0.5	1.1	0.3	0.3	1.5
Benthic invertebrate C/Os	0.8	0.4	2.8	1.6	0.6	1.2	0.1	0.2	0.7
Literature BSAF values used for comparison^a									
Sample size	18 (USEPA); 35 (USACE)			823 (USEPA); 307 (USACE)			27 (USEPA); 20 (USACE)		
Average	0.9 (USEPA); 0.6 (USACE)			2.1 (USEPA); 2.3 (USACE)			0.03 (USEPA); 0.2 (USACE)		
Median	0.5 (USEPA); 0.3 (USACE)			0.7 (USEPA); 1.6 (USACE)			0.02 (USEPA); 0.1 (USACE)		
Range of values	0.03–5.8 ^b			0.002–37 (0.04–6.0) ^c			0.0005–0.89		

Red text indicates BSAF value outside of range of values from USEPA and USACE BSAF databases.

- ^a Literature BSAFs are expressed as tissue concentration (mg/kg-lipid)/sediment concentration (mg/kg-OC) and include values in the USEPA and USACE BSAF databases.
- ^b A single BSAF value of 71 was excluded from the USACE database for 2,3,7,8-TCDD; this value was an order of magnitude higher than the next highest reported BSAF value. The inclusion of this value would have significantly impacted the summary statistics (average of 2.5, median of 0.35, and range of 0.03 to 71).
- ^c Because of the large number of samples in the tetraCB database and the potential presence of outliers, the 10th to 90th percentile is also presented.
- BSAF – biota-sediment accumulation factor FF – benthic invertebrate filter feeder TCDD – tetrachlorodibenzo-*p*-dioxin
C/O – benthic invertebrate carnivore/omnivore HpCDF – heptachlorodibenzofuran tetraCB – tetrachlorobiphenyl
DEP – benthic invertebrate deposit feeder LPRSA – Lower Passaic River Study Area USACE – US Army Corps of Engineers
DET – benthic invertebrate detritivore OC – organic carbon USEPA – US Environmental Protection Agency
RM – river mile

4.3 DISCUSSION OF MODEL PERFORMANCE

This section presents a discussion of model performance relative to patterns of sediment concentrations in the LPRSA (Section 4.3.1) and a discussion of the contributions of the six input media (i.e., sediment, porewater, bioavailable water, suspended detrital particulates, suspended algal particulates, and near-bottom particulates [fluff]) to the predicted tissue concentrations (Section 4.3.2). These topics help to better define the key factors influencing the calibration and performance of the bioaccumulation model.

4.3.1 Examination of sediment concentration by river mile relative to model performance

As part of understanding and evaluating model performance, it is useful to understand the patterns of chemical concentrations in the LPRSA by modeling area. Concentrations of dioxins/furans and PCBs in sediment decrease in the upper portion of the LPRSA, particularly in the RM 14.7 to Dundee Dam modeling area; this decrease is far more pronounced for 2,3,7,8-TCDD than for tetraCB and 1,2,3,4,6,7,8-HpCDF (Figure 4-4):

- ◆ **TetraCB and 1,2,3,4,6,7,8-HpCDF** – The average spatially weighted average concentration (SWAC) above RM 14 is about 10 to 15 times lower than the average SWAC below RM 14.
- ◆ **2,3,7,8-TCDD** – The average SWAC above RM 14 is more than 1,000 times lower than the average SWAC below RM 14.

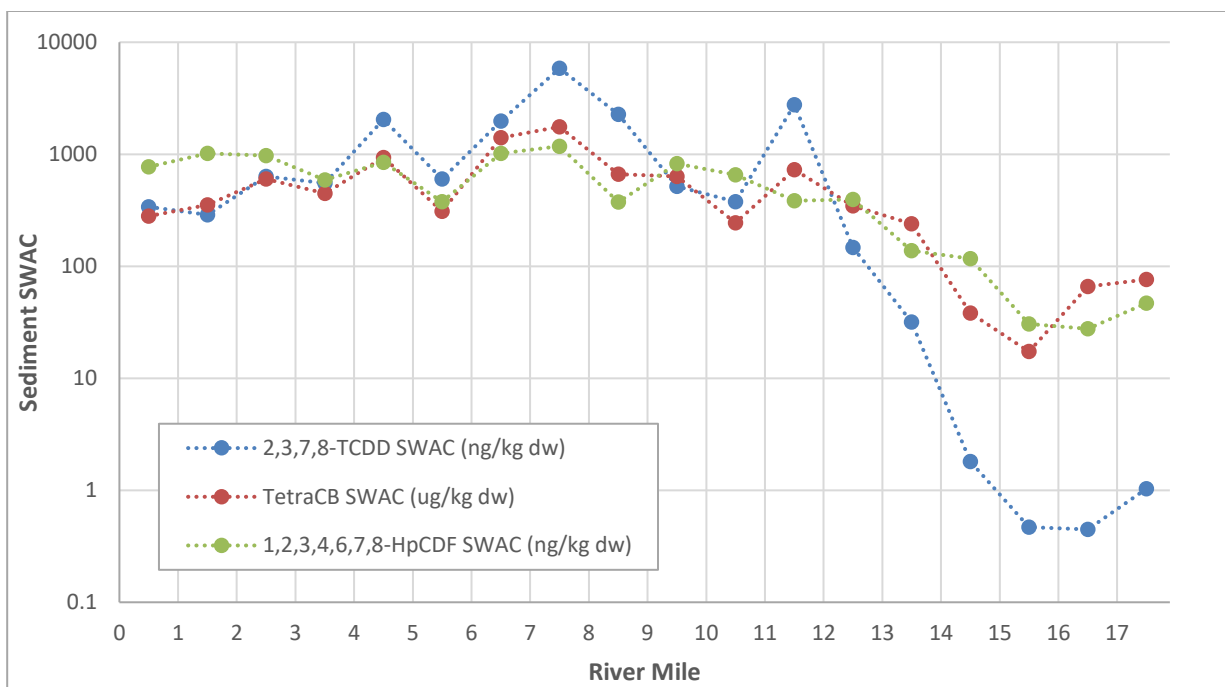


Figure 4-4. Comparison of sediment SWACs by LPRSA river mile

These concentration patterns are important when considering model performance, particularly for 2,3,7,8-TCDD. While tissue concentrations for 2,3,7,8-TCDD are less in the upper portion of the LPRSA, they are not as low as might be expected based on sediment concentration alone (Figure 4-5). This is, in part, because of the impacts of other inputs of 2,3,7,8-TCDD (e.g., water and particulates); but more importantly, it is because the home ranges for most species (and their prey) are sufficiently large that they are likely exposed to sediments with higher concentrations downstream of RM 14 (even if the samples in question were collected above RM 14). This explains two things: 1) why the model underpredicts the empirical data by a large margin for 2,3,7,8-TCDD in the RM 14.7 to Dundee Dam modeling area (Table 4-4), and 2) why this does not occur for tetraCB and 1,2,3,4,6,7,8-HpCDF: because concentrations in sediment for these chemicals are not as different in the upper reach as they are in the rest of the LPRSA.

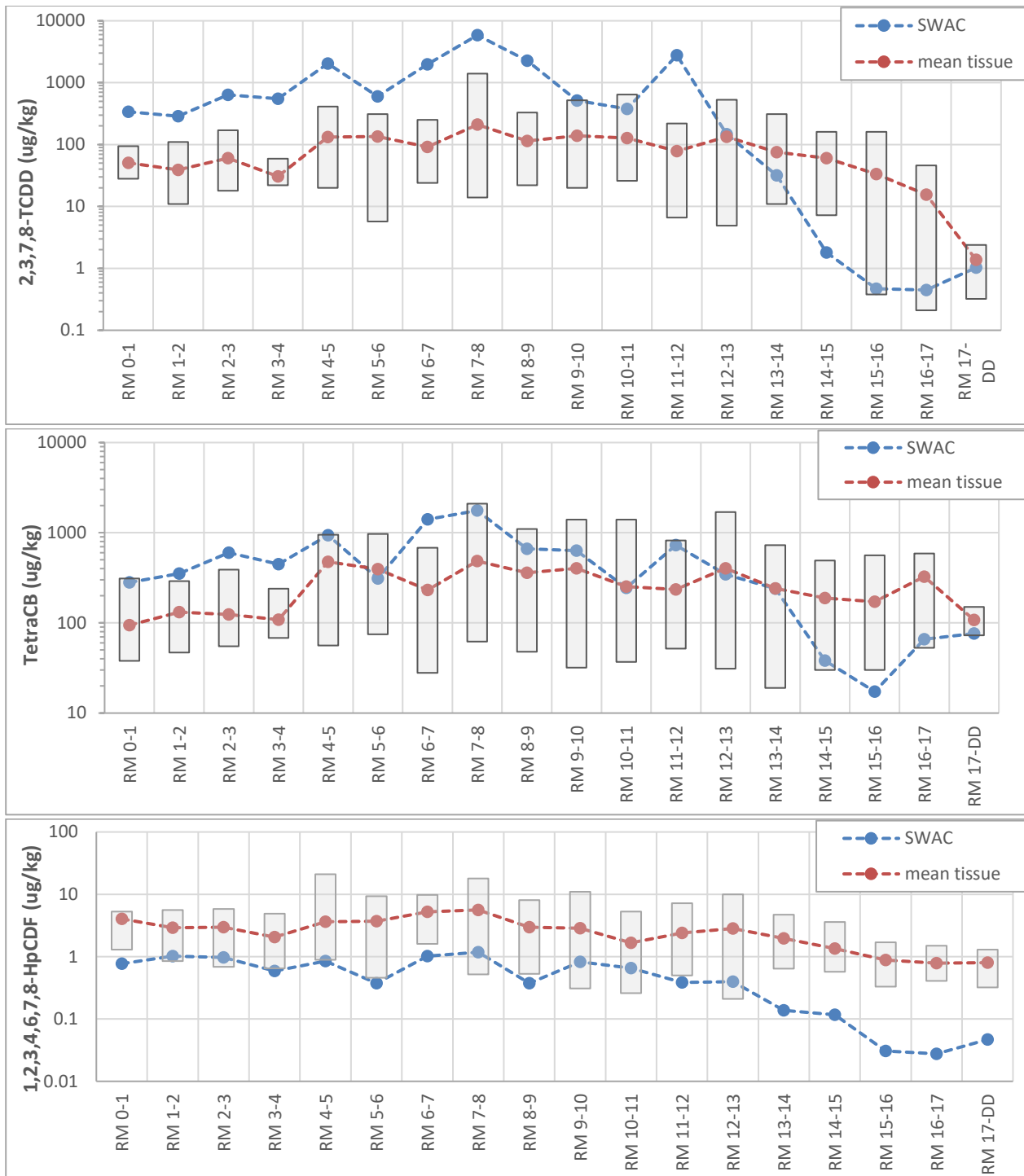


Figure 4-5. Comparison of tissue and sediment concentrations by river mile

4.3.2 Percent contribution by media to model-predicted tissue concentrations

A benefit of using a mechanistic bioaccumulation model is that it allows users to understand the contributions of various exposure media to overall bioaccumulation for each modeled species. This ability also allows for a better understanding of what factors influence model performance. Figure 4-6 presents the relative percent contribution of each model input (i.e., sediment, porewater, bioavailable water, suspended detrital particulates, suspended algal particulates, and near-bottom particulates) to the predicted tissue concentrations of 2,3,7,8-TCDD, tetraCB, and 1,2,3,4,6,7,8-HpCDF for each modeled species. Percent contributions are presented for all species and modeling areas, as there are important differences across the chemicals, species, and areas. These percentages reflect both direct exposure to chemicals in a given medium and indirect exposure via dietary uptake. Several important observations can be made from this evaluation:

- ◆ **Sediment and near-bottom particulates drive model predictions for most species** – With the exception of phytoplankton, zooplankton, and small filter-feeding fish, the primary contributors to tissue concentrations of all three calibration chemicals were sediment and near-bottom particulates. Understanding that these inputs drive predicted concentrations is useful in understanding model calibration. For example, this fact helps explain why parameters that influence uptake from sediment into invertebrates (which, in turn, is the primary pathway for sediment exposure in upper-trophic-level species) are so influential in model calibration.
- ◆ **The relative importance of sediment for all three chemicals reflects the patterns of concentrations in sediment** (Figure 4-4) – This observation is especially true for 2,3,7,8-TCDD. Sediment is of high importance for the RM 0 to RM 6 and RM 6 to 14.7 modeling areas, where concentrations of 2,3,7,8-TCDD in sediment are higher. Sediment is of much lower relative importance for the RM 14.7 to Dundee Dam modeling area, where concentrations of 2,3,7,8-TCDD in sediment are much lower and where fine-grained sediments are less prevalent. From RM 14.7 to Dundee Dam, concentrations in near-bottom particulates are greater than those in the predominately coarser-grained sediments, so near-bottom particulates are the primary contributor to tissue concentrations for most species. Sediment is of lower relative importance for tetraCB and 1,2,3,4,6,7,8-HpCDF in all modeling areas, although it is still an important driver in determining predicted tissue concentrations.
- ◆ **Patterns of relative importance for the model inputs are very different for plankton and filter-feeding fish than for other species** – Concentrations for these species are primarily driven by concentrations in the water column. Phytoplankton concentrations are calculated from suspended algal particulates; thus, 100% of the predicted concentration is based on suspended algal particulates. For zooplankton, predicted concentrations are based on a mix of

suspended algal particulates (because phytoplankton are assumed to be 100% of the diet of zooplankton) and bioavailable concentrations in water. The diet of filter-feeding fish is assumed to be a mix of plankton and detrital particulates in the water column. Of these, water column particulates have the highest concentration, making them the primary driver for predicted tissue concentrations for filter-feeding fish.

- ◆ **Differences in patterns across upper-trophic-level species for a given chemical reflect the different uptake patterns of their prey, as well as the different chemical concentrations in each modeling area** – For example, bioavailable concentrations in water are more important for bass than for carp, although both species are primarily influenced by sediment and near-bottom particulates. The comparison of bass and carp (for which diets are assumed to be quite different) illustrates that area-specific differences may be more important for understanding these results than species-specific differences.

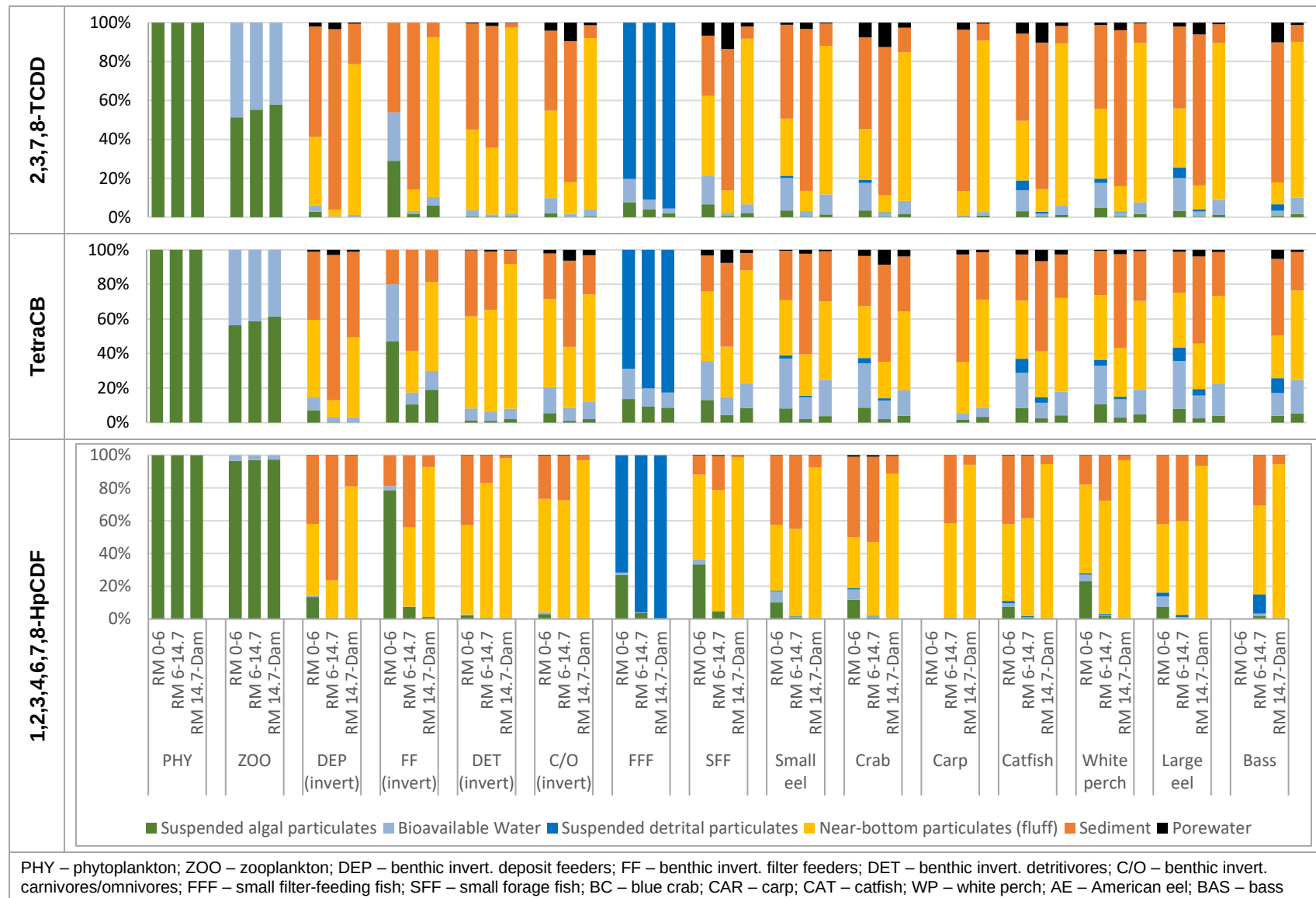


Figure 4-6. Percent contributions of chemical sources to predicted tissue concentrations

The differences in the percent contributions across the modeled species resulting from behavioral differences and differences in chemistry patterns have an important influence on the levels of bioaccumulation in each species (i.e., differences in species-specific bioaccumulation). This is important not only for understanding the calibrated model performance, but also when considering how different remedial options (which typically focus on sediment) will have various levels of effectiveness in reducing tissue concentrations in the modeled species.

5 Evaluation of Model Uncertainty and Sensitivity

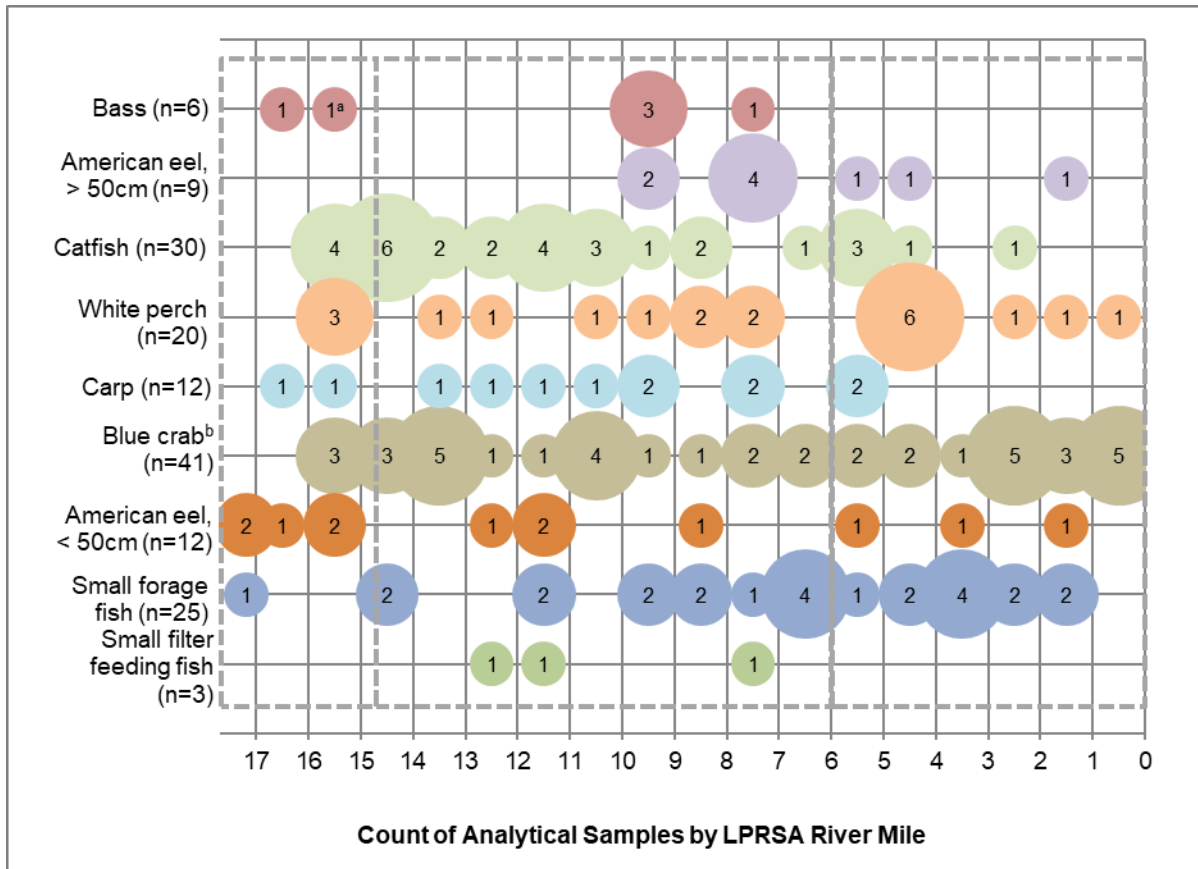
This section presents an evaluation of the representativeness of the calibration dataset (Section 5.1), potential alternate calibrations for the bioaccumulation model (Section 5.2), and key model uncertainties (Section 5.3).

5.1 REPRESENTATIVENESS OF THE CALIBRATION DATASET

The empirical tissue data were evaluated to determine their suitability for use in calibrating the bioaccumulation model (i.e., whether the available data are representative of the average concentration in the LPRSA for each species). LPRSA tissue data included in the calibration dataset were collected and analyzed as part of sampling efforts conducted during the summer/fall of 2009 and spring/summer of 2010 (Windward 2018a, b). These sampling events were designed to develop a comprehensive tissue sample database for the LPRSA. Details regarding the empirical tissue data used for model calibration (which included data for small fish, blue crab, carp, catfish, white perch, American eel, and bass) are presented in Section 3.3.4. The following factors were considered to evaluate the representativeness of the empirical tissue data:

- ◆ **Number of available samples** – A reasonable number of samples (defined as a minimum of 10 samples) were available for most species, providing confidence that the average of the calibration dataset is reasonably representative of the average for the entire population. Two exceptions are for small filter-feeding fish ($n = 3$) and bass ($n = 6$); uncertainty is greater for these species.
- ◆ **Spatial coverage of samples** – Samples for each species in the calibration dataset were generally distributed throughout the applicable modeling areas, as shown in Figure 5-1. Exceptions for small and large eel are noted in Table 5-1.
- ◆ **Sample type (individual vs. composite)** – The calibration dataset included a mix of individual and composite sample types (see Table 3-13), depending on fish size. Because the bioaccumulation model uses the average concentration to calibrate the model, a dataset composed of this mix of sample types still provides a representative estimate of the mean concentration for each species.

More details regarding the dataset for each species and the spatial coverages of those datasets are presented in Figure 5-1 and Table 5-1. Based on the evaluation presented herein, uncertainty associated with the use of the empirical dataset to calibrate the LPRSA bioaccumulation model is considered low.



Note: Gray dashed boxes identify the modeling areas.

^a This bass composite sample contained two individuals from RM 15 to RM 16 and one individual from RM 16 to RM 17; this composite sample is shown as being collected from RM 15 to RM 16.

^b Blue crab samples from above RM 10 were whole-body concentrations estimated using muscle/hepatopancreas data.

Figure 5-1. Number of analytical samples by LPRSA river mile for the calibration dataset

Table 5-1. Summary of available samples in the calibration dataset

Species	Count Samples	Notes Regarding Representativeness of Dataset
Benthic invertebrates	0	No appropriate field-collected benthic invertebrate data were available for the LPRSA against which to compare model predictions.
Small filter-feeding fish	3	Small dataset (n = 3). All three samples in RM 6 to RM 14.7 modeling area. The small number of samples suggests that the sample average is more uncertain than the averages for other species.
Small forage fish	25	Spatial distribution of samples is relatively even across modeling area, although few samples were available above RM 12 (n = 3).
Small American eel	12	Spatial distribution of samples is moderate (coverage relatively even for the RM 14.7 to Dundee Dam modeling area; small number of samples below RM 14).

Species	Count Samples	Notes Regarding Representativeness of Dataset
Blue crab	41	Spatial distribution of samples is relatively even across modeling area. No whole-body samples were available above RM 10; there, whole-body concentrations were estimated using site-specific regression that related concentrations in muscle/hepatopancreas samples with those in whole-body samples (Appendix E). Based on the strength of the regression ($r^2 > 0.9$), the use of these estimated concentrations is not expected to impact model calibration.
Carp ^a	12	Spatial distribution of samples is relatively even across modeling area.
White perch	20	Spatial distribution of samples is relatively even across modeling area.
Catfish	30	Spatial distribution of samples is relatively even across modeling area, although relatively few catfish were present in the RM 0 to RM 6 modeling area because of higher salinity.
Large American eel	9	Spatial coverage of samples below RM 10 is relatively even; however, no samples above RM 10.
Bass ^a	6	Small dataset (n = 6). Only six bass composite samples were available for calibration in modeled areas (four from the RM 6 to RM 14.7 modeling area and two from the RM 14.7 to Dundee Dam modeling area). The small number and uneven spatial distribution of bass collected from the LPRSA suggest that this sample average is more uncertain than the sample average for other species.

^a As described in Section 3.2.5, bass and carp were not modeled in the RM 0 to RM 6 modeling area.

LPRSA – Lower Passaic River Study Area

RM – river mile

5.2 ALTERNATE MODEL CALIBRATIONS

In complex models, there are often multiple combinations of input values that will produce results that meet the model performance criteria. Based on discussions of this topic between USEPA and CPG, USEPA agreed to run alternate model simulations for the LPRSA bioaccumulation model to evaluate whether there are alternate parameter sets that could be used to calibrate the LPRSA bioaccumulation model.

USEPA ran three types of alternate model calibration simulations. All three simulation types were run with both K_{OW} held constant (i.e., equal to the value used in the CFT model) and K_{OW} allowed to vary, for a total of six alternate calibrations. The alternate calibration simulations are as follows:

- ◆ **Optimize all SPAFs** – The objective of this simulation was to find the set of model inputs that minimized the average SPAFs for all species.
- ◆ **Optimize priority SPAFs** – The objective of this simulation was to find the set of model inputs that minimized the average SPAFs for priority calibration targets (i.e., those presented in Table 4-1).
- ◆ **Maximum likelihood estimation (MLE)** – The objective of this simulation was to maximize the probability that the model would accurately represent the central tendency of each biotic dataset (i.e., account for the degree of variability in the observed data and the number of samples).

For simplicity, these alternate calibrations were conducted only for 2,3,7,8-TCDD and tetraCB (i.e., 1,2,3,4,6,7,8-HpCDF was not included). A total of 74 parameters (or 72 when the K_{OW} was held constant) were allowed to vary when developing these alternate calibrations, including the following:

- ◆ Chemical-specific K_{OW} ($n = 2$)
- ◆ Chemical-specific E_D ($n = 2$)
- ◆ Body weight for each invertebrate group and modeling area ($n = 12$)
- ◆ Lipid fraction and water fraction for zooplankton and invertebrates ($n = 10$)
- ◆ Chemical- and species-specific K_M values ($n = 16$)
- ◆ Species-specific fraction of porewater ventilated ($n = 8$)
- ◆ Select dietary absorption efficiency parameters for invertebrates ($n = 8$)
- ◆ DO saturation multiplier ($n = 1$)
- ◆ Select dietary fraction parameters ($n = 17$)

The selected values for each of these parameters for the six alternate calibrations are presented in Appendix H.

5.2.1 Model performance for alternate calibrations

Results for these alternate calibrations were reviewed for both the steady-state and dynamic models. Table 5-2 presents a summary of the steady-state model performance (measured as SPAFs) for 2,3,7,8-TCDD and tetraCB (dynamic model output is presented in Appendix H). As shown in Table 5-2, average priority SPAFs were ≤ 2.5 for the alternate calibrations, indicating that alternate parameter sets that meet the calibrated model performance criteria can be developed successfully. The SPAFs for the alternate calibrations also highlight tradeoffs that occur during calibration depending on the model objective—some aspects of the model performance may improve while others get worse (e.g., the average SPAF may improve for one area but get worse for another).

Table 5-2. Summary of steady-state model performance for alternate calibrations

Simulation	Kow	Average of All SPAFs by Area			Priority SPAFs	
		RM 0–RM 6	RM 6–RM 14.7	RM 14.7–Dam	Range	Average
2,3,7,8-TCDD						
Calibrated model	constant	2.1	2.2	13.7	-2.1 to 4.8	2.2
Optimize all SPAFs	constant	2.0	2.7	4.0	-1.0 to 4.7	2.5
Optimize priority SPAFs	constant	3.1	1.2	14.3	-1.6 to 1.8	1.2
MLE	constant	1.3	2.1	7.0	-1.2 to 5.4	2.0

Simulation	K _{ow}	Average of All SPAFs by Area			Priority SPAFs	
		RM 0–RM 6	RM 6–RM 14.7	RM 14.7–Dam	Range	Average
Optimize all SPAFs	variable	2.0	2.1	4.0	-1.4 to 3.4	2.1
Optimize priority SPAFs	variable	2.8	1.2	11.9	-1.5 to 1.5	1.2
MLE	variable	1.3	1.9	6.3	-1.2 to 4.1	1.8
TetraCB						
Calibrated model	constant	2.8	1.6	1.8	-3.6 to 2.0	1.8
Optimize all SPAFs	constant	2.8	1.5	1.4	-3.6 to 1.2	1.8
Optimize priority SPAFs	constant	1.8	1.2	1.4	-1.6 to 1.3	1.2
MLE	constant	1.6	1.3	1.3	-1.9 to 1.3	1.4
Optimize all SPAFs	variable	1.8	1.3	1.3	-2.1 to 1.7	1.5
Optimize priority SPAFs	variable	1.6	1.1	1.5	-1.5 to 1.3	1.1
MLE	variable	1.4	1.2	1.4	-1.9 to 1.3	1.3

K_{ow} – octanol-water partition coefficient

MLE – maximum likelihood estimation

RM – river mile

SPAF – species predictive accuracy factor

TCDD – tetrachlorodibenzo-*p*-dioxin

tetraCB – tetrachlorobiphenyl

In addition to looking at model performance, it is important to recognize differences in the approaches used to develop these calibrations. These differences can be used to understand differences in model performance and potential uncertainties associated with the parameter sets. Key differences are summarized below:

- ◆ **Selection of parameter values** – While the same distributions were used for both calibration efforts, there were differences in how the calibrated values were selected. During model calibration, efforts were made to avoid selecting values at the extreme ends of the distributions, particularly when there was information to suggest that the nominal values were more realistic than those at the ends of the distribution. For the alternate calibrations, any value within the defined distribution was considered acceptable. Across the six simulations, approximately 80% of the parameter values were in the upper or lower 10th percentiles of the distributions, potentially indicating greater uncertainty about the representativeness of these parameter values.
- ◆ **Treatment of K_M values** – When calibrating the model, the decision was made to group species with regard to K_M values (i.e., the K_M values for some species, such as small and large eel, were set equal to one another, rather than letting these values vary independently). For the alternate calibration simulations, K_M values for each species/chemical were all allowed to vary independently, which allowed the model to be more closely fit to the empirical data (thus resulting in lower SPAFs). Because there is considerable uncertainty in the true K_M values for a given species, it is unknown which approach would reduce uncertainty.

- ◆ **Exclusion of 1,2,3,4,7,8,9-HpCDF** – Model calibration (as described in Section 4) accounted for model performance for 1,2,3,4,7,8,9-HpCDF; the alternate calibration simulations were only run for 2,3,7,8-TCDD and tetraCB. However, given that the calibrated model worked well for 1,2,3,4,7,8,9-HpCDF with limited adjustments, the impact of this difference is likely small.

5.2.2 Conclusions regarding alternate calibrations

The alternate calibrations developed by USEPA show that alternate parameter sets can be developed that successfully meet the calibrated model performance criteria (Section 5.2.1). Model performance based on alternate calibrations was generally similar to or better than that of the selected calibration under specific circumstances. These differences can be explained by differences in the approaches for developing these calibrations.

It is also important to recognize that while the alternate calibrations meet the performance criteria, there is some potential uncertainty associated with these parameter sets. As described in Section 5.2.1, approximately 80% of the parameter values for the six alternate calibrations were in the upper or lower 10th percentiles of the distributions, indicating that there may be increased uncertainty associated with some of these parameter values selected from the extreme ends of their distributions. While the calibration dataset is considered to be representative of the species and concentrations present in the LPRSA and is suitable for use in calibrating the bioaccumulation model (Section 5.1), care should be taken to avoid over-calibrating to the average concentrations, particularly when datasets are small (e.g., for bass) or when there is a high level of variability (as is the case for many species).

Ultimately, despite these uncertainties, the alternate calibrations provide valuable information to better understand the bioaccumulation model calibration. In addition, when using the bioaccumulation model to predict future tissue concentrations (e.g., for post-remedy conditions), the alternate calibrations could provide a tool to better evaluate the possible range of future tissue concentrations. Simulations of post-remedy conditions could be run through the bioaccumulation model using the alternate calibrations, and the range of resulting tissue concentrations could be used to better understand potential uncertainty relating to the tissue predictions.

5.3 KEY MODEL UNCERTAINTIES AND SENSITIVITIES

Key uncertainties associated with the LPRSA bioaccumulation model include those related to exposure assumptions, changes to the model code, the calibration dataset, and selected values for model parameters.

- ◆ **Exposure assumptions, changes to model code, and the calibration dataset** – A discussion of key uncertainties associated with these aspects of

the model and their potential impact on model calibration are presented in Table 5-3.

- ◆ **Sensitive model parameters** – Key model parameters (i.e., those to which the model is highly sensitive) are discussed in Table 5-4. Calibrated values for these parameters were selected based on model performance. As can be seen in the alternate calibrations (Appendix H), the calibrated values for these parameters differ across the calibrations, indicating that there is uncertainty as to the actual values for these parameters.

Table 5-3. Key model uncertainties related to exposure, model structure, and the calibration dataset

Uncertainty	Description	Potential Impact to Model Calibration
Exposure Assumptions		
Small forage fish modeling area	Small forage fish were assumed to use only mudflat areas of the LPRSA (Section 3.2.5). Like for most other fish, tissue concentrations in small forage fish are primarily driven by concentrations in sediment and near-bottom particulates (Section 4.3.2); thus, differences in exposure concentrations by modeling area were examined.	Baseline differences in concentrations between the river-wide and mudflat-only areas are relatively small (Table 3-6), indicating that the impact of changes to this assumption on predicted baseline concentrations for small forage fish would be low.
Use of CFT model output as model input	As described in Sections 2.6 and 3.3, physical parameter values (e.g., water temperature) and chemical-specific concentrations (e.g., sediment and water) were based on values from the CFT model.	The current calibration of the model relies on these physical and chemical input values. While there is uncertainty associated with these input values (Anchor QEA et al. 2019), the CFT model was calibrated to site conditions based on empirical data; thus, it provides the most comprehensive estimate of parameter values for the LPRSA. The extent of the uncertainty is anticipated to be low.
Near-bottom particulate concentrations	As described in Section 2.6, the near-bottom particulate (i.e., fluff layer) concentrations were not directly estimated by the CFT model. Rather, the values used in the bioaccumulation model are equal to the concentrations estimated for the bottom 10% of the water column.	No empirical data are available against which to evaluate the uncertainty of these estimates for near-bottom particulate concentrations. Given that this input is influential in the model predictions (as discussed in Section 4.3.2), changes to these concentrations could have a large impact on model predictions.
Changes to Model Structure and Associated Parameters		
Use of suspended algal particulates to calculate phytoplankton	As discussed in Section 2.5 and Appendix B, CPG and USEPA agreed to change the method used to calculate phytoplankton concentrations in the bioaccumulation model (Section 2.5). Rather than using the equation in the Arnot and Gobas model (2004), the chemical concentration in phytoplankton was estimated using the concentration associated with suspended algal particulates from the CFT model.	This change in calculation methods resulted in an increase in predicted phytoplankton concentrations: Concentrations were about 6 times higher for 2,3,7,8-TCDD, about 20 times higher for tetraCB, and about 95 times higher for 1,2,3,4,6,7,8-HpCDF. Despite these increases in the predicted plankton concentrations, the impact on the overall model was relatively low, largely because exposure to suspended algal particulates (which occurs via the consumption of plankton) contributes a relatively small fraction of the predicted concentrations for fish and crab (Section 4.3.2).

Uncertainty	Description	Potential Impact to Model Calibration
Growth and consumption rate equations	As discussed in Section 2.5 and Appendix B, CPG and USEPA agreed to change the way that organism-specific growth and consumption rates were calculated. Rather than the standard equations from Arnot and Gobas (2004), output from the FB4 model was used to develop species-specific equations. This change reduced the seasonal variability in the model-predicted tissue concentrations for many of the modeled organisms.	While there is some uncertainty as to which approach results in more accurate estimates of growth and consumption, CPG and USEPA agreed that the use of species-specific equations that reduced seasonal variation in tissue concentrations was preferable. It is expected that the use of species-specific equations contributes to improved model performance.
FB4 model parameters	The FB4 model output (which is used to develop the growth and consumption rate equations) is dependent on several factors, including the selection of surrogate species and required user-defined inputs (e.g., organism start and end weights, water temperature, and diet portions). The uncertainty of these assumptions was evaluated in Appendix B.	An evaluation of the sensitivity of the FB4 model output to the various user-defined inputs was conducted (Appendix B). The impact of changes to the FB4 model parameters on the growth and consumption rate equations was found to be low, and impacts on the overall model are also expected to be low. As noted, it is expected that the use of species-specific equations contributes to improved model performance.
Calibration Dataset		
Representativeness of the calibration dataset	As described in Section 3.3.4, the bioaccumulation model calibration used the whole-body fish and crab tissue data collected from the LPRSA in 2009/2010.	The representativeness of the calibration dataset was evaluated in Section 5.1, and the uncertainty associated with the use of the empirical dataset to calibrate the LPRSA bioaccumulation model is considered low. However, the lack of benthic invertebrate data against which to calibrate the four benthic invertebrate model compartments represents a source of uncertainty. To help alleviate this uncertainty, benthic invertebrate BSAFs were used as a calibration metric (Section 4.1.1.3). The calibrated model generally met the performance goals for this metric, so while the BSAFs themselves are uncertain, this metric indicates that the magnitude of this uncertainty is likely low.

AE – absorption efficiency

BSAF – biota-sediment accumulation factor

CFT – contaminant fate and transport

CPG – Cooperating Parties Group

DEP – benthic invertebrate deposit feeder

HpCDF – heptachlorodibenzofuran

LPRSA – Lower Passaic River Study Area

RM – river mile

TCDD – tetrachlorodibenzo-*p*-dioxin

tetraCB – tetrachlorobiphenyl

USEPA – US Environmental Protection Agency

Table 5-4. Key parameters and model sensitivity

Parameter	Discussion of Model Sensitivity
Water temperature	Predicted tissue concentrations are moderately sensitive to water temperature. As presented in Section 4.2, the calibrated average water temperature for the LPRSA model was set at 22°C for all model areas. This value was selected to match the average water temperature during the time period when the majority of the fish were collected (i.e., Aug/Sept 2009), and to improve model performance.
Chemical-specific K_{OW} and E_D	Predicted tissue concentrations are sensitive to K_{OW} and E_D . As described in Section 2.5, CPG and USEPA agreed that the E_D parameter for the LPRSA bioaccumulation model should be a separate input parameter (rather than calculated from the K_{OW}). To maintain consistency between models, the K_{OW} values used for the bioaccumulation model were the same as those used for the CFT model; thus, the E_D parameter is a key focus of model calibration. This parameter was calibrated to improve model performance.
Chemical- and species-specific K_M	Predicted tissue concentrations are sensitive to changes in K_M . As described in Section 3.3 (Table 3-5) and Appendix C, limited information was available regarding K_M values, particularly when attempting to develop values for different species. For example, no species-specific information was available for benthic invertebrates or blue crab for 2,3,7,8-TCDD and 1,2,3,4,6,7,8-HpCDF, and thus rates available for fish species were used as surrogates. In addition, it is possible that metabolic biotransformation could be serving as a surrogate process for other related processes that could affect the uptake or elimination of chemicals for a given species. K_M values were calibrated to improve model performance.
Dietary AEs for invertebrates	Invertebrate dietary AEs for lipids, NLOC, and NLOM are parameters to which the model was determined to be sensitive and regarding which there is considerable uncertainty. Dietary AEs of NLOM and NLOC for invertebrates are expected to be less than those for fish, particularly those for pelagic fish (Gobas 2014). The calibrated value was selected to improve model performance and was based on a consideration of the invertebrate AE value relative to that of fish.
Species-specific diet fractions	As described in Section 3.3 (Tables 3-11 and 3-12), diet fractions were developed for each species based on the available information in literature, as well as LPRSA-specific information regarding the abundance of invertebrates and small fish. Many species are opportunistic in their feeding habits, so diet fractions are likely to vary with prey availability. In general, the sensitivity of the bioaccumulation model to changes in the diet fractions was found to be low. However, in some cases (e.g., the fraction of sediment consumed by DEPs), changes to the diets were found to improve model calibration.

AE – absorption efficiency

CFT – contaminant fate and transport

CPG – Cooperating Parties Group

DEP – benthic invertebrate deposit feeder

E_D – dietary chemical transfer efficiency

HpCDF – heptachlorodibenzofuran

K_M – metabolic biotransformation rate constant

K_{OW} – octanol-water partition coefficient

LPRSA – Lower Passaic River Study Area

NLOC – non-lipid organic carbon

NLOM – non-lipid organic matter

TCDD – tetrachlorodibenzo-*p*-dioxin

USEPA – US Environmental Protection Agency

Mechanistic models are the best available tool for evaluating the effectiveness of proposed sediment remediation options at reducing tissue concentrations. An alternative approach is to rely on baseline data and statistical models (e.g., BSAFs) to draw inferences, but this approach is not suitable for extrapolating beyond the range of the empirical data. That restriction limits the use of statistical models in predicting how tissue concentrations will respond to sediment remediation.

Mechanistic models can be used to extrapolate beyond the range of the empirical data, because they describe the underlying processes governing how the modeled system would respond to particular changes. Thus, while there is uncertainty associated with

the informed judgments and parameter estimates used in mechanistic models – which in turn, leads to uncertainty in model output – mechanistic models are appropriate and necessary for estimating future conditions under alternative remedies. Ultimately, the evaluation of the uncertainties associated with the LPRSA bioaccumulation model supports the conclusion that the model is a reliable tool for estimating fish and invertebrate tissue concentrations and associated risks to ecological receptors and human health over time. Furthermore, the model validation and/or refinement process that will occur as part of the adaptive management approach (see Section 6) will help provide increased confidence in model predictions. This process will use the current conditions biota dataset for the upper 9 miles of the LPRSA (collected in 2019 and 2021), along with updated CFT model results that will be informed by the current conditions surface water data collected from 2019 through 2022 and the results of the comprehensive sediment sampling that will occur as part of the IR pre-design investigation.

6 Conclusions

The LPRSA bioaccumulation model provides a reliable method for predicting concentrations of hydrophobic organic chemicals in biota tissue based on chemical concentrations in the water and sediment.

The model was calibrated using the available LPRSA empirical tissue data and the process outlined in Section 4. Calibrated model performance met the performance criteria outlined for this project. Although there are uncertainties associated with any model, consideration of these uncertainties relative to model calibration indicates that the bioaccumulation model is a reliable tool for estimating fish and invertebrate tissue concentrations.

The LPRSA bioaccumulation model is intended to be used to develop initial PRGs for the upper 9 miles of the LPRSA, pursuant to the Adaptive Management Approach (Appendix D) of the USEPA-approved *Upper 9-Mile Interim Remedy Feasibility Study* (Integral et al. 2021b).¹⁷ This study identified the IR alternative and adaptive management approach for the upper 9 miles of the LPRSA, as selected in the September 28, 2021, ROD signed by USEPA Administrator Regan.

As anticipated by the adaptive management approach (Integral et al. 2021a), there is uncertainty associated with some of the parameters and assumptions used in the LPRSA bioaccumulation model (see Section 5.3). As described in Section 5.1 of the adaptive management approach, the uncertainty in the initial PRGs will be characterized to highlight where opportunities may exist to reduce uncertainty associated with the bioaccumulation model, as well as to improve the subsequent review of and possible changes to ensure protective PRGs.

¹⁷ Future use of the bioaccumulation model may consider, at USEPA's direction (as appropriate), guidance on climate change (USEPA 2018, 2021).

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