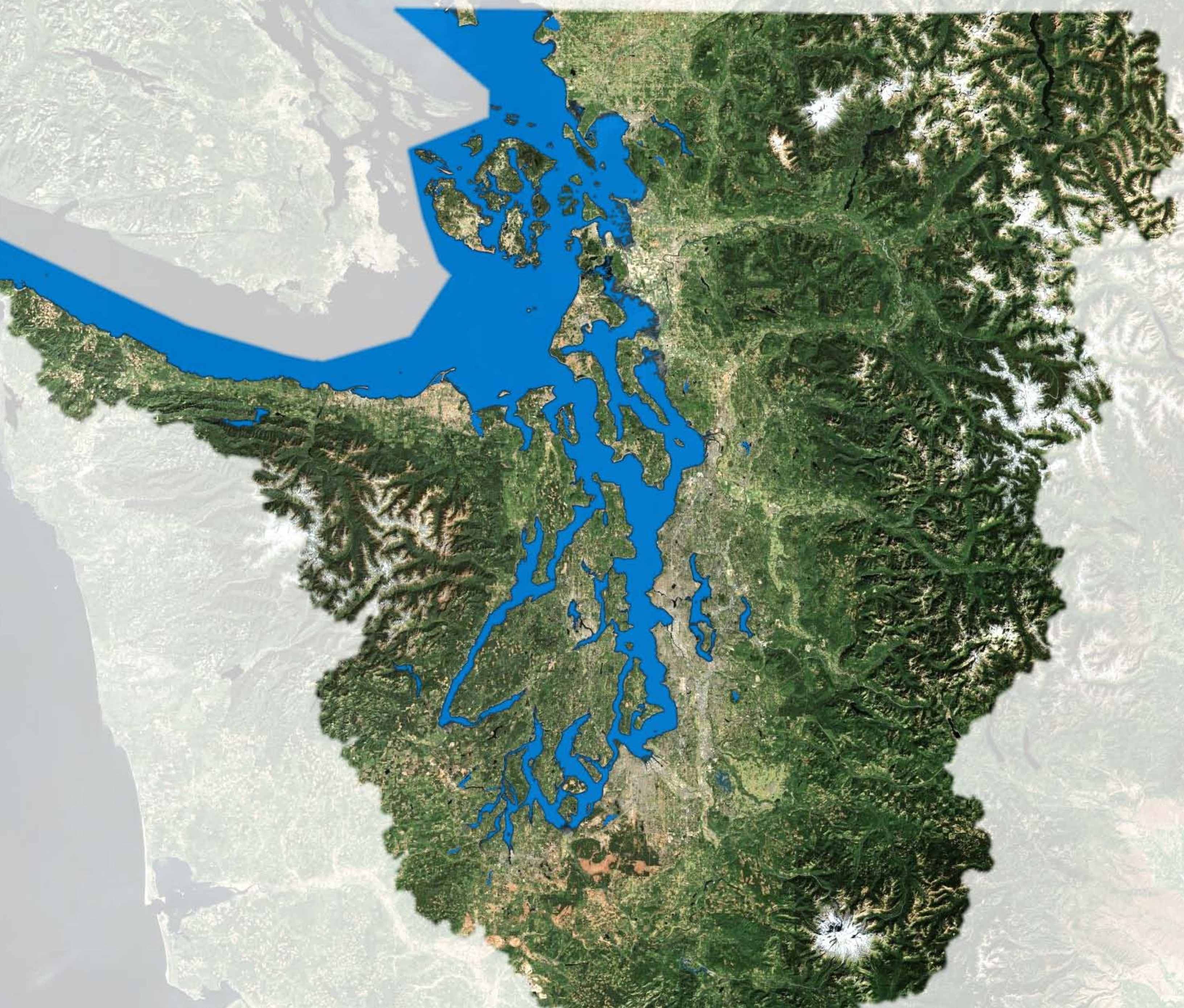

Control of Toxic Chemicals in Puget Sound

Phase 2: Sediment Flux/Puget Sound Sediments Bioaccumulation Model - Derived Concentrations for Toxics Final Summary Technical Report

DEPARTMENT OF ECOLOGY
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ecology and environment, inc.
International Specialists in the Environment

Control of
Toxic Chemicals in Puget Sound

Phase 2: Sediment Flux/Puget Sound Sediments Bioaccumulation Model – Derived Concentrations for Toxics
Final Summary Technical Report

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You can print or download this document from our website at:
http://www.ecy.wa.gov/programs/wq/pstoxics/index.html

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Acronyms

ABC	Aquatic Biogeochemical Cycling [Model]
ADDAMS	Automated Dredging and Disposal Alternatives Modeling System
BEHP	bis(2-ethylhexyl) phthalate
BFSD	Benthic Flux Sampling Device
BSAF	Biota Sediment Accumulation Factor
CEL	carcinogenic effect level
DOC	dissolved organic carbon
E & E	Ecology and Environment, Inc.
Ecology	Washington State Department of Ecology
ED50/EC50	effective dose/concentration (produces effect in 50% of population)
EFDC	Environmental Fluid Dynamic Code
ERED	Environmental Residue-Effects Database
HOBO	Hammersley Inlet Oakland Bay Oceanographic [Model]
HPAH	high molecular weight polycyclic aromatic hydrocarbon
LD50/LC50	lethal dose/concentration (lethal to 50% of subject population)
LOEL/LOEC	lowest observable effects level/concentration
LPAH	low molecular weight polycyclic aromatic hydrocarbon
MATC	maximum acceptable toxicant concentration
NCEL	non-carcinogenic effect level
NOEL/NOEC	no observable effects level/concentration
NPDES	National Pollutant Discharge Elimination System
PAH	polycyclic aromatic hydrocarbon
PBDE	polybrominated diphenyl ether
PCB	polychlorinated biphenyl
POTW	publicly owned treatment works
PSAMP	Puget Sound Assessment and Monitoring Program
PSDDA	Puget Sound Dredged Disposal Analysis
PSMEM-C	Puget Sound Marine Environmental Modeling Consortium
RSET	Regional Sediment Evaluation Team
SMS	Washington Sediment Management Standards 173-204 WAC
SOG	Strait of Georgia
SPASM	South Puget Sound Area Synthesis Model
SQS	Sediment Quality Standards criteria
SSFATE	Suspended Sediment Fate
TEQ	toxic equivalency quotient
TMDL	total maximum daily load
US EPA	United States Environmental Protection Agency
WASP	Water Quality Analysis Simulation Program
WDFW	Washington Department of Fish and Wildlife

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Executive Summary

"Control of Toxic Chemicals in Puget Sound" is a multi-phase project initiated by the Washington State Department of Ecology (Ecology) in cooperation with the Puget Sound Partnership. The goal of the project is to inform a source control strategy to reduce the loading of toxics into Puget Sound. To achieve this goal, Ecology has completed an initial investigation of toxics loading into Puget Sound titled "Initial Estimate of Loadings". While loading information is incomplete, the initial study helps identify gaps in Ecology's knowledge of which contaminants are entering the Sound and their sources and routes. To improve these initial loading estimates, Ecology will complete several tasks. One key task will be using the Puget Sound Box Model to elucidate how toxic chemicals move between water, marine sediment, and the wide variety of biological organisms in the Puget Sound ecosystem.

Ecology will use all the information gathered in this multi-phase project to implement controls on the sources of toxics to Puget Sound. The information from all components of the project will help Ecology prioritize actions and funding for the most urgent issues facing the Sound.

This report addresses bioaccumulation modeling for contaminants in sediment. Bioaccumulation refers to certain toxic compounds persisting within individual organisms and existing at greater concentrations in higher levels of the food web. For example, if small fish retain a toxic compound in their tissues rather than flushing it through their systems, then larger fish consuming many of these small fish over time will have much higher concentrations of the compound in their tissues.

Bioaccumulation modeling predicts the concentrations of toxic chemicals that will be present in organisms at various levels of the food web, given a particular concentration in Puget Sound sediments. The bioaccumulation model used here assumes what may be considered one kind of worst-case scenario; that the chemical concentrations allowed under Washington's Sediment Management Standards (SMS) Sediment Quality Standards (SQS) exist in Puget Sound sediments. Using those concentrations, the model shows how much of each chemical studied would accumulate in each type of organism. The model then compares these amounts with various criteria by which toxic effects to organisms are evaluated. The model results will provide more initial information to assist Ecology to determine whether the sediment standards are sufficient to protect human health and the marine life of Puget Sound from bioaccumulative contaminants.

The model used in this study is based on a bioaccumulation model developed by Condon in 2007. Condon's model evaluates PCB accumulation in biota of the Strait of Georgia, which is adjacent to Puget Sound and within the same major watershed. Modified to evaluate Puget Sound toxics, the model showed how several toxic compounds move (flux) from sediment to biota. The modified model also shows that toxic compounds flux differently depending on their concentrations and chemical properties. In some instances, the modified model indicates that concentrations of certain toxic compounds in sediment at the SQS levels would fail to protect human and wildlife receptors from bioaccumulative effects.

New criteria for regional and site-specific conditions are typically more stringent than older or more general criteria. These new criteria have yielded values for some SMS compounds that allow more accurate predictions of how sediment contaminant concentrations will affect the ecosystem. Using the new criteria, the modified bioaccumulation model predicts toxic effects to receptors in substantially more cases than were found when using older, more general criteria.

As with all modeling studies and in light of the uncertainties associated with the assumptions used in this particular study, judgment must be exercised when using modeling studies for regulatory or management decisions. All models make assumptions that may not perfectly match given conditions. For example, site conditions and surrounding land uses vary throughout Puget Sound; no single model can capture all possible ecological and physiochemical variations. This broad analysis is a useful first step in identifying problem areas and deficiencies in standards. Specialized models developed for specific locations or particular chemical classes will be better able to capture variability in the physical parameters and demographics crucial for defining exposure parameters. In addition, any model used should continue to be refined through comparison with empirically determined values.

1.0 Introduction

This report is one of several tools the Washington State Department of Ecology (Ecology) will use to help model toxic chemicals in Puget Sound as part of its multi-phase “Control of Toxic Chemicals in Puget Sound” project. The goal of the project is to restore the environmental health of Puget Sound. This final summary technical report presents the results from a bioaccumulation model that was identified and used to estimate the flux of toxics from marine sediment to biota. Sediment chemical concentrations used in the model equaled the current Washington Sediment Management Standards (SMS) Chapter 173-204 WAC Marine Sediment Quality Standards (SQS), except for metals which were not modeled (Table 1-1). The SMS is the “rule” and the SQS are one level of criteria within the SMS.

The goal of the SMS is to reduce or eliminate adverse effects on biological resources and significant threats to human health from surface sediment contamination. The rule establishes standards (SQS) for surface sediment quality, applies the standards to manage and reduce pollutant discharges, and provides a management and decision process for cleanup of contaminated sediments. The SMS rule provides multiple criteria used to identify surface sediments that have no adverse acute or chronic effects on biological resources and no significant risk to humans. This report focuses on one of those criteria, chemical concentrations in marine sediments.

The purposes of the bioaccumulation model study are to provide a first look at quantitatively describing the relationship between pollutant concentrations in sediment and biota and to provide a preliminary evaluation of whether SQS levels effectively protect marine life and human health from bioaccumulative effects. The evaluation compares concentrations the model predicts will be in water and organisms based on the SQS concentrations in sediments to various criteria that have been established based on toxicity and bioaccumulation effects on organisms. This will help Ecology determine whether the efficacy of the SMS for bioaccumulative effects to biota.

The “Control of Toxic Chemicals in Puget Sound” project has provided initial estimates of toxic loadings to Puget Sound (Phase 1). Those loading estimates are being improved in Phase 2 (this report is one part of Phase 2). Future work will target priority toxic sources for restorative action (Phase 3). There are multiple activities within the Phase 2 work. To help improve loading estimates, Ecology is upgrading a numerical box model for Puget Sound. The box model will help Ecology understand how toxic chemicals move within Puget Sound between water, marine sediment, and the wide variety of biological organisms in the Puget Sound ecosystem. This report focuses on one component of the box model: a bioaccumulation model that describes how toxics are transferred from sediment to biota in Puget Sound. The bioaccumulation model describes the movement of toxics up the food web via bioaccumulation (the increase of a toxic’s concentration in an organism above the concentration of that toxic in the environment) and biomagnification (the increase of a toxic’s concentration as it passes through successive levels of the food web).

Table 1-1. Washington Marine Sediment Quality Standards Chemical Criteria.

Chemical Parameter	Concentration *ppm dry*	Chemical Parameter	Concentration *ppb dry*
Arsenic*	57	Phenol	420
Cadmium*	5.1	2-Methylphenol	63
Chromium*	260	4-Methylphenol	670
Copper*	390	2,4-Dimethylphenol	29
Lead*	450	Pentachlorophenol	360
Mercury*	0.41	Benzyl Alcohol	57
Silver*	6.1	Bezoic Acid	650
Zinc*	410		
	ppm carbon		*ppm carbon*
LPAH	370	Dibenzo(a,h)anthracene	12
Naphthalene	99	Benzo(g,h,i)perylene	31
Acenaphthylene	66	1,2-Dichlorobenzene	2.3
Acenaphthene	16	1,4-Dichlorobenzene	3.1
Fluorene	23	1,2,4 Trichlorobenzene	0.81
Phenanthrene	100	Hexachlorobenzene	0.38
Anthracene	220	Dimethyl phthalate	53
2-Methylnaphthalene	38	Diethyl phthalate	61
HPAH	960	Di-N-Butyl phthalate	220
Fluoranthene	160	Butyl benzyl phthalate	4.9
Pyrene	1000	Bis (2-ethylhexyl) phthalate	47
Benz(a)anthracene	110	Di-N-Octyl phthalate	58
Chrysene	110	Dibezofuran	15
Total Bezofluoranthenes	230	Hexachlorobutadiene	3.9
Benzo(a)pyrene	99	N-Nitrosodiphenylamine	11
Indeno(1,2,3-CD)pyrene	34	Total PCBs	12

*** not modeled in this study (see Section 4); ppm = parts per million; ppb = parts per billion**

Bioaccumulation model outputs, which consist of predicted toxic concentrations in biota, are compared to measured levels of toxics in Puget Sound biota and to various criteria developed to protect biological resources and human health.

A brief summary of Ecology's "Control of Toxic Chemicals in Puget Sound" project and how this program fits within Washington State's Puget Sound Partnership is presented in Section 2. A conceptual model for bioaccumulation in Puget Sound and an explanation of how the model fits within Ecology's overall approach to modeling circulation, sediment flux, and bioaccumulation of toxics is presented in Section 3. Section 4 provides details on the bioaccumulation model chosen to represent the flux of toxics from sediment to biota and the food web in Puget Sound. Model-derived concentrations in biota are presented in Section 5. Section 6 compares the model-derived concentrations to measured concentration of toxics in Puget Sound biota and compares the model-derived concentrations in biota to various criteria designed to protect biota and humans. Study conclusions and discussion, including recommendations, are presented in Section 7.

The original scope of work for this bioaccumulation model study was to determine the flux of contaminants from sediment to water. As part of this original scope, E & E (1) reviewed readily available models that could be used to estimate the flux of toxics between marine sediment and water, and (2) identified sediment to water flux studies conducted in Puget Sound. Results of this work are presented in Appendices A and B, respectively, and summarized below.

Two sediment-water flux models, the Davis model, which describes the long-term fate of PCBs in San Francisco Bay, and the Water Quality Analysis Simulation Program (WASP), were identified as potential models to represent the flux of toxics from sediment to water in Puget Sound. However, neither model addresses bioaccumulation. Ecology's Puget Sound Box Model for Analysis and the Food Web can accommodate input from either of these two models. Between the Davis and WASP models, WASP offers the greatest flexibility. It also addresses some factors, such as flocculation, not addressed by the Davis model.

Qualitative and quantitative data exist on toxics in marine sediments and provide information on the nature and extent of contamination in Puget Sound sediments. However, very few empirical studies have been conducted in Puget Sound that measured the flux of toxics between the sediment and water.

Ecology expanded the original scope of work to include a screening-level study using a sediment to biota and food web model to estimate the levels of contamination that would be found in various biological receptors using chemical concentrations set at the current SQS levels. Modeled toxics concentrations in biota and higher trophic levels are compared to available measured toxic concentrations in the biota of Puget Sound and published toxicity data. These toxicity data establish "no observed adverse effects" levels, and help form the basis for Target Tissue Levels that are being developed for protection of human health and wildlife.

This report compares bioaccumulation model outputs to measured levels of toxic compounds in plankton and higher trophic levels. The report also compares model outputs to toxicity-based benchmarks. The comparison supports using the bioaccumulation model as one component of Ecology's Puget Sound Box Model for Analysis of Toxics and the Food Web because results provide a reasonable basis for evaluating the protectiveness of existing SQS values.

Ecology and Environment, Inc., (E & E) was tasked by Ecology under Contract: C0700036, Work Assignment No.: EANE014, Project: Toxics Loading Study Phase 2: Sediment Flux/Puget Sound Sediments to complete the study described above and prepare this report.

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2.0 Ecology's "Control of Toxic Chemicals in Puget Sound" Project

Ecology and other groups including the Puget Sound Partnership (PSP 2008a) are working toward the overall goal of restoring the environmental health of Puget Sound by 2020. This multi-year effort requires development of strategies, actions, and performance measures for restoring the Puget Sound ecosystem (Ecology 2008).

Objectives

Project objectives include:

- Identifying toxic chemicals of greatest ecological and human health concern for the Puget Sound marine ecosystem;
- Estimating loadings of key contaminants from major pathways to all or selected portions of the Puget Sound marine ecosystem;
- Describing the mass budget of toxic chemicals in the Puget Sound marine ecosystem, including characterizing toxic chemical loading, accumulation, and loss;
- Evaluating the potential for reductions in toxic chemical loadings for major pathways;
- Increasing understanding of the levels and sources of uncertainty in each phase of the characterization and evaluation;
- Developing recommendations for appropriate uses of results and suggestions for data presentation to assure clear communication of the uncertainties; and
- Preparing a strategy that identifies the actions, practices, and policies necessary to protect and restore the overall health of the Puget Sound ecosystem.

Phases

Ecology's Control of Toxic Chemicals in Puget Sound Project has three phases, which are described in the following subsections. The work completed by E & E and documented in this report is one component of one of the Phase 2 tasks. A more detailed explanation of the work is included within the description of Phase 2 below.

Phase 1 - Initial Estimate of Toxic Chemical Loadings to Puget Sound

Phase 1 of this project led to Ecology Publication No. 07-10-079, "Phase 1: Initial Estimate of Toxic Chemical Loadings to Puget Sound" (Ecology 2007). The Phase 1 study yielded estimates for the loadings of 17 chemicals (six metals, total polychlorinated biphenyls (PCBs), total polybrominated diphenyl ethers (PBDEs), carcinogenic polycyclic aromatic hydrocarbons (PAHs), other high molecular weight PAHs, low molecular weight PAHs, bis(2-ethylhexyl) phthalate (BEHP), total dioxin toxic equivalency quotient (TEQ), total DDT, Triclopyr, nonylphenol, and oil and other petroleum products) into the Puget Sound ecosystem. Sources included surface runoff, atmospheric deposition to the marine area of the watershed, some of the many permitted wastewater point source discharges, and direct spills to the watershed surface waters. Several pathways were not evaluated, including loading of contaminants to the marine sediments of Puget Sound and leaching of contaminants from marine sediments into the water column.

The report provided loadings for six hydrologic study units: Bellingham, Whidbey, Main, South Sound, Hood Canal, and Olympic Peninsula. The report acknowledged the high uncertainty of the loading estimates and recommended collection of additional data. Simple models were identified that could be used to evaluate toxic chemical loadings into the Puget Sound ecosystem.

Phase 2- Improve Loading Estimates

Phase 2 work builds on the initial Phase 1 investigation. Information will be gathered to better understand and quantify sources of toxic contaminants to Puget Sound and to improve understanding of toxics movement within the ecosystem. Combined Phase 1 and Phase 2 information is critical for determining the priorities for actions to reduce and, whenever possible, avoid toxics-based harm to the Puget Sound ecosystem.

Eight tasks have been identified for Phase 2:

A: Improve loading estimates from roadways;

B: Improve loading estimates for publicly owned treatment works (POTWs) and industries;

C: Improve loading estimates for sediments;

D: Identify and evaluate water column data for Puget Sound and its ocean boundary;

E: Conduct studies to support a human health risk assessment;

F: Upgrade a simple numeric model of Puget Sound;

G: Design a biological observing system (BIOS) for Puget Sound; and

H: Improve loading estimates for biota.

The work described in this report is one component of the task to upgrade a simple numeric model of Puget Sound (Task F). Ecology’s Environmental Assessment Program is overseeing this task. The overall goal of Task F is to expand the capabilities of an existing numerical model of Puget Sound. To support this goal, Ecology has developed the “Puget Sound Box Model for Analysis of Toxics and the Food Web”. This box model will be used to predict impacts of toxic contaminant loading on the concentrations of the toxics in Puget Sound water and biota. Sediment acts as a sink and a source for most contaminants that enter the marine system. Even if other sources were eliminated, sediment would continue to act as a source of contaminants to the water and biota of Puget Sound for decades. The bioaccumulation model described in this report is one component of the box model and describes the flux of toxics from sediment through the food web. This is described conceptually in Section 3, which begins by explaining how the bioaccumulation model fits into the box model. Ecology will use the box model to study circulation and the fate and transport of toxics within the entire Puget Sound ecosystem.

Phase 3- Targeting Priority Toxic Sources

Phase 3 continues Ecology's stewardship of Puget Sound with ongoing measurement and control of the sources of toxics to Puget Sound. Ecology will assign risks to toxics from specific sources, then select and implement actions to clean up and prevent contamination from sources that cause the highest risks to Puget Sound.

While the specific tasks identified below are currently part of Ecology's strategy to control toxic chemicals in Puget Sound, the results of the Phase 1 and Phase 2 studies may lead to modifications of some of the tasks:

A: Quantify toxics from roadways;

B: Quantify toxics from combined sewer overflow discharges;

C: Evaluate air deposition of fuel oil soot emissions from mobile sources;

D: Evaluate toxics exchange between Puget Sound and the Pacific Ocean; and

E: Refine the numeric model of toxics in Puget Sound, and evaluate pollution reduction scenarios.

Puget Sound Partnership

The Puget Sound Partnership (PSP 2008a) is a recently created state agency whose mandate is coordination and leadership of the effort to restore water quality in Puget Sound. One of the most significant early tasks of the Partnership is development of the "2020 Action Agenda" (PSP 2008b). The Agenda is required to include clear, measurable goals for the recovery of Puget Sound by 2020. Specifically, the Agenda will set goals, identify strategies, prioritize, and include both long- and near-term actions and plans for cleaning up Puget Sound. The Partnership has identified four initial strategic priorities:

A: Ensuring that activities and funding are focused on the most urgent and important problems facing the Sound;

B: Protecting the intact ecosystem processes that sustain Puget Sound;

C: Implementing restoration projects that will reestablish ecosystem processes; and

D: Preventing the sources of water pollution.

While the Partnership does not have regulatory authority, its mandate includes (1) identifying entities responsible for restoring Puget Sound (for example, Ecology) and (2) ensuring that these entities receive state funding for work identified in the 2020 Action Agenda. The Partnership must issue its 2020 Action Agenda by December 1, 2008.

3.0 Conceptual Model for Uptake and Bioaccumulation of Toxics from Sediment to Biota and the Food Web

As described in Section 2, the work presented in this report is a subpart of a much larger Ecology project. It is critical that the bioaccumulation model chosen for this study be compatible with Ecology's ongoing work under the Phase 2 Task F upgrade of a simple numerical model of Puget Sound. A conceptual model of bioaccumulation within Puget Sound was developed to ensure that the work completed under this study would be compatible with modeling studies being conducted by other groups working on Phase 2 tasks. This section briefly describes the overall context of Ecology's simple box model, the "Puget Sound Box Model for Analysis of Toxics and the Food Web," and provides background for the bioaccumulation model used in this study.

3.1 Ecology's Puget Sound Box Model for Analysis of Toxics and the Food Web

Ecology, Washington Department of Fish and Wildlife (WDFW), and groups such as the Puget Sound Marine Environmental Modeling Consortium (PSMEM-C) have worked with the Puget Sound Action Team and its successor, the Puget Sound Partnership, to monitor the condition of Puget Sound since 1990. Ongoing monitoring and research activities continue under the Puget Sound Assessment and Monitoring Program (PSAMP). This work includes considerable effort toward development of a Puget Sound Box Model for Analysis of Toxics and the Food Web (Pelletier 2008).

Ecology's Puget Sound Box Model for Analysis of Toxics and the Food Web includes:

- A box model for inter-basin circulation of water (Babson et al. 2006)
- A sediment flux model that addresses the kinetics of pollution fate and transport (Davis 2004) and
- A food web bioaccumulation model (Arnot and Gobas 2004; Condon 2007).

The box model includes seven basins within Puget Sound (South Hood Canal, North Hood Canal, Admiralty Inlet, Whidbey, Main Basin, Narrows, and South Sound) and three embayments (Commencement Bay, Elliot Bay, and Sinclair/Dyes Inlets). Each basin/embayment is divided vertically into an upper and lower water layer and a sediment layer. The box model currently addresses total PCBs. The food web bioaccumulation model is a general model for all Puget Sound that may be used to model smaller "boxes" by inputting site-specific parameters. The model was also adapted to include other toxics, as described in Section 4.

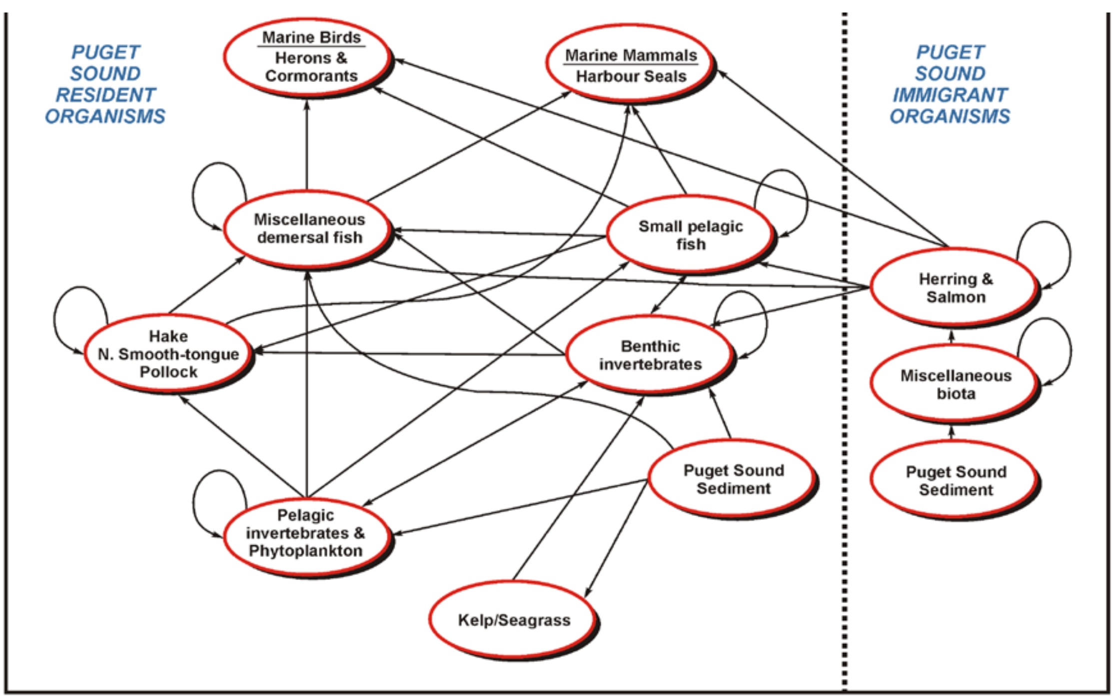
For more information related to the Puget Sound Box Model for Analysis of Toxics and the Food Web, visit Ecology's website at: http://www.ecy.wa.gov/programs/wq/pstoxics/index.html.

3.2 Food Web Bioaccumulation Conceptual Model

For this project, E & E and Ecology selected Condon's (2007) model to address uptake and bioaccumulation of toxics from sediment to biota and the food web. Condon's model evaluated PCB accumulation in Strait of Georgia biota. This model is appropriate for this study for several reasons, including:

- PCBs are reasonably representative of other persistent organic pollutants because like PCBs, their flux from sediment to biota is in large part governed by physiochemical properties and food web relationships
- The Strait of Georgia is adjacent to Puget Sound and within the same major watershed
- Toxic contaminants in both water bodies are similar
- Biota in both water bodies are similar
- Model performance has been evaluated and found reasonable, albeit against a very limited set of Strait of Georgia field data
- Model performance was also compared to similar models such as the Davis model used for San Francisco Bay, and the results were in good agreement
- This model has been peer reviewed by aquatic ecosystems modelers.

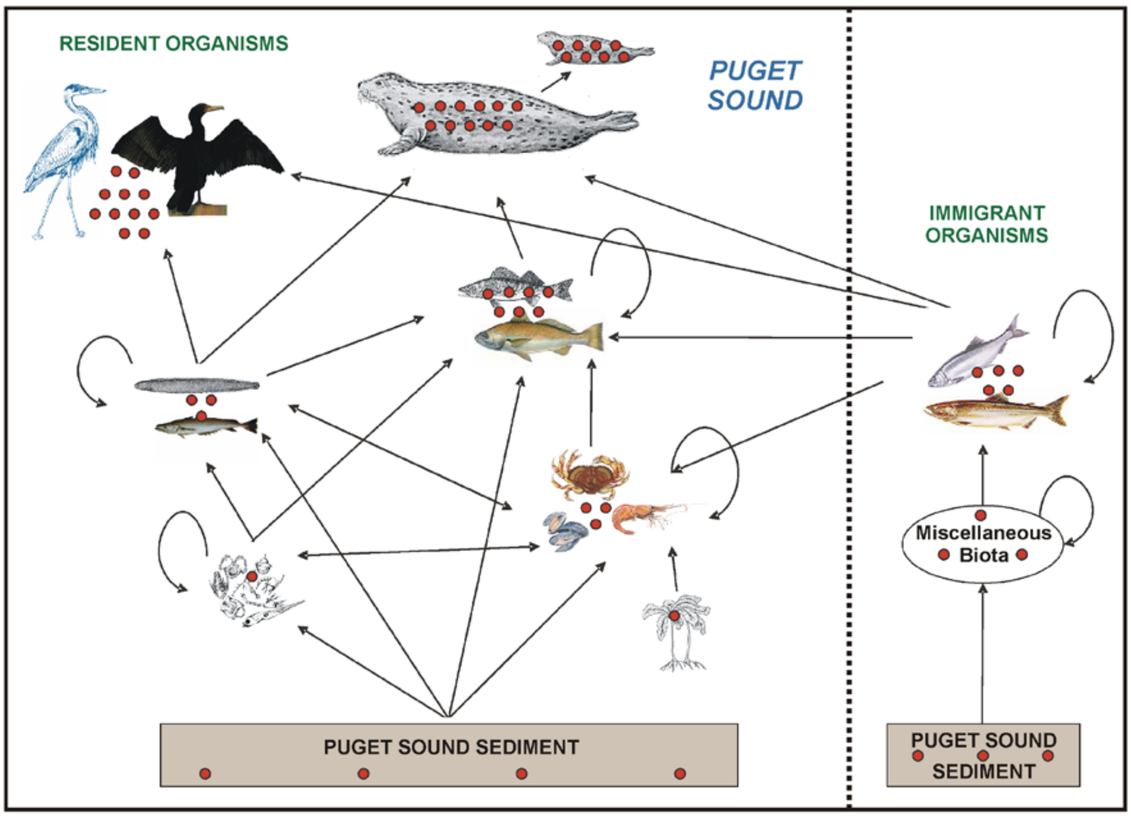
The conceptual bioaccumulation model presented in the following pages outlines the important components and processes of the sediment-biota food chain system and diagrams how these components and processes are connected. Graphical illustrations and text depict the marine sediment-biota food web. Figure 3-1 illustrates the connections between sediment and biota at various trophic levels. Arrows identify the movement of toxics up the food chain.



Source: Modified from Condon 2007.

Figure 3-1. Conceptual model of toxics transfer via the food chains in Puget Sound.

This conceptual model is more graphically illustrated below (Figure 3-2). The movement of toxics up the food web via bioaccumulation (the increase of a toxic's concentration in an organism above the concentration of that toxic in the environment) and biomagnification (the increase of a toxic's concentration as it passes through successive levels of the food chain) is represented by the increasing number of dots associated with each receptor illustrated in the conceptual model.

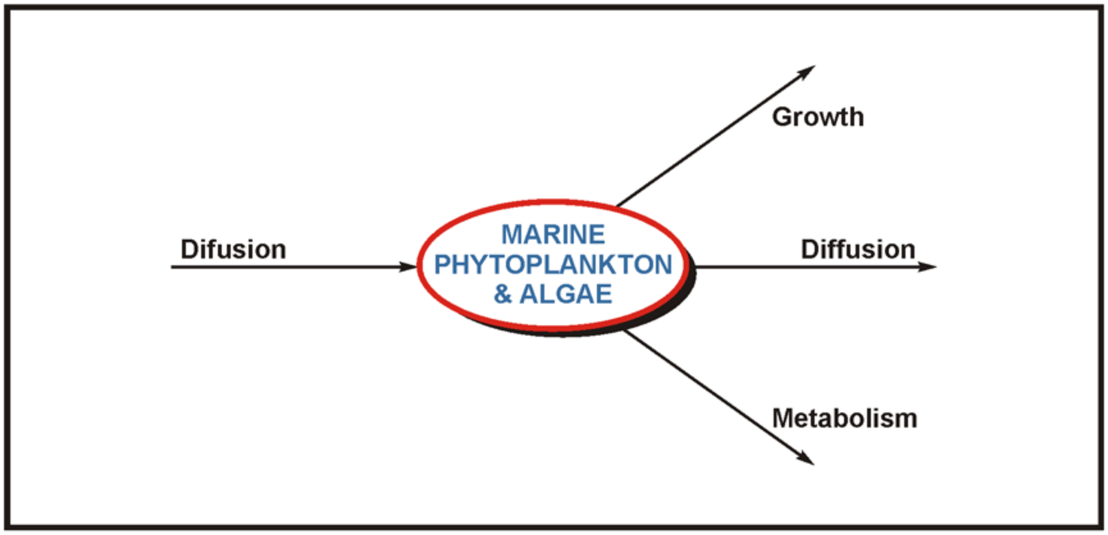


Source: Adapted from Condon REM 699 Presentation.

Figure 3-2. Accumulation of toxics from sediment by biota in Puget Sound.

One historical example of biomagnification made famous by Rachel Carson in her 1962 book Silent Spring is the accumulation of DDE, a breakdown product of the pesticide DDT, in birds. The United States Geological Service (USGS 2007) provides a teaching tool that presents the following detailed summary of how DDT impacts our ecosystem. Fresh water algae and plants have measured DDE levels on the order of 0.04 micrograms per gram (µg/g or parts per million [ppm]). Crayfish consume the plants and algae and accumulate DDE at concentrations ranging from 0.2 to 1.2 ug/g. DDE levels in the bass that consume these crayfish range from 1 to 2 ug/g. Osprey consume these bass and have measured levels of DDE that range from 3 to 76 ug/g. Osprey suffer total reproductive failure (eggshell thinning) when DDE concentrations equal or exceed 17.6 ug/g.

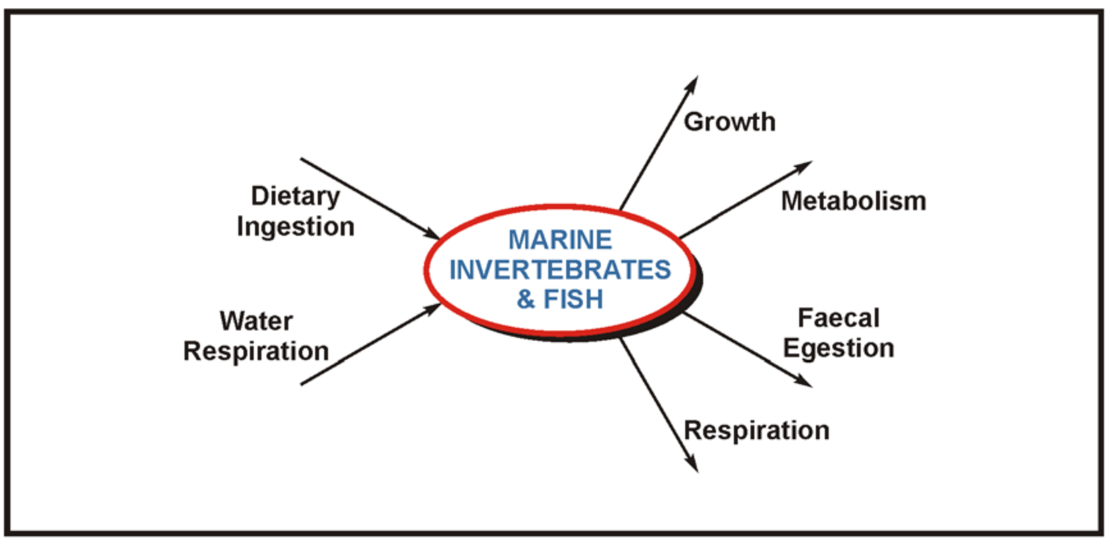
Figures 3-3 through 3-5 outline bioaccumulation to illustrate some of the complexities in modeling the flux of toxics from sediment to biota and the food chain. The figures provide a simplified picture of the balance between toxic uptake and loss, first for marine algae and phytoplankton, then for fish and invertebrates, and lastly for birds and seals.



Source: Adapted from Condon 2007.

Figure 3-3. Toxics uptake and loss pathways for marine phytoplankton and algae.

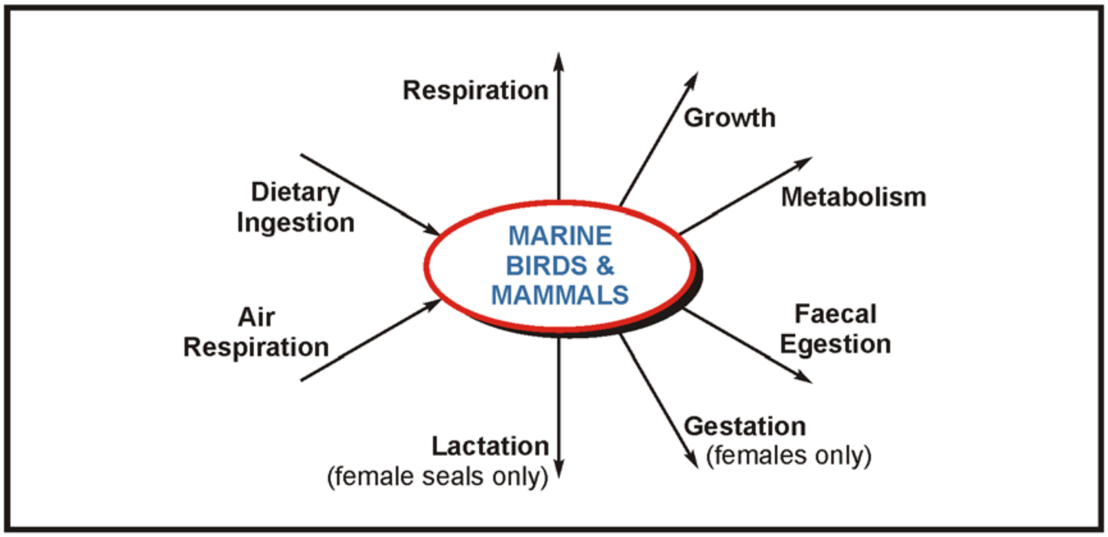
Toxic uptake and loss in phytoplankton and algae are illustrated above (Figure 3-3). Toxic concentrations in marine algae and phytoplankton are a function of the uptake (diffusion) versus loss (diffusion, metabolism, and growth). More properly, it is the rates of these processes that determine the toxic burden (concentration) that will be found in any living organism.



Source: Adapted from Condon 2007.

Figure 3-4. Toxics uptake and loss pathways for marine invertebrates and fish.

Toxic uptake and loss in invertebrates and fish are illustrated above (Figure 3-4). Toxic concentrations in marine invertebrates and fish are a function of the uptake (dietary ingestion and water respiration) versus loss (respiration, egestion, metabolism, and growth). As with plants, rates of these processes determine toxic burden. These rates vary diurnally, seasonally, spatially and over the life cycle of each organism, as well as by species, sex, and other factors such as diet.



Source: Adapted from Condon 2007.

Figure 3-5. Toxics uptake and loss pathways for marine birds and seals.

Toxic uptake and loss in birds and mammals are illustrated above (Figure 3-5). Toxic concentrations in marine birds and seals are a function of uptake (dietary ingestion and air respiration) versus loss (respiration, egestion, metabolism, growth, gestation (females only), and lactation (female seals only)). As with lower trophic levels, rates of these processes determine toxic burden. Again, these rates vary diurnally, seasonally, spatially and over the life cycle of each organism; as well as by species, sex, and other factors such as diet.

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4.0 Bioaccumulation Model

As noted previously in this report, bioaccumulation modeling is one component of Ecology's much broader Puget Sound Box Model. Bioavailability, uptake, and elimination are used to characterize the accumulation of toxics in marine biota and the food web. This section describes the model chosen and modified to estimate bioaccumulation of toxics from sediment to biota in Puget Sound and presents data on verification of the modified model (*note: verification was limited because of a lack of empirical data and appropriate field observations*).

4.1 Condon Bioaccumulation Model (2007)

Based on a review of applicable models and recommendations from Ecology, the Food Web Bioaccumulation Model developed by Condon (2007) was selected to address the flux of toxics from sediment to biota. The Condon (2007) model employs the well-established bioaccumulation equation that equates the rate of change in toxic concentration in an aquatic organism with the sum of the fluxes into and out of the organism. Fluxes include:

- Direct diffusion from water
- Uptake from feeding
- Uptake from respiration
- Loss due to metabolism
- Loss due to growth
- Loss due to diffusion
- Loss due to respiration
- Loss due to faecal egestion (excretion)
- Losses related to birth and nursing.

To predict bioaccumulation in a top predator, the bioaccumulation mass balance is repeatedly applied to biota in successive trophic levels to simulate the biomagnifications of toxics from sediment to primary producers (plants) to secondary producers (herbivores) to forage species (carnivores and omnivores) to top predators (seals or marine birds).

Bioaccumulation Model Modifications and Assumptions

Condon's original model used a series of equations to estimate bioaccumulation of PCBs in the marine food web of the Strait of Georgia (SOG), which forms the northern border of Puget Sound. E & E modified the original model to predict bioaccumulation of the non-PCB compounds outlined in the SMS (Table 1-1). SMS metals are not included in this exercise because empirically measured chemical characteristics needed as input data are not available (see octanol-water (Kow) & octanol-air (Koa) coefficients discussion below). Modifications to Condon's original model mostly consist of code changes for reading input worksheets and other changes as noted in this document. Bioaccumulation and environmental partitioning (air and water) equations are unaltered. Unless otherwise noted, the modified bioaccumulation model retains all the assumptions of Condon's model (e.g., steady state concentrations). Implicit in these assumptions is that the modified bioaccumulation model works equally well for all SMS compounds, even though the chemical properties for these compounds can vary substantially (e.g., Kow values at 9.5°C span seven orders of magnitude). This assumption has not yet been tested and could produce inaccurate results. Model validation for additional chemical classes should be performed in the future. Bioaccumulation and environmental partitioning equations, model assumptions not discussed in this document, environmental physiochemical properties and biota physiochemical properties (Appendix C) are fully documented in Condon (2007).

Food Web

The modified bioaccumulation model uses the same food web as Condon's, which was developed for the Strait of Georgia based on empirical data. However, in Condon's model, PCB concentration data were input (not predicted) for herring and salmon (chum, Coho and Chinook) because these fishes are migrants and tend to feed mostly in the open ocean. Because empirical data were not available for each SMS compound for each species, the modified bioaccumulation model assumes a closed system for Puget Sound (herring and salmon are treated as if they feed only in Puget Sound) and predicts concentrations for all the species in the food web. This was accomplished by modifying Condon's original code by removing command lines directing the model to use input concentrations and adding lines directing the model to read the diet matrix below (Table 4-1) and calculate biota concentrations using the same methods as for other species. The closed system assumption is conservative because concentrations of SMS compounds are likely to be lower in the open ocean than in Puget Sound so concentrations for these species and for those in higher trophic levels feeding on these species are more likely to be over- than under-predicted. The extent to which the closed system assumption causes over and/or under predictions is unknown because appropriate empirical data needed for comparisons are not available.

Treating Puget Sound as a closed system necessitates formulating dietary composition values for herring and salmon. This is a somewhat subjective process given differences among populations and age classes and the requirement that herring and salmon prey consist of organisms contained in the SOG food web. Based on selected research (James & Unwin 1996; Pauly & Christensen 1996; Schweigert et al. 2007; Zacolokin et al. 2007) and best professional judgment, the following diet compositions are assumed (Table 4-1).

Table 4-1. Herring and salmon prey compositions used in the modified bioaccumulation model food web.

Herring Prey Composition		**Salmon Prey Composition**	
prey	*% of diet*	*prey*	*% of diet*
Herbivorous zooplankton	10	Euphausiids	25
N. plumchrus	10	Herring	45
P. minutus	10	Small pelagic fish	30
Carnivorous zooplankton	10		
Euphausiids	50		
Predatory invertebrates	5		
Small pelagic fish	5		

Octanol-Water (Kow) & Octanol-Air (Koa) Coefficients

E & E conducted extensive literature reviews to determine Kow and Koa values for each of the contaminants listed in the SMS. These values (Table 4-2) are used as model inputs and are important variables for deriving water, air, and tissue contaminant concentrations from sediment data. E & E estimated Kow and Koa values based on research and data from multiple sources (Bahadur et al. 1997; Lei et al. 2000; Wania et al. 2002; Mackay et al. 2006; Odabasi et al. 2006).

Determination of Kow and Koa was hindered because literature values for these coefficients vary greatly, values are not available for all compounds, and for most compounds there has been very little research on the dependence of these coefficients on temperature (however, the general conclusion is that the variability of Kow/Koa coefficients over the range of temperatures found in the environment is small). Much of the available research on Kow and Koa relationships is based on gas chromatography retention times and values are calculated using an empirically determined energy of phase transfer for octanol to water and octanol to air. E & E used these calculations to determine Kow and Koa values at 9.5 and 37.5^{o}C. In some cases (for example, 2-methyl naphthalene), the energy of phase transfer was not available in the literature. In such instances, E & E assumed a value based on molecular weight and the relationship between Kow and Koa for compounds where both Kow and Koa are known. Note, however, that there appear to be no studies that address the relationship of Kow and Koa for polar compounds. For the purposes of this modeling exercise, E & E assumes those relationships would be the same as for non-polar compounds, but has no mechanism to test this assumption. It is unlikely that this assumption would hold true in practice. Therefore, model results based on true Kow and Koa values would likely vary from the ones presented in this study. There are no available Kow/Koa data for metals and thus there is no basis for assumptions that would allow use of the metals in this model exercise.

An additional drawback is that the SQS criteria include three general compound categories (total PCBs, low molecular weight polycyclic aromatic hydrocarbons (LPAHs), and high molecular weight polycyclic aromatic hydrocarbons (HPAHs)), but Kow and Koa are metrics of single compounds and not of composite groups. To predict total PCBs, LPAHs, and HPAHs, we used the median value of molecular weights, Kows, and Koas for compounds within each group as model inputs.

Table 4-2. Log Kow and Koa coefficients used in the modified bioaccumulation model.

	log Kow		log Koa		Kow / Koa estimation
	9.5°C	37.5°C	10.3°C	37.5°C	method
LPAH	4.13	3.76	6.03	6.61	3
Naphthalene	3.35	3.05	4.85	5.13	1
Acenaphthylene	3.87	3.52	6.03	6.61	1
Acenaphthene	4.13	3.76	6.00	6.57	1
Fluorene	4.41	4.01	6.46	7.07	1
Phenanthrene	4.70	4.28	7.15	7.84	1
Anthracene	4.69	4.27	7.18	7.87	1
2-Methylnaphthalene	4.07	3.70	3.86	4.07	2
HPAH	6.11	5.56	10.64	10.84	3
Fluoranthene	5.44	4.95	8.19	8.97	1
Pyrene	5.15	4.68	8.32	9.12	1
Benz(a)anthracene	6.11	5.56	9.03	9.90	1
Chrysene	6.10	5.55	9.89	10.84	1
Total Bezofluoranthenes	6.10	5.55	10.64	11.66	1
Benzo(a)pyrene	6.30	5.73	12.54	10.82	1
Indeno(1,2,3-CD)pyrene	7.09	6.45	11.81	12.94	1
Dibenzo(a,h)anthracene	6.86	6.24	13.66	11.78	1
Benzo(g,h,i)perylene	6.99	6.36	13.61	11.75	1
1,2-Dichlorobenzene	3.35	3.05	4.12	4.51	1
1,4-Dichlorobenzene	3.63	3.30	3.97	4.36	1
1,2,4 Trichlorobenzene	4.24	3.86	4.60	5.04	1
Hexachlorobenzene	6.04	5.50	7.02	7.69	1
Dimethyl phthalate	1.65	1.50	6.66	7.30	1
Diethyl phthalate	4.40	4.55	7.18	7.87	1
Di-N-Butyl phthalate	4.98	4.53	8.12	8.90	1
Butyl benzyl phthalate	4.84	4.41	8.35	9.15	1
Bis (2-ethylhexyl) phthalate	8.31	7.56	10.01	10.97	1
Di-N-Octyl phthalate	8.50	7.74	10.01	10.97	1
Dibezofuran	4.35	3.95	4.12	4.35	2
Hexachlorobutadiene	5.04	4.59	4.78	5.04	2
N-Nitrosodiphenylamine	3.30	3.00	3.13	3.30	2
Total PCBs	6.52	6.41	9.87	8.58	3
Phenol	1.55	1.42	1.46	1.54	2
2-Methylphenol	2.17	2.05	1.95	2.06	2
4-Methylphenol	2.42	2.10	1.94	2.05	2
2,4-Dimethylphenol	2.43	2.21	2.30	2.43	2
Pentachlorophenol	3.27	2.32	5.12	5.40	2
Benzyl Alcohol	2.57	2.59	1.10	1.16	2
Bezoic Acid	1.76	1.39	1.87	1.97	2

Estimation methods: 1 – literature based; 2 – assumed value based on molecular weight and Kow / Koa relationship; 3 – assumed value using the median value for the compound class (group). See text for full details.

Metabolic Transformation Rates (Km)

Condon's (2007) model assumed PCB Km rates of zero for SOG lower trophic levels (through fish) and used derived rates of metabolic elimination for birds and seals. However, many other toxics are substantially metabolized even at lower trophic levels; therefore, metabolism is an important elimination pathway. Stevenson (2003) examined the effect of metabolism on PAH bioaccumulation in a marine food web and found that including a metabolic factor increased the precision of the model when compared to empirical data. Additionally, Stevenson used intermediate Km values from reported ranges, applied them to trophic levels (increasing with increasing trophic level), and concluded that individual PAH-specific values were not needed (accurate results compared to empirical data were obtained without use of PAH-specific values). As such, the modified bioaccumulation model uses Stevenson's PAH Km values. For most other SMS compounds, there is very little published research relating to metabolic transformation rates. Based on the chemical properties of phthalates and phenols in relation to PAHs as well as on prior research on and discussion of phenols (Call 1980; Environment Canada 2000) and phthalates (Gobas et al. 2002; Mackintosh et al. 2004), the modified bioaccumulation model uses PAH Km values for all phenol and phthalate compounds. For total PCBs, the mean value for all PCB congeners for which Condon was able to estimate metabolic elimination is used. For all other compounds, literature is not readily available to either determine Km values or infer reasonable assumptions; therefore, these Km values are conservatively assumed to be zero.

The Condon food web and the Stevenson food web are not identical; the Dungeness crab occupies the top trophic level in the Stevenson model. To determine Km values for the modified bioaccumulation model, organisms or organism groups were assigned the most appropriate category available in the Stevenson model (Table 4-3). If a group from the Condon food web could be described by more than one of the general categories from Stevenson (2003), the group was assigned the lower Km value (conservative approach). Likewise, because Km values for PAHs in the Stevenson model generally increased with increasing trophic level, all fish and higher organisms in the modified bioaccumulation model were assigned the greatest Km value from the Stevenson model (fish: Km=2). This is a conservative assumption because higher vertebrates are known to more readily metabolize PAHs.

Table 4-3. Km values and organism groupings.

4.2 Bioaccumulation Model Verification

It was necessary to ensure that there were no errors resulting from the code changes applied to the modified bioaccumulation model. To verify model agreement, PCB data (congeners 8 & 15) from Condon's model were used as inputs in the modified bioaccumulation model and the outputs from both models were compared (Table 4-4). Model outputs agreed for all the lowest trophic levels, but predicted concentrations differ for many of the higher trophic levels. This difference is expected because, while Condon's model *input* tissue PCB concentration data for herring and salmon fishes, the modified bioaccumulation model *predicts* PCB concentrations for these fishes based on sediment concentrations, physiochemical properties, and food web relationships (see previous food web discussion). Therefore, PCB concentrations for these species differ between the two models, as do PCB concentrations for organisms feeding on herring and salmon. For those organisms feeding on these species, the degree to which PCB concentrations differ between the models is dependent on the amount of herring and salmon in their diets. For example, substantial differences are observed for river lamprey, whose diet is largely comprised of herring and salmon (79.5%), and relatively small differences are observed for hake, whose diet is mainly devoid of these fishes (0.3%). These effects are expected to hold true for all contaminants as a result of treating the Puget Sound as a closed system and, as a general rule, will be exacerbated as contaminant levels in herring's and salmon's home ranges differ from Puget Sound contaminant levels.

Condon's and the modified bioaccumulation model may also be used to determine Biota Sediment Accumulation Factors (BSAFs), which in the simplest form can be described as the ratio of a given contaminant concentration in an organism to its concentration in the sediment. Specifically, BSAFs characterize bioavailability and the potential for bioaccumulation but only reliably so for non-polar organic compounds. Typically non-logged values greater than one are considered potentially problematic for BSAFs normalized for lipid and organic carbon content. BSAFs are species- and chemical-specific and in theory can be considered independent of location, assuming sediment and tissue contaminant concentrations are accurately measured or predicted. In practice, however, BSAFs do vary both spatially and temporally, sometimes by orders of magnitude. This variation is the result of factors associated with the age and sex of organisms sampled, physiological differences related to time of year and reproductive state, movement in and out of contaminated areas by sample organisms, residence time of the organisms in relation to exposure time of the sediment to the contaminants, and physical properties of the environment including sediment grain size and organic material type. Despite this variation, reliable ranges of organisms/chemical-specific BSAFs are known.

SQS values were input (see Model Prediction section below) into the modified bioaccumulation model to determine whether the model accurately predicts BSAFs. Resulting log BSAF values (Table 4-5) are compared to values summarized in Stevenson (2003) for Dungeness crabs and The United States Army Corp of Engineers (USACE) BSAF database (http://el.erdc.usace.army.mil/bsaf/bsaf.html) for *Macoma* species. Such comparisons implicitly assume that BSAFs are independent of sediment concentrations and other factors (see above paragraph). In general there is good agreement between modeled BSAF values and observed values, with most of the modified model's predictions falling within or near the reported ranges and none falling outside reported ranges by more than a factor of two. The similarity between predicted and observed BSAF ranges suggests that the modified bioaccumulation model's assumptions, calculations, and resulting concentration predictions are reasonable. Otherwise, faulty assumptions and or calculation errors would have resulted in predicted tissue concentrations that would have skewed BSAF estimates either too high (high tissue concentrations in relation to sediment concentrations) or too low. Note that the modified bioaccumulation model groups all shellfish and all crabs in its predictions and we would expect even greater resolution had the model's food web consisted of Dungeness crabs and *Macoma* species separately.

Table 4-4. Predicted concentrations of PCB congeners 8 and 15 for Condon's original bioaccumulation model and the modified bioaccumulation model.

Shaded cells indicate differences between the models (see previous text). Concentrations are ppb.

	PCB 8		PCB 15	
	Condon	*modified*	*Condon*	*modified*
Sediment	3.6E-02	3.6E-02	1.3E-01	1.3E-01
Water	3.1E-07	3.1E-07	6.5E-07	6.5E-07
Air	1.5E-09	1.5E-09	6.9E-10	6.9E-10
Phytoplankton	8.0E-05	8.0E-05	2.8E-04	2.8E-04
Kelp / Seagrass	1.5E-03	1.5E-03	5.3E-03	5.3E-03
Herbivorous zooplankton	4.8E-03	4.8E-03	2.1E-02	2.1E-02
N. plumchrus	1.3E-02	1.3E-02	5.6E-02	5.6E-02
P. minutus	4.8E-03	4.8E-03	2.1E-02	2.1E-02
Shellfish	1.4E-02	1.4E-02	5.0E-02	5.0E-02
Crabs	5.1E-02	5.1E-02	2.3E-01	2.3E-01
Grazing invertebrates	2.2E-02	2.2E-02	9.0E-02	9.0E-02
Carnivorous zooplankton	1.0E-02	1.0E-02	3.8E-02	3.8E-02
E. pacifica	5.5E-03	5.5E-03	2.0E-02	2.0E-02
Predatory invertebrates	3.9E-02	3.9E-02	1.8E-01	1.8E-01
Herring	9.7E-03	1.3E-02	2.2E-03	7.3E-02
Pelagic fish (seal prey)	1.3E-02	1.3E-02	7.6E-02	7.8E-02
Pelagic fish (bird prey)	4.8E-03	4.8E-03	2.6E-02	2.7E-02
River lamprey	2.7E-02	3.8E-02	7.2E-02	2.9E-01
Demersal fish (seal prey)	2.0E-02	2.0E-02	1.0E-01	1.1E-01
Demersal fish (bird prey)	9.7E-03	9.7E-03	4.6E-02	4.6E-02
Chum	2.2E-03	2.4E-02	7.7E-04	1.7E-01
Coho	8.9E-03	3.0E-02	1.5E-03	2.0E-01
Chinook	8.0E-03	2.6E-02	0.0E+00	1.8E-01
Hake	1.6E-02	1.6E-02	8.2E-02	8.4E-02
Dogfish	7.4E-02	8.9E-02	4.0E-01	5.9E-01
Pollock	7.0E-03	7.1E-03	3.7E-02	4.0E-02
Northern smoothtongue	4.6E-03	4.6E-03	3.0E-02	3.1E-02
English sole	2.9E-02	2.9E-02	1.8E-01	1.8E-01
Cormorant (adult male)	2.4E-01	2.4E-01	1.3E+00	1.4E+00
Cormorant (adult female)	2.4E-01	2.4E-01	1.3E+00	1.4E+00
Heron (adult male)	2.1E-01	2.1E-01	1.3E+00	1.3E+00
Heron (adult female)	2.0E-01	2.0E-01	1.2E+00	1.3E+00
Seal (adult male)	4.3E-02	4.7E-02	1.5E-02	2.0E-02
Seal (adult female)	5.2E-02	5.7E-02	2.3E-02	3.1E-02
Seal (juvenile)	4.3E-02	4.8E-02	1.7E-02	2.3E-02
Seal (pup)	1.9E-01	2.1E-01	1.3E-02	1.8E-02
Cormorant egg	1.4E-01	1.5E-01	8.0E-01	8.3E-01
Heron egg	1.6E-01	1.6E-01	1.0E+00	1.0E+00

ppb = parts per billion

Table 4-5.Log BSAF statistics for Dungeness crabs and *Macoma* species and modified bioaccumulation model predictions for all crab and shellfish species.

Dungeness crab data were summarized in Stevenson 2003. *Macoma* data are from USACE's BSAF database and were only included for those compounds having three or more records. Shaded cells indicate the modified bioaccumulation model-predicted BSAFs that fall outside observed ranges.

Chemical	**Dungeness crabs**			**All crabs**
	mean	*min*	*max*	*model*
Anthracene	-2.76	-4.31	-0.66	-1.51
Benz(a)anthracene	-3.99	-6.25	-1.75	-2.14
Benzo(a)pyrene	-4.24	-6.20	-2.69	-2.17
Chrysene	-3.61	-5.54	-1.10	-2.14
Fluoranthene	-3.43	-4.90	-1.27	-1.96
Phenanthrene	-3.47	-5.30	-1.26	-1.51
Pyrene	-3.61	-4.95	-1.49	-1.82
	Macoma species			**Shellfish**
	mean	*min*	*max*	*model*
Benz(a)anthracene	-0.63	-1.59	-0.21	-1.47
Benzo(g,h,i)perylene	-1.70	-1.96	-1.46	-2.01
Benzo(a)pyrene	-0.71	-1.82	-0.07	-1.61
Chrysene	-0.55	-1.60	-0.21	-1.46
Fluoranthene	-0.06	-2.05	0.58	-0.97
Hexachlorobenzene	0.23	-0.16	0.40	-0.34
Indeno(1,2,3-CD)pyrene	-1.77	-2.15	-1.60	-2.07
Naphthalene	-0.39	-1.46	0.03	-0.42
Phenanthrene	-1.15	-1.40	-0.94	-0.58
Pyrene	-0.52	-1.70	-0.28	-0.78

BSAF = biota-sediment accumulation factor
min = minimum
max = maximum
Model-predicted BSAF values presented as ng/g wet wt in biota per ng/g dry wt in sediment
Observed BSAF values are unitless (USACE) and unknown (Stevenson)
USACE = United States Army Corps of Engineers

5.0 Modified Bioaccumulation Model Predictions

The modified bioaccumulation model was used to estimate the levels of contamination in various biological receptors using sediment toxics concentrations set at concentrations equal to the current Washington Sediment Management Standards Chapter 173-204 WAC (SMS), Marine Sediment Quality Standards (SQS). The purpose is to evaluate whether SQS levels effectively protect marine life and human health. The evaluation compares model predicted concentrations in water and organisms based on the SQS amounts in sediments to various criteria that have been established based on toxicity and bioaccumulation effects on organisms. This will allow Ecology to determine whether SQS levels result in water and tissue contaminant concentrations that fall below exposure thresholds established by these various criteria.

SQS data as input

Condon's original model used dry sediment weight (ppb or equivalent) as input data. The SQS concentration data for all compounds except the phenols, benzyl alcohol, and benzoic acid were presented as mg/kg organic carbon. These compounds were converted to dry sediment weight by multiplying the SQS organic carbon concentrations by the organic content (percentage) of the sediment. Following Condon's original model, we assumed a sediment organic carbon content of 2.69% and converted SQS values from ppm to ppb. For example, the SQS concentration for phenanthrene was 100 mg/kg organic carbon and after conversion was input as 2690 ppb (100 x 0.0269 x 1000). The converted SQS values were then used as input data to allow the modified bioaccumulation model to predict tissue concentrations and BSAFs for all organisms in the food web.

Bioaccumulation Model Output

Model-predicted chemical concentrations and BSAFs for PAHs (Table 5-1), phthalates (Table 5-2), phenols (Table 5-3), chlorinated benzenes (Table 5-4), and other miscellaneous chemical compounds (Table 5-5) listed in the SQS are found on the following pages. Environmental (air, water, and sediment) and biota concentrations are presented as ppb or equivalent (biota and sediment, ng/g; air and water, ng/ml). Though treated as unitless for the purposes of this study, BSAFs produced by both Condon's and the modified bioaccumulation model are not technically unitless because tissue concentrations were wet weight and sediment concentrations were dry weight. Likewise, as the modified bioaccumulation model uses Condon's method of calculating BSAFs, these values have not been carbon and lipid normalized.

To demonstrate the range of predicted bioaccumulation potentials using a standardized scale, model-predicted BSAFs were log transformed and plotted (Figure 5-1) for hexachlorobenzene, a contaminant known to bioaccumulate, and fluorene, a contaminant not known for its bioaccumulation potential. Because these are logged values, negative log-BSAFs indicate BSAFs less than one (not likely to bioaccumulate) and positive log-BSAFs are BSAFs greater than one (more likely to bioaccumulate).

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Table 5-1. Modified bioaccumulation model-predicted PAH concentrations and BSAFs.

	LPAH		Naphthalene		Acenaphthylene		Acenaphthene		Fluorene	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	9.95E+03		2.66E+03		1.78E+03		4.30E+02		6.19E+02	
Water	1.09E+00		1.85E+00		3.60E-01		4.73E-02		3.48E-02	
Air	1.87E-02		7.59E-02		3.34E-03		8.68E-04		4.33E-04	
Phytoplankton	2.34E+01	2.35E-03	7.80E+00	2.93E-03	4.33E+00	2.44E-03	1.01E+00	2.35E-03	1.42E+00	2.29E-03
Kelp / Seagrass	4.45E+02	4.47E-02	1.21E+02	4.53E-02	7.96E+01	4.48E-02	1.92E+01	4.47E-02	2.75E+01	4.45E-02
Herbivorous zooplankton	9.26E+02	9.31E-02	2.43E+02	9.12E-02	1.63E+02	9.19E-02	4.01E+01	9.31E-02	5.92E+01	9.57E-02
N. plumchrus	2.38E+03	2.39E-01	6.65E+02	2.50E-01	4.34E+02	2.45E-01	1.03E+02	2.39E-01	1.42E+02	2.29E-01
P. minutus	9.26E+02	9.30E-02	2.43E+02	9.12E-02	1.63E+02	9.19E-02	4.00E+01	9.30E-02	5.91E+01	9.56E-02
Shellfish	3.42E+03	3.43E-01	1.02E+03	3.83E-01	6.43E+02	3.62E-01	1.48E+02	3.43E-01	1.92E+02	3.11E-01
Crabs	9.01E+02	9.05E-02	8.83E+02	3.32E-01	2.61E+02	1.47E-01	3.90E+01	9.05E-02	3.24E+01	5.24E-02
Grazing invertebrates	2.52E+03	2.53E-01	1.06E+03	3.99E-01	5.57E+02	3.14E-01	1.09E+02	2.53E-01	1.13E+02	1.83E-01
Carnivorous zooplankton	2.74E+03	2.75E-01	7.44E+02	2.79E-01	4.91E+02	2.77E-01	1.18E+02	2.75E-01	1.69E+02	2.72E-01
E. pacifica	1.34E+03	1.35E-01	3.82E+02	1.44E-01	2.47E+02	1.39E-01	5.81E+01	1.35E-01	7.91E+01	1.28E-01
Predatory invertebrates	1.53E+03	1.54E-01	1.01E+03	3.80E-01	3.97E+02	2.24E-01	6.63E+01	1.54E-01	6.04E+01	9.76E-02
Herring	1.50E+02	1.50E-02	1.39E+02	5.23E-02	4.23E+01	2.38E-02	6.47E+00	1.50E-02	5.59E+00	9.04E-03
Pelagic fish (seal prey)	1.61E+02	1.62E-02	1.32E+02	4.97E-02	4.40E+01	2.48E-02	6.97E+00	1.62E-02	6.20E+00	1.00E-02
Pelagic fish (bird prey)	2.18E+02	2.19E-02	1.02E+02	3.84E-02	5.02E+01	2.83E-02	9.44E+00	2.19E-02	9.57E+00	1.55E-02
River lamprey	2.25E+02	2.26E-02	2.57E+02	9.66E-02	6.87E+01	3.87E-02	9.71E+00	2.26E-02	7.47E+00	1.21E-02
Demersal fish (seal prey)	3.16E+02	3.17E-02	2.86E+02	1.07E-01	8.94E+01	5.04E-02	1.37E+01	3.17E-02	1.16E+01	1.87E-02
Demersal fish (bird prey)	7.06E+02	7.10E-02	3.49E+02	1.31E-01	1.67E+02	9.39E-02	3.05E+01	7.10E-02	2.96E+01	4.79E-02
Chum	3.64E+01	3.66E-03	4.84E+01	1.82E-02	1.12E+01	6.33E-03	1.58E+00	3.66E-03	1.26E+00	2.03E-03
Coho	3.82E+01	3.84E-03	5.20E+01	1.95E-02	1.18E+01	6.67E-03	1.65E+00	3.84E-03	1.31E+00	2.12E-03
Chinook	3.76E+01	3.77E-03	5.04E+01	1.89E-02	1.16E+01	6.54E-03	1.62E+00	3.77E-03	1.29E+00	2.09E-03
Hake	4.43E+02	4.45E-02	2.45E+02	9.19E-02	1.09E+02	6.16E-02	1.91E+01	4.45E-02	1.76E+01	2.84E-02
Dogfish	5.44E+01	5.47E-03	6.80E+01	2.55E-02	1.62E+01	9.12E-03	2.35E+00	5.47E-03	1.97E+00	3.18E-03
Pollock	1.23E+02	1.24E-02	9.31E+01	3.50E-02	3.31E+01	1.86E-02	5.33E+00	1.24E-02	4.77E+00	7.70E-03
Northern smoothtongue	2.79E+01	2.80E-03	2.76E+00	1.04E-03	3.92E+00	2.21E-03	1.21E+00	2.80E-03	2.02E+00	3.27E-03
English sole	4.06E+02	4.08E-02	3.99E+02	1.50E-01	1.19E+02	6.73E-02	1.76E+01	4.08E-02	1.39E+01	2.25E-02
Cormorant (adult male)	1.02E+02	1.02E-02	7.14E+01	2.68E-02	2.36E+01	1.33E-02	4.41E+00	1.03E-02	4.14E+00	6.69E-03
Cormorant (adult female)	1.02E+02	1.02E-02	7.16E+01	2.69E-02	2.36E+01	1.33E-02	4.42E+00	1.03E-02	4.14E+00	6.70E-03
Heron (adult male)	6.13E+01	6.16E-03	5.17E+01	1.94E-02	1.41E+01	7.93E-03	2.67E+00	6.21E-03	2.45E+00	3.97E-03
Heron (adult female)	6.18E+01	6.21E-03	5.27E+01	1.98E-02	1.42E+01	8.00E-03	2.69E+00	6.26E-03	2.47E+00	4.00E-03
Seal (adult male)	1.33E+01	1.33E-03	1.76E+01	6.60E-03	3.23E+00	1.82E-03	5.81E-01	1.35E-03	4.75E-01	7.67E-04
Seal (adult female)	1.95E+01	1.96E-03	2.23E+01	8.38E-03	4.82E+00	2.72E-03	8.51E-01	1.98E-03	7.14E-01	1.15E-03
Seal (juvenile)	1.55E+01	1.55E-03	2.12E+01	7.98E-03	3.74E+00	2.11E-03	6.79E-01	1.58E-03	5.49E-01	8.88E-04
Seal (pup)	3.89E+00	3.91E-04	1.05E+01	3.96E-03	8.17E-01	4.60E-04	1.75E-01	4.08E-04	1.14E-01	1.84E-04
Cormorant egg	6.24E+01	6.27E-03	4.42E+01	1.66E-02	1.45E+01	8.18E-03	2.71E+00	6.30E-03	2.54E+00	4.11E-03
Heron egg	5.06E+01	5.08E-03	4.32E+01	1.62E-02	1.16E+01	6.54E-03	2.20E+00	5.12E-03	2.02E+00	3.27E-03

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor, LPAH = low molecular weight polycyclic aromatic hydrocarbons

Table 5-1 (continued). Modified bioaccumulation model-predicted PAH concentrations and BSAFs.

	Phenanthrene		Anthracene		2-Methylnaphthalene		HPAH		Fluoranthene	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	2.69E+03		5.92E+03		1.02E+03		2.58E+04		4.30E+03	
Water	7.60E-02		1.72E-01		1.30E-01		2.54E-02		2.14E-02	
Air	3.84E-04		7.89E-04		2.69E-03		1.19E-06		5.61E-05	
Phytoplankton	6.09E+00	2.26E-03	1.34E+01	2.27E-03	2.42E+00	2.36E-03	5.68E+01	2.20E-03	9.62E+00	2.24E-03
Kelp / Seagrass	1.19E+02	4.42E-02	2.62E+02	4.42E-02	4.57E+01	4.47E-02	8.61E+02	3.33E-02	1.80E+02	4.19E-02
Herbivorous zooplankton	2.71E+02	1.01E-01	5.95E+02	1.01E-01	9.48E+01	9.27E-02	6.35E+03	2.46E-01	6.12E+02	1.42E-01
N. plumchrus	5.72E+02	2.13E-01	1.26E+03	2.14E-01	2.46E+02	2.41E-01	2.94E+03	1.14E-01	6.58E+02	1.53E-01
P. minutus	2.71E+02	1.01E-01	5.94E+02	1.00E-01	9.47E+01	9.27E-02	6.13E+03	2.37E-01	6.05E+02	1.41E-01
Shellfish	7.03E+02	2.61E-01	1.56E+03	2.64E-01	3.56E+02	3.49E-01	8.63E+02	3.34E-02	4.66E+02	1.08E-01
Crabs	8.23E+01	3.06E-02	1.85E+02	3.12E-02	1.04E+02	1.02E-01	1.86E+02	7.21E-03	4.72E+01	1.10E-02
Grazing invertebrates	3.26E+02	1.21E-01	7.29E+02	1.23E-01	2.74E+02	2.68E-01	6.29E+02	2.43E-02	1.83E+02	4.24E-02
Carnivorous zooplankton	7.18E+02	2.67E-01	1.58E+03	2.67E-01	2.82E+02	2.76E-01	4.17E+03	1.61E-01	9.82E+02	2.28E-01
E. pacifica	3.11E+02	1.16E-01	6.88E+02	1.16E-01	1.39E+02	1.36E-01	7.04E+02	2.73E-02	2.78E+02	6.45E-02
Predatory invertebrates	1.65E+02	6.12E-02	3.69E+02	6.23E-02	1.73E+02	1.69E-01	4.69E+02	1.82E-02	1.09E+02	2.54E-02
Herring	1.49E+01	5.55E-03	3.34E+01	5.65E-03	1.71E+01	1.68E-02	3.62E+01	1.40E-03	9.15E+00	2.13E-03
Pelagic fish (seal prey)	1.70E+01	6.31E-03	3.80E+01	6.42E-03	1.83E+01	1.79E-02	4.47E+01	1.73E-03	1.12E+01	2.61E-03
Pelagic fish (bird prey)	2.79E+01	1.04E-02	6.23E+01	1.05E-02	2.40E+01	2.34E-02	6.49E+01	2.51E-03	1.77E+01	4.11E-03
River lamprey	1.68E+01	6.23E-03	3.79E+01	6.40E-03	2.63E+01	2.57E-02	6.21E+00	2.40E-04	4.90E+00	1.14E-03
Demersal fish (seal prey)	2.97E+01	1.10E-02	6.67E+01	1.13E-02	3.63E+01	3.55E-02	5.80E+01	2.25E-03	1.63E+01	3.79E-03
Demersal fish (bird prey)	8.05E+01	2.99E-02	1.81E+02	3.05E-02	7.80E+01	7.64E-02	1.16E+02	4.51E-03	3.95E+01	9.17E-03
Chum	3.06E+00	1.14E-03	6.88E+00	1.16E-03	4.26E+00	4.16E-03	2.35E+00	9.11E-05	1.27E+00	2.96E-04
Coho	3.18E+00	1.18E-03	7.16E+00	1.21E-03	4.47E+00	4.37E-03	2.42E+00	9.36E-05	1.32E+00	3.06E-04
Chinook	3.14E+00	1.17E-03	7.07E+00	1.19E-03	4.39E+00	4.29E-03	2.40E+00	9.28E-05	1.30E+00	3.02E-04
Hake	4.52E+01	1.68E-02	1.02E+02	1.72E-02	4.94E+01	4.84E-02	3.12E+01	1.21E-03	1.74E+01	4.05E-03
Dogfish	5.10E+00	1.90E-03	1.14E+01	1.93E-03	6.30E+00	6.16E-03	8.67E+00	3.36E-04	2.82E+00	6.55E-04
Pollock	1.29E+01	4.78E-03	2.88E+01	4.87E-03	1.40E+01	1.37E-02	1.85E+01	7.18E-04	7.01E+00	1.63E-03
Northern smoothtongue	9.44E+00	3.51E-03	2.07E+01	3.50E-03	2.73E+00	2.67E-03	1.10E+02	4.25E-03	1.55E+01	3.60E-03
English sole	3.19E+01	1.19E-02	7.21E+01	1.22E-02	4.71E+01	4.61E-02	1.45E+01	5.62E-04	9.88E+00	2.30E-03
Cormorant (adult male)	1.10E+01	4.09E-03	2.47E+01	4.17E-03	1.14E+01	1.12E-02	1.60E+01	6.18E-04	5.39E+00	1.25E-03
Cormorant (adult female)	1.10E+01	4.09E-03	2.47E+01	4.17E-03	1.14E+01	1.12E-02	1.60E+01	6.18E-04	5.39E+00	1.25E-03
Heron (adult male)	6.42E+00	2.39E-03	1.44E+01	2.43E-03	6.98E+00	6.83E-03	9.31E+00	3.60E-04	3.14E+00	7.29E-04
Heron (adult female)	6.46E+00	2.40E-03	1.45E+01	2.44E-03	7.05E+00	6.89E-03	9.36E+00	3.62E-04	3.15E+00	7.33E-04
Seal (adult male)	1.13E+00	4.19E-04	2.52E+00	4.26E-04	1.57E+00	1.54E-03	1.28E+00	4.97E-05	4.94E-01	1.15E-04
Seal (adult female)	1.74E+00	6.46E-04	3.89E+00	6.58E-04	2.28E+00	2.23E-03	2.01E+00	7.79E-05	7.71E-01	1.79E-04
Seal (juvenile)	1.29E+00	4.81E-04	2.89E+00	4.89E-04	1.84E+00	1.80E-03	1.47E+00	5.68E-05	5.65E-01	1.31E-04
Seal (pup)	2.02E-01	7.51E-05	4.45E-01	7.52E-05	5.10E-01	4.99E-04	1.84E-01	7.12E-06	7.68E-02	1.78E-05
Cormorant egg	6.75E+00	2.51E-03	1.51E+01	2.56E-03	7.03E+00	6.88E-03	9.79E+00	3.79E-04	3.30E+00	7.67E-04
Heron egg	5.28E+00	1.96E-03	1.18E+01	2.00E-03	5.77E+00	5.64E-03	7.65E+00	2.96E-04	2.58E+00	5.99E-04

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor, HPAH = molecular weight polycyclic aromatic hydrocarbons

Table 5-1 (continued). Modified bioaccumulation model-predicted PAH concentrations and BSAFs.

	Pyrene		Benz(a)anthracene		Chrysene		Total Bezofluoranthenes	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	2.69E+04		2.96E+03		2.96E+03		6.19E+03	
Water	2.63E-01		2.98E-03		3.04E-03		6.15E-03	
Air	2.60E-04		5.57E-06		7.69E-07		2.86E-07	
Phytoplankton	6.04E+01	2.24E-03	6.52E+00	2.20E-03	6.52E+00	2.20E-03	1.36E+01	2.20E-03
Kelp / Seagrass	1.16E+03	4.32E-02	9.93E+01	3.35E-02	9.97E+01	3.37E-02	2.07E+02	3.34E-02
Herbivorous zooplankton	3.20E+03	1.19E-01	7.21E+02	2.44E-01	7.17E+02	2.42E-01	1.52E+03	2.45E-01
N. plumchrus	4.75E+03	1.77E-01	3.37E+02	1.14E-01	3.38E+02	1.14E-01	7.05E+02	1.14E-01
P. minutus	3.18E+03	1.18E-01	6.96E+02	2.35E-01	6.93E+02	2.34E-01	1.46E+03	2.36E-01
Shellfish	4.42E+03	1.64E-01	1.01E+02	3.40E-02	1.02E+02	3.45E-02	2.09E+02	3.37E-02
Crabs	4.08E+02	1.52E-02	2.14E+01	7.23E-03	2.15E+01	7.25E-03	4.47E+01	7.23E-03
Grazing invertebrates	1.66E+03	6.16E-02	7.24E+01	2.45E-02	7.27E+01	2.46E-02	1.51E+02	2.44E-02
Carnivorous zooplankton	6.70E+03	2.49E-01	4.80E+02	1.62E-01	4.82E+02	1.63E-01	1.00E+03	1.62E-01
E. pacifica	2.32E+03	8.63E-02	8.17E+01	2.76E-02	8.25E+01	2.79E-02	1.70E+02	2.74E-02
Predatory invertebrates	8.96E+02	3.33E-02	5.39E+01	1.82E-02	5.40E+01	1.83E-02	1.13E+02	1.82E-02
Herring	7.87E+01	2.93E-03	4.15E+00	1.40E-03	4.17E+00	1.41E-03	8.70E+00	1.41E-03
Pelagic fish (seal prey)	9.37E+01	3.48E-03	5.13E+00	1.73E-03	5.15E+00	1.74E-03	1.07E+01	1.74E-03
Pelagic fish (bird prey)	1.53E+02	5.68E-03	7.46E+00	2.52E-03	7.49E+00	2.53E-03	1.56E+01	2.52E-03
River lamprey	5.93E+01	2.21E-03	7.28E-01	2.46E-04	7.41E-01	2.50E-04	1.50E+00	2.43E-04
Demersal fish (seal prey)	1.46E+02	5.42E-03	6.67E+00	2.25E-03	6.70E+00	2.26E-03	1.39E+01	2.25E-03
Demersal fish (bird prey)	3.80E+02	1.41E-02	1.34E+01	4.54E-03	1.35E+01	4.56E-03	2.80E+01	4.53E-03
Chum	1.33E+01	4.93E-04	2.74E-01	9.26E-05	2.77E-01	9.38E-05	5.69E-01	9.19E-05
Coho	1.37E+01	5.11E-04	2.81E-01	9.51E-05	2.85E-01	9.64E-05	5.84E-01	9.44E-05
Chinook	1.36E+01	5.05E-04	2.79E-01	9.43E-05	2.83E-01	9.55E-05	5.79E-01	9.36E-05
Hake	1.89E+02	7.04E-03	3.63E+00	1.23E-03	3.68E+00	1.24E-03	7.53E+00	1.22E-03
Dogfish	2.55E+01	9.47E-04	1.00E+00	3.38E-04	1.01E+00	3.40E-04	2.09E+00	3.38E-04
Pollock	6.52E+01	2.42E-03	2.14E+00	7.24E-04	2.16E+00	7.30E-04	4.47E+00	7.22E-04
Northern smoothtongue	9.59E+01	3.56E-03	1.25E+01	4.23E-03	1.25E+01	4.22E-03	2.63E+01	4.25E-03
English sole	1.17E+02	4.33E-03	1.70E+00	5.73E-04	1.72E+00	5.81E-04	3.51E+00	5.68E-04
Cormorant (adult male)	5.16E+01	1.92E-03	1.84E+00	6.23E-04	1.85E+00	6.26E-04	3.84E+00	6.21E-04
Cormorant (adult female)	5.16E+01	1.92E-03	1.84E+00	6.23E-04	1.85E+00	6.26E-04	3.84E+00	6.21E-04
Heron (adult male)	2.99E+01	1.11E-03	1.08E+00	3.63E-04	1.08E+00	3.65E-04	2.24E+00	3.62E-04
Heron (adult female)	3.01E+01	1.12E-03	1.08E+00	3.65E-04	1.09E+00	3.67E-04	2.25E+00	3.64E-04
Seal (adult male)	4.87E+00	1.81E-04	1.49E-01	5.04E-05	1.49E-01	5.05E-05	3.09E-01	5.00E-05
Seal (adult female)	7.61E+00	2.83E-04	2.33E-01	7.88E-05	2.34E-01	7.91E-05	4.84E-01	7.83E-05
Seal (juvenile)	5.56E+00	2.07E-04	1.70E-01	5.75E-05	1.71E-01	5.76E-05	3.53E-01	5.70E-05
Seal (pup)	7.25E-01	2.69E-05	2.19E-02	7.41E-06	2.15E-02	7.26E-06	4.43E-02	7.16E-06
Cormorant egg	3.16E+01	1.18E-03	1.13E+00	3.82E-04	1.13E+00	3.84E-04	2.35E+00	3.81E-04
Heron egg	2.46E+01	9.15E-04	8.84E-01	2.99E-04	8.87E-01	3.00E-04	1.84E+00	2.97E-04

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-1 (continued). Modified bioaccumulation model-predicted PAH concentrations and BSAFs.

	Benzo(a)pyrene		Indeno(1,2,3-CD)pyrene		Dibenzo(a,h)anthracene		Benzo(g,h,i)perylene	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	2.66E+03		9.15E+02		3.23E+02		8.34E+02	
Water	1.69E-03		9.07E-05		5.28E-05		1.05E-04	
Air	1.55E-09		2.86E-09		1.42E-11		4.13E-11	
Phytoplankton	5.81E+00	2.18E-03	1.75E+00	1.91E-03	6.55E-01	2.03E-03	1.65E+00	1.98E-03
Kelp / Seagrass	7.79E+01	2.92E-02	9.33E+00	1.02E-02	4.73E+00	1.47E-02	1.02E+01	1.22E-02
Herbivorous zooplankton	7.32E+02	2.75E-01	2.48E+02	2.71E-01	9.68E+01	3.00E-01	2.38E+02	2.85E-01
N. plumchrus	2.84E+02	1.07E-01	6.52E+01	7.13E-02	2.70E+01	8.37E-02	6.42E+01	7.70E-02
P. minutus	7.01E+02	2.63E-01	2.32E+02	2.53E-01	9.09E+01	2.82E-01	2.23E+02	2.67E-01
Shellfish	6.60E+01	2.48E-02	7.78E+00	8.51E-03	3.63E+00	1.13E-02	8.10E+00	9.71E-03
Crabs	1.79E+01	6.74E-03	4.06E+00	4.43E-03	1.69E+00	5.25E-03	4.01E+00	4.81E-03
Grazing invertebrates	5.93E+01	2.23E-02	1.28E+01	1.40E-02	5.38E+00	1.67E-02	1.27E+01	1.52E-02
Carnivorous zooplankton	3.89E+02	1.46E-01	7.29E+01	7.97E-02	3.27E+01	1.01E-01	7.47E+01	8.95E-02
E. pacifica	5.88E+01	2.21E-02	9.30E+00	1.02E-02	4.11E+00	1.27E-02	9.43E+00	1.13E-02
Predatory invertebrates	4.58E+01	1.72E-02	1.06E+01	1.16E-02	4.40E+00	1.36E-02	1.04E+01	1.25E-02
Herring	3.54E+00	1.33E-03	6.64E-01	7.26E-04	3.14E-01	9.71E-04	6.98E-01	8.37E-04
Pelagic fish (seal prey)	4.30E+00	1.61E-03	7.54E-01	8.24E-04	3.62E-01	1.12E-03	7.99E-01	9.58E-04
Pelagic fish (bird prey)	6.16E+00	2.31E-03	1.06E+00	1.16E-03	5.10E-01	1.58E-03	1.12E+00	1.35E-03
River lamprey	4.29E-01	1.61E-04	2.72E-02	2.97E-05	1.56E-02	4.84E-05	3.13E-02	3.76E-05
Demersal fish (seal prey)	5.48E+00	2.06E-03	1.11E+00	1.21E-03	4.85E-01	1.50E-03	1.12E+00	1.34E-03
Demersal fish (bird prey)	1.07E+01	4.00E-03	2.03E+00	2.22E-03	8.96E-01	2.77E-03	2.06E+00	2.47E-03
Chum	1.83E-01	6.86E-05	1.79E-02	1.95E-05	9.50E-03	2.94E-05	1.98E-02	2.38E-05
Coho	1.87E-01	7.04E-05	1.83E-02	2.00E-05	9.72E-03	3.01E-05	2.03E-02	2.43E-05
Chinook	1.86E-01	6.98E-05	1.81E-02	1.98E-05	9.65E-03	2.99E-05	2.01E-02	2.41E-05
Hake	2.44E+00	9.17E-04	2.58E-01	2.82E-04	1.34E-01	4.15E-04	2.83E-01	3.40E-04
Dogfish	7.79E-01	2.93E-04	1.14E-01	1.24E-04	5.66E-02	1.75E-04	1.22E-01	1.47E-04
Pollock	1.61E+00	6.03E-04	2.21E-01	2.42E-04	1.10E-01	3.42E-04	2.38E-01	2.86E-04
Northern smoothtongue	1.17E+01	4.38E-03	2.55E+00	2.79E-03	1.18E+00	3.65E-03	2.65E+00	3.18E-03
English sole	1.08E+00	4.07E-04	1.04E-01	1.14E-04	5.39E-02	1.67E-04	1.14E-01	1.37E-04
Cormorant (adult male)	1.46E+00	5.50E-04	2.76E-01	3.02E-04	1.23E-01	3.80E-04	2.81E-01	3.37E-04
Cormorant (adult female)	1.46E+00	5.50E-04	2.76E-01	3.02E-04	1.23E-01	3.80E-04	2.81E-01	3.37E-04
Heron (adult male)	8.54E-01	3.21E-04	1.61E-01	1.76E-04	7.14E-02	2.21E-04	1.64E-01	1.96E-04
Heron (adult female)	8.59E-01	3.22E-04	1.62E-01	1.77E-04	7.18E-02	2.22E-04	1.65E-01	1.97E-04
Seal (adult male)	1.14E-01	4.30E-05	1.86E-02	2.03E-05	8.74E-03	2.71E-05	1.94E-02	2.33E-05
Seal (adult female)	1.79E-01	6.73E-05	2.91E-02	3.18E-05	1.37E-02	4.24E-05	3.04E-02	3.65E-05
Seal (juvenile)	1.31E-01	4.90E-05	2.12E-02	2.32E-05	9.98E-03	3.09E-05	2.22E-02	2.66E-05
Seal (pup)	1.64E-02	6.15E-06	2.65E-03	2.90E-06	1.25E-03	3.87E-06	2.78E-03	3.33E-06
Cormorant egg	8.97E-01	3.37E-04	1.69E-01	1.85E-04	7.51E-02	2.33E-04	1.72E-01	2.07E-04
Heron egg	7.02E-01	2.64E-04	1.32E-01	1.44E-04	5.87E-02	1.82E-04	1.35E-01	1.61E-04

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-2. Modified bioaccumulation model-predicted phthalate concentrations and BSAFs.

	Dimethyl phthalate		Diethyl phthalate		Di-N-Butyl phthalate	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	1.43E+03		1.64E+03		5.92E+03	
Water	4.46E+01		8.47E-02		6.75E-02	
Air	6.29E-04		2.19E-04		9.06E-05	
Phytoplankton	4.72E+01	3.31E-02	3.76E+00	2.29E-03	1.33E+01	2.25E-03
Kelp / Seagrass	1.04E+02	7.29E-02	7.30E+01	4.45E-02	2.57E+02	4.34E-02
Herbivorous zooplankton	1.65E+02	1.16E-01	1.58E+02	9.61E-02	6.82E+02	1.15E-01
N. plumchrus	3.95E+02	2.77E-01	3.73E+02	2.27E-01	1.08E+03	1.82E-01
P. minutus	1.65E+02	1.16E-01	1.58E+02	9.60E-02	6.79E+02	1.15E-01
Shellfish	9.14E+02	6.41E-01	5.01E+02	3.05E-01	1.06E+03	1.79E-01
Crabs	1.32E+03	9.25E-01	8.03E+01	4.89E-02	9.81E+01	1.66E-02
Grazing invertebrates	9.92E+02	6.96E-01	2.86E+02	1.74E-01	4.01E+02	6.78E-02
Carnivorous zooplankton	5.19E+02	3.64E-01	4.46E+02	2.72E-01	1.49E+03	2.53E-01
E. pacifica	3.26E+02	2.29E-01	2.08E+02	1.27E-01	5.40E+02	9.12E-02
Predatory invertebrates	1.11E+03	7.77E-01	1.51E+02	9.20E-02	2.13E+02	3.59E-02
Herring	1.84E+02	1.29E-01	1.39E+01	8.49E-03	1.88E+01	3.18E-03
Pelagic fish (seal prey)	1.56E+02	1.10E-01	1.55E+01	9.44E-03	2.22E+01	3.76E-03
Pelagic fish (bird prey)	9.77E+01	6.85E-02	2.42E+01	1.47E-02	3.65E+01	6.16E-03
River lamprey	3.75E+02	2.63E-01	1.83E+01	1.11E-02	1.52E+01	2.57E-03
Demersal fish (seal prey)	3.94E+02	2.76E-01	2.87E+01	1.75E-02	3.52E+01	5.95E-03
Demersal fish (bird prey)	3.34E+02	2.34E-01	7.43E+01	4.53E-02	9.29E+01	1.57E-02
Chum	1.46E+02	1.03E-01	3.09E+00	1.89E-03	3.29E+00	5.56E-04
Coho	1.73E+02	1.21E-01	3.23E+00	1.97E-03	3.41E+00	5.76E-04
Chinook	1.57E+02	1.10E-01	3.18E+00	1.94E-03	3.37E+00	5.69E-04
Hake	1.95E+02	1.36E-01	4.38E+01	2.67E-02	4.73E+01	8.00E-03
Dogfish	2.37E+02	1.66E-01	4.88E+00	2.98E-03	6.15E+00	1.04E-03
Pollock	1.12E+02	7.83E-02	1.19E+01	7.25E-03	1.58E+01	2.67E-03
Northern smoothtongue	1.43E-01	1.00E-04	5.44E+00	3.32E-03	2.11E+01	3.57E-03
English sole	5.25E+02	3.69E-01	3.41E+01	2.08E-02	2.97E+01	5.02E-03
Cormorant (adult male)	4.54E+01	3.18E-02	1.01E+01	6.15E-03	1.26E+01	2.13E-03
Cormorant (adult female)	4.54E+01	3.18E-02	1.01E+01	6.15E-03	1.26E+01	2.13E-03
Heron (adult male)	2.60E+01	1.83E-02	5.86E+00	3.57E-03	7.33E+00	1.24E-03
Heron (adult female)	2.62E+01	1.84E-02	5.90E+00	3.59E-03	7.37E+00	1.24E-03
Seal (adult male)	7.66E+00	5.37E-03	1.06E+00	6.48E-04	1.20E+00	2.03E-04
Seal (adult female)	1.19E+01	8.38E-03	1.65E+00	1.01E-03	1.88E+00	3.17E-04
Seal (juvenile)	8.74E+00	6.13E-03	1.22E+00	7.42E-04	1.37E+00	2.32E-04
Seal (pup)	1.06E+00	7.43E-04	1.76E-01	1.07E-04	1.82E-01	3.07E-05
Cormorant egg	3.32E+01	2.33E-02	6.19E+00	3.77E-03	7.74E+00	1.31E-03
Heron egg	2.32E+01	1.62E-02	4.82E+00	2.94E-03	6.02E+00	1.02E-03

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-2 (continued). Modified bioaccumulation model-predicted phthalate concentrations and BSAFs.

	Butyl benzyl phthalate		Bis (2-ethylhexyl) phthalate		Di-N-Octyl phthalate	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	1.32E+02		1.26E+03		1.56E+03	
Water	2.00E-03		4.92E-06		3.92E-06	
Air	1.19E-06		2.49E-07		3.08E-07	
Phytoplankton	2.97E-01	2.25E-03	5.32E-01	4.21E-04	4.55E-01	2.91E-04
Kelp / Seagrass	5.77E+00	4.38E-02	6.48E-01	5.13E-04	5.19E-01	3.32E-04
Herbivorous zooplankton	1.44E+01	1.09E-01	5.83E+01	4.61E-02	4.83E+01	3.10E-02
N. plumchrus	2.54E+01	1.93E-01	1.39E+01	1.10E-02	1.15E+01	7.37E-03
P. minutus	1.44E+01	1.09E-01	5.41E+01	4.28E-02	4.48E+01	2.87E-02
Shellfish	2.70E+01	2.05E-01	1.22E+00	9.62E-04	9.98E-01	6.40E-04
Crabs	2.60E+00	1.98E-02	8.27E-01	6.54E-04	6.81E-01	4.37E-04
Grazing invertebrates	1.07E+01	8.11E-02	2.54E+00	2.01E-03	2.09E+00	1.34E-03
Carnivorous zooplankton	3.40E+01	2.58E-01	6.68E+00	5.28E-03	5.02E+00	3.22E-03
E. pacifica	1.32E+01	9.98E-02	1.63E+00	1.29E-03	1.34E+00	8.59E-04
Predatory invertebrates	5.51E+00	4.18E-02	2.15E+00	1.70E-03	1.77E+00	1.13E-03
Herring	4.93E-01	3.74E-03	2.25E-02	1.78E-05	1.26E-02	8.06E-06
Pelagic fish (seal prey)	5.75E-01	4.36E-03	2.31E-02	1.83E-05	1.29E-02	8.24E-06
Pelagic fish (bird prey)	9.50E-01	7.21E-03	3.29E-02	2.60E-05	1.84E-02	1.18E-05
River lamprey	4.47E-01	3.39E-03	1.13E-03	8.96E-07	8.87E-04	5.69E-07
Demersal fish (seal prey)	9.39E-01	7.13E-03	1.75E-01	1.39E-04	1.42E-01	9.11E-05
Demersal fish (bird prey)	2.53E+00	1.92E-02	3.08E-01	2.44E-04	2.49E-01	1.60E-04
Chum	9.12E-02	6.92E-04	5.02E-04	3.97E-07	3.11E-04	2.00E-07
Coho	9.45E-02	7.17E-04	5.16E-04	4.08E-07	3.20E-04	2.05E-07
Chinook	9.34E-02	7.09E-04	5.11E-04	4.04E-07	3.18E-04	2.04E-07
Hake	1.33E+00	1.01E-02	8.04E-03	6.36E-06	5.14E-03	3.29E-06
Dogfish	1.64E-01	1.24E-03	2.99E-03	2.36E-06	1.67E-03	1.07E-06
Pollock	4.19E-01	3.18E-03	6.32E-03	5.00E-06	3.60E-03	2.30E-06
Northern smoothtongue	4.70E-01	3.57E-03	9.16E-02	7.24E-05	5.08E-02	3.25E-05
English sole	8.66E-01	6.57E-03	4.21E-03	3.33E-06	2.82E-03	1.81E-06
Cormorant (adult male)	3.42E-01	2.60E-03	3.71E-02	2.93E-05	2.86E-02	1.83E-05
Cormorant (adult female)	3.42E-01	2.60E-03	3.71E-02	2.93E-05	2.86E-02	1.83E-05
Heron (adult male)	1.98E-01	1.51E-03	2.12E-02	1.68E-05	1.64E-02	1.05E-05
Heron (adult female)	1.99E-01	1.51E-03	2.14E-02	1.69E-05	1.65E-02	1.06E-05
Seal (adult male)	3.29E-02	2.49E-04	1.42E-03	1.12E-06	1.06E-03	6.81E-07
Seal (adult female)	5.14E-02	3.90E-04	2.20E-03	1.74E-06	1.64E-03	1.05E-06
Seal (juvenile)	3.76E-02	2.85E-04	1.62E-03	1.28E-06	1.22E-03	7.81E-07
Seal (pup)	4.83E-03	3.67E-05	2.23E-04	1.76E-07	1.77E-04	1.14E-07
Cormorant egg	2.10E-01	1.59E-03	2.27E-02	1.80E-05	1.75E-02	1.12E-05
Heron egg	1.63E-01	1.24E-03	1.75E-02	1.38E-05	1.35E-02	8.63E-06

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-3. Modified bioaccumulation model-predicted phenol concentrations and BSAFs.

	Phenol		**2-Methylphenol**		**4-Methylphenol**		**2,4-Dimethylphenol**		**Pentachlorophenol**	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	4.20E+02		6.30E+01		6.70E+02		2.90E+01		3.60E+02	
Water	2.00E+01		6.88E-01		4.13E+00		1.67E-01		2.71E-01	
Air	5.04E+00		1.35E-01		1.49E+00		1.82E-02		1.14E-06	
Phytoplankton	2.05E+01	4.89E-02	8.24E-01	1.31E-02	5.60E+00	8.37E-03	2.31E-01	7.97E-03	1.08E+00	2.99E-03
Kelp / Seagrass	3.67E+01	8.73E-02	3.44E+00	5.46E-02	3.37E+01	5.03E-02	1.45E+00	4.99E-02	1.63E+01	4.54E-02
Herbivorous zooplankton	5.41E+01	1.29E-01	6.24E+00	9.91E-02	6.38E+01	9.53E-02	2.75E+00	9.50E-02	3.28E+01	9.12E-02
N. plumchrus	1.22E+02	2.90E-01	1.64E+01	2.60E-01	1.72E+02	2.56E-01	7.42E+00	2.56E-01	9.00E+01	2.50E-01
P. minutus	5.41E+01	1.29E-01	6.24E+00	9.91E-02	6.38E+01	9.53E-02	2.75E+00	9.49E-02	3.28E+01	9.12E-02
Shellfish	3.25E+02	7.75E-01	2.98E+01	4.74E-01	2.91E+02	4.34E-01	1.25E+01	4.31E-01	1.38E+02	3.84E-01
Crabs	4.41E+02	1.05E+00	4.67E+01	7.41E-01	4.50E+02	6.71E-01	1.92E+01	6.63E-01	1.25E+02	3.46E-01
Grazing invertebrates	3.48E+02	8.28E-01	3.33E+01	5.28E-01	3.26E+02	4.86E-01	1.40E+01	4.83E-01	1.45E+02	4.03E-01
Carnivorous zooplankton	1.72E+02	4.09E-01	1.94E+01	3.08E-01	1.97E+02	2.95E-01	8.51E+00	2.94E-01	1.01E+02	2.79E-01
E. pacifica	1.15E+02	2.74E-01	1.09E+01	1.73E-01	1.07E+02	1.60E-01	4.60E+00	1.59E-01	5.18E+01	1.44E-01
Predatory invertebrates	3.81E+02	9.06E-01	3.82E+01	6.07E-01	3.74E+02	5.58E-01	1.60E+01	5.53E-01	1.40E+02	3.89E-01
Herring	5.92E+01	1.41E-01	6.93E+00	1.10E-01	6.81E+01	1.02E-01	2.92E+00	1.01E-01	1.96E+01	5.45E-02
Pelagic fish (seal prey)	5.12E+01	1.22E-01	5.82E+00	9.23E-02	5.75E+01	8.58E-02	2.47E+00	8.50E-02	1.85E+01	5.15E-02
Pelagic fish (bird prey)	3.41E+01	8.11E-02	3.31E+00	5.25E-02	3.24E+01	4.84E-02	1.39E+00	4.81E-02	1.40E+01	3.89E-02
River lamprey	1.16E+02	2.76E-01	1.48E+01	2.35E-01	1.45E+02	2.17E-01	6.23E+00	2.15E-01	3.66E+01	1.02E-01
Demersal fish (seal prey)	1.33E+02	3.16E-01	1.39E+01	2.20E-01	1.34E+02	2.01E-01	5.75E+00	1.98E-01	4.02E+01	1.12E-01
Demersal fish (bird prey)	1.16E+02	2.76E-01	1.14E+01	1.81E-01	1.12E+02	1.67E-01	4.81E+00	1.66E-01	4.79E+01	1.33E-01
Chum	4.79E+01	1.14E-01	5.01E+00	7.95E-02	4.45E+01	6.64E-02	1.88E+00	6.48E-02	6.98E+00	1.94E-02
Coho	5.58E+01	1.33E-01	5.90E+00	9.37E-02	5.16E+01	7.71E-02	2.18E+00	7.51E-02	7.52E+00	2.09E-02
Chinook	5.11E+01	1.22E-01	5.39E+00	8.55E-02	4.76E+01	7.10E-02	2.01E+00	6.93E-02	7.27E+00	2.02E-02
Hake	6.24E+01	1.49E-01	7.58E+00	1.20E-01	7.74E+01	1.16E-01	3.34E+00	1.15E-01	3.36E+01	9.34E-02
Dogfish	7.56E+01	1.80E-01	8.12E+00	1.29E-01	7.01E+01	1.05E-01	2.95E+00	1.02E-01	9.82E+00	2.73E-02
Pollock	3.80E+01	9.04E-02	3.90E+00	6.18E-02	3.80E+01	5.67E-02	1.63E+00	5.62E-02	1.30E+01	3.61E-02
Northern smoothtongue	4.35E-02	1.04E-04	8.64E-03	1.37E-04	1.30E-01	1.93E-04	5.87E-03	2.02E-04	3.51E-01	9.76E-04
English sole	1.72E+02	4.08E-01	1.95E+01	3.09E-01	1.91E+02	2.85E-01	8.18E+00	2.82E-01	5.62E+01	1.56E-01
Cormorant (adult male)	1.41E+02	3.35E-01	1.53E+01	2.43E-01	1.63E+02	2.43E-01	4.42E+00	1.52E-01	6.48E+00	1.80E-02
Cormorant (adult female)	1.41E+02	3.36E-01	1.54E+01	2.44E-01	1.63E+02	2.44E-01	4.44E+00	1.53E-01	6.48E+00	1.80E-02
Heron (adult male)	1.40E+02	3.34E-01	1.51E+01	2.39E-01	1.61E+02	2.40E-01	4.23E+00	1.46E-01	3.71E+00	1.03E-02
Heron (adult female)	1.41E+02	3.35E-01	1.52E+01	2.42E-01	1.62E+02	2.42E-01	4.32E+00	1.49E-01	3.73E+00	1.04E-02
Seal (adult male)	3.30E+02	7.85E-01	1.61E+01	2.56E-01	1.76E+02	2.63E-01	2.51E+00	8.66E-02	9.99E-01	2.78E-03
Seal (adult female)	1.89E+02	4.50E-01	1.36E+01	2.16E-01	1.47E+02	2.20E-01	2.54E+00	8.76E-02	1.56E+00	4.35E-03
Seal (juvenile)	1.68E+02	3.99E-01	1.38E+01	2.18E-01	1.49E+02	2.22E-01	2.78E+00	9.57E-02	1.14E+00	3.17E-03
Seal (pup)	3.00E+02	7.14E-01	1.43E+01	2.27E-01	1.57E+02	2.34E-01	2.19E+00	7.56E-02	1.41E-01	3.92E-04
Cormorant egg	1.06E+02	2.52E-01	1.00E+01	1.59E-01	1.06E+02	1.58E-01	2.85E+00	9.82E-02	4.12E+00	1.14E-02
Heron egg	1.26E+02	3.00E-01	1.28E+01	2.03E-01	1.36E+02	2.03E-01	3.60E+00	1.24E-01	3.10E+00	8.61E-03

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-4. Modified bioaccumulation model-predicted chlorinated benzenes concentrations and BSAFs.

	1,2-Dichlorobenzene		1,4-Dichlorobenzene		1,2,4 Trichlorobenzene		Hexachlorobenzene	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	6.19E+01		8.34E+01		2.18E+01		1.02E+01	
Water	4.37E-02		3.09E-02		1.91E-03		1.27E-05	
Air	9.47E-03		1.80E-02		1.10E-03		1.97E-06	
Phytoplankton	1.82E-01	2.94E-03	2.17E-01	2.61E-03	5.07E-02	2.32E-03	2.26E-02	2.21E-03
Kelp / Seagrass	2.80E+00	4.53E-02	3.75E+00	4.50E-02	9.72E-01	4.46E-02	3.60E-01	3.52E-02
Herbivorous zooplankton	5.65E+00	9.13E-02	7.63E+00	9.16E-02	2.06E+00	9.47E-02	3.88E+00	3.79E-01
N. plumchrus	1.57E+01	2.54E-01	2.12E+01	2.55E-01	5.74E+00	2.64E-01	9.94E+00	9.72E-01
P. minutus	5.65E+00	9.13E-02	7.63E+00	9.16E-02	2.06E+00	9.47E-02	3.87E+00	3.79E-01
Shellfish	2.42E+01	3.91E-01	3.24E+01	3.88E-01	8.42E+00	3.87E-01	4.67E+00	4.57E-01
Crabs	4.71E+01	7.61E-01	6.39E+01	7.66E-01	1.79E+01	8.20E-01	4.34E+01	4.24E+00
Grazing invertebrates	2.81E+01	4.54E-01	3.78E+01	4.53E-01	1.01E+01	4.64E-01	1.37E+01	1.34E+00
Carnivorous zooplankton	1.73E+01	2.80E-01	2.33E+01	2.79E-01	6.07E+00	2.79E-01	5.33E+00	5.21E-01
E. pacifica	8.98E+00	1.45E-01	1.20E+01	1.44E-01	3.14E+00	1.44E-01	2.15E+00	2.10E-01
Predatory invertebrates	3.46E+01	5.59E-01	4.70E+01	5.63E-01	1.32E+01	6.07E-01	3.21E+01	3.14E+00
Herring	7.32E+00	1.18E-01	1.01E+01	1.21E-01	3.01E+00	1.38E-01	2.45E+01	2.40E+00
Pelagic fish (seal prey)	5.90E+00	9.54E-02	8.15E+00	9.78E-02	2.52E+00	1.16E-01	3.20E+01	3.13E+00
Pelagic fish (bird prey)	2.87E+00	4.65E-02	3.92E+00	4.70E-02	1.14E+00	5.24E-02	1.03E+01	1.01E+00
River lamprey	1.67E+01	2.70E-01	2.27E+01	2.72E-01	6.38E+00	2.93E-01	2.21E+02	2.16E+01
Demersal fish (seal prey)	1.37E+01	2.21E-01	1.86E+01	2.23E-01	5.35E+00	2.46E-01	3.86E+01	3.78E+00
Demersal fish (bird prey)	9.86E+00	1.59E-01	1.33E+01	1.60E-01	3.64E+00	1.67E-01	1.29E+01	1.26E+00
Chum	7.18E+00	1.16E-01	9.94E+00	1.19E-01	3.15E+00	1.44E-01	8.83E+01	8.64E+00
Coho	9.18E+00	1.48E-01	1.27E+01	1.52E-01	4.00E+00	1.84E-01	1.07E+02	1.05E+01
Chinook	7.94E+00	1.28E-01	1.10E+01	1.32E-01	3.47E+00	1.59E-01	9.56E+01	9.35E+00
Hake	7.43E+00	1.20E-01	1.03E+01	1.24E-01	3.28E+00	1.50E-01	2.48E+01	2.42E+00
Dogfish	1.47E+01	2.37E-01	2.13E+01	2.55E-01	8.34E+00	3.83E-01	2.96E+02	2.90E+01
Pollock	3.69E+00	5.97E-02	5.07E+00	6.08E-02	1.52E+00	6.98E-02	1.56E+01	1.52E+00
Northern smoothtongue	8.26E-02	1.34E-03	2.09E-01	2.50E-03	2.32E-01	1.06E-02	1.43E+01	1.40E+00
English sole	1.98E+01	3.20E-01	2.68E+01	3.22E-01	7.45E+00	3.42E-01	1.05E+02	1.03E+01
Cormorant (adult male)	3.45E+01	5.57E-01	4.29E+01	5.14E-01	2.05E+01	9.40E-01	4.03E+02	3.94E+01
Cormorant (adult female)	3.44E+01	5.56E-01	4.28E+01	5.13E-01	2.04E+01	9.34E-01	3.98E+02	3.89E+01
Heron (adult male)	3.06E+01	4.95E-01	3.91E+01	4.69E-01	1.62E+01	7.44E-01	3.91E+02	3.83E+01
Heron (adult female)	3.04E+01	4.92E-01	3.89E+01	4.67E-01	1.60E+01	7.34E-01	3.71E+02	3.63E+01
Seal (adult male)	1.59E+02	2.56E+00	2.05E+02	2.46E+00	8.61E+01	3.95E+00	3.53E+03	3.46E+02
Seal (adult female)	5.67E+01	9.17E-01	7.36E+01	8.83E-01	2.90E+01	1.33E+00	4.49E+02	4.39E+01
Seal (juvenile)	4.43E+01	7.17E-01	5.75E+01	6.90E-01	2.31E+01	1.06E+00	7.71E+02	7.55E+01
Seal (pup)	2.87E+02	4.64E+00	3.48E+02	4.17E+00	1.75E+02	8.01E+00	3.06E+03	2.99E+02
Cormorant egg	2.12E+01	3.43E-01	2.63E+01	3.16E-01	1.25E+01	5.73E-01	2.44E+02	2.38E+01
Heron egg	2.50E+01	4.03E-01	3.19E+01	3.82E-01	1.31E+01	6.00E-01	3.03E+02	2.97E+01

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-5. Modified bioaccumulation model-predicted concentrations and BSAFs for miscellaneous chemical compounds.

	Benzyl Alcohol		Bezoic Acid		Total PCBs	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	5.70E+01		6.50E+02		3.23E+02	
Water	2.46E-01		1.79E+01		1.19E-04	
Air	2.42E+00		1.85E+00		8.83E-08	
Phytoplankton	3.72E-01	6.54E-03	1.91E+01	2.94E-02	6.91E-01	2.14E-03
Kelp / Seagrass	2.77E+00	4.86E-02	4.52E+01	6.95E-02	7.55E+00	2.34E-02
Herbivorous zooplankton	5.35E+00	9.38E-02	7.32E+01	1.13E-01	3.01E+02	9.33E-01
N. plumchrus	1.46E+01	2.55E-01	1.78E+02	2.74E-01	6.58E+02	2.04E+00
P. minutus	5.35E+00	9.38E-02	7.32E+01	1.13E-01	3.01E+02	9.31E-01
Shellfish	2.40E+01	4.20E-01	3.97E+02	6.11E-01	2.09E+02	6.47E-01
Crabs	4.46E+01	7.83E-01	6.32E+02	9.73E-01	2.60E+03	8.05E+00
Grazing invertebrates	2.74E+01	4.81E-01	4.37E+02	6.72E-01	7.78E+02	2.41E+00
Carnivorous zooplankton	1.65E+01	2.90E-01	2.30E+02	3.54E-01	4.77E+02	1.48E+00
E. pacifica	8.84E+00	1.55E-01	1.42E+02	2.19E-01	1.19E+02	3.68E-01
Predatory invertebrates	3.32E+01	5.83E-01	5.02E+02	7.72E-01	1.96E+03	6.06E+00
Herring	6.76E+00	1.19E-01	8.82E+01	1.36E-01	2.44E+03	7.56E+00
Pelagic fish (seal prey)	5.46E+00	9.58E-02	7.35E+01	1.13E-01	3.62E+03	1.12E+01
Pelagic fish (bird prey)	2.77E+00	4.85E-02	4.33E+01	6.67E-02	1.19E+03	3.70E+00
River lamprey	1.54E+01	2.70E-01	1.85E+02	2.85E-01	3.07E+04	9.52E+01
Demersal fish (seal prey)	1.29E+01	2.27E-01	1.86E+02	2.86E-01	4.58E+03	1.42E+01
Demersal fish (bird prey)	9.56E+00	1.68E-01	1.48E+02	2.28E-01	1.43E+03	4.42E+00
Chum	6.59E+00	1.16E-01	8.62E+01	1.33E-01	1.06E+04	3.27E+01
Coho	8.39E+00	1.47E-01	1.06E+02	1.64E-01	1.27E+04	3.94E+01
Chinook	7.28E+00	1.28E-01	9.39E+01	1.44E-01	1.14E+04	3.53E+01
Hake	6.78E+00	1.19E-01	8.83E+01	1.36E-01	2.59E+03	8.03E+00
Dogfish	1.27E+01	2.23E-01	1.54E+02	2.37E-01	3.40E+04	1.05E+02
Pollock	3.49E+00	6.13E-02	5.15E+01	7.92E-02	1.75E+03	5.43E+00
Northern smoothtongue	1.50E-02	2.63E-04	6.71E-02	1.03E-04	1.62E+03	5.01E+00
English sole	1.86E+01	3.26E-01	2.50E+02	3.85E-01	1.49E+04	4.62E+01
Cormorant (adult male)	1.40E+01	2.46E-01	2.82E+02	4.34E-01	1.76E+04	5.44E+01
Cormorant (adult female)	1.40E+01	2.46E-01	2.82E+02	4.34E-01	1.75E+04	5.41E+01
Heron (adult male)	1.40E+01	2.45E-01	2.79E+02	4.29E-01	5.93E+03	1.84E+01
Heron (adult female)	1.40E+01	2.45E-01	2.79E+02	4.29E-01	5.91E+03	1.83E+01
Seal (adult male)	7.30E+01	1.28E+00	1.13E+03	1.73E+00	4.64E+03	1.44E+01
Seal (adult female)	2.65E+01	4.64E-01	4.57E+02	7.03E-01	6.41E+03	1.99E+01
Seal (juvenile)	2.11E+01	3.69E-01	3.74E+02	5.76E-01	5.04E+03	1.56E+01
Seal (pup)	7.03E+01	1.23E+00	1.18E+03	1.82E+00	1.60E+04	4.94E+01
Cormorant egg	8.75E+00	1.54E-01	2.13E+02	3.28E-01	1.07E+04	3.32E+01
Heron egg	1.15E+01	2.02E-01	2.51E+02	3.86E-01	4.83E+03	1.50E+01

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

Table 5-5 (continued). Modified bioaccumulation model-predicted concentrations and BSAFs for miscellaneous chemical compounds.

	Dibezofuran		Hexachlorobutadiene		N-Nitrosodiphenylamine	
	conc. ppb	*BSAF*	*conc. ppb*	*BSAF*	*conc. ppb*	*BSAF*
Sediment	4.04E+02		1.05E+02		2.96E+02	
Water	2.66E-02		1.34E-03		2.02E-01	
Air	2.03E-04		1.27E-06		6.47E-03	
Phytoplankton	9.29E-01	2.30E-03	2.36E-01	2.25E-03	8.64E-01	2.92E-03
Kelp / Seagrass	1.80E+01	4.45E-02	4.57E+00	4.36E-02	1.34E+01	4.53E-02
Herbivorous zooplankton	3.88E+01	9.61E-02	1.26E+01	1.20E-01	2.70E+01	9.13E-02
N. plumchrus	1.08E+02	2.67E-01	3.49E+01	3.32E-01	7.50E+01	2.54E-01
P. minutus	3.88E+01	9.61E-02	1.26E+01	1.20E-01	2.70E+01	9.13E-02
Shellfish	1.56E+02	3.87E-01	4.10E+01	3.91E-01	1.16E+02	3.91E-01
Crabs	3.40E+02	8.43E-01	1.29E+02	1.23E+00	2.25E+02	7.61E-01
Grazing invertebrates	1.89E+02	4.69E-01	5.90E+01	5.62E-01	1.34E+02	4.53E-01
Carnivorous zooplankton	1.13E+02	2.79E-01	2.99E+01	2.85E-01	8.28E+01	2.80E-01
E. pacifica	5.83E+01	1.45E-01	1.57E+01	1.50E-01	4.29E+01	1.45E-01
Predatory invertebrates	2.53E+02	6.26E-01	9.78E+01	9.32E-01	1.65E+02	5.59E-01
Herring	5.88E+01	1.46E-01	3.01E+01	2.87E-01	3.50E+01	1.18E-01
Pelagic fish (seal prey)	4.98E+01	1.24E-01	2.89E+01	2.76E-01	2.83E+01	9.55E-02
Pelagic fish (bird prey)	2.21E+01	5.49E-02	1.07E+01	1.02E-01	1.37E+01	4.65E-02
River lamprey	1.23E+02	3.04E-01	7.17E+01	6.84E-01	7.98E+01	2.70E-01
Demersal fish (seal prey)	1.03E+02	2.56E-01	4.61E+01	4.40E-01	6.54E+01	2.21E-01
Demersal fish (bird prey)	6.87E+01	1.70E-01	2.44E+01	2.33E-01	4.72E+01	1.59E-01
Chum	6.31E+01	1.57E-01	4.72E+01	4.50E-01	3.44E+01	1.16E-01
Coho	8.01E+01	1.98E-01	5.88E+01	5.60E-01	4.39E+01	1.48E-01
Chinook	6.95E+01	1.72E-01	5.15E+01	4.91E-01	3.80E+01	1.28E-01
Hake	6.53E+01	1.62E-01	3.63E+01	3.46E-01	3.55E+01	1.20E-01
Dogfish	1.78E+02	4.40E-01	1.72E+02	1.64E+00	7.03E+01	2.38E-01
Pollock	2.98E+01	7.38E-02	1.58E+01	1.50E-01	1.77E+01	5.97E-02
Northern smoothtongue	5.75E+00	1.42E-02	8.76E+00	8.35E-02	4.07E-01	1.38E-03
English sole	1.42E+02	3.52E-01	6.39E+01	6.09E-01	9.46E+01	3.20E-01
Cormorant (adult male)	1.97E+03	4.88E+00	7.47E+02	7.12E+00	4.36E+02	1.47E+00
Cormorant (adult female)	1.94E+03	4.81E+00	7.37E+02	7.02E+00	4.33E+02	1.46E+00
Heron (adult male)	1.88E+03	4.66E+00	7.33E+02	6.98E+00	3.31E+02	1.12E+00
Heron (adult female)	1.79E+03	4.43E+00	6.95E+02	6.62E+00	3.23E+02	1.09E+00
Seal (adult male)	7.93E+03	1.96E+01	4.40E+03	4.19E+01	1.57E+03	5.32E+00
Seal (adult female)	1.04E+03	2.57E+00	5.50E+02	5.25E+00	4.45E+02	1.50E+00
Seal (juvenile)	1.75E+03	4.33E+00	9.57E+02	9.12E+00	4.09E+02	1.38E+00
Seal (pup)	7.06E+03	1.75E+01	3.75E+03	3.57E+01	2.86E+03	9.68E+00
Cormorant egg	1.19E+03	2.95E+00	4.52E+02	4.30E+00	2.67E+02	9.04E-01
Heron egg	1.46E+03	3.62E+00	5.68E+02	5.41E+00	2.65E+02	8.97E-01

Abbreviations and units: conc. = concentration, ppb =parts per billon, BSAF = Biota Sediment Accumulation Factor

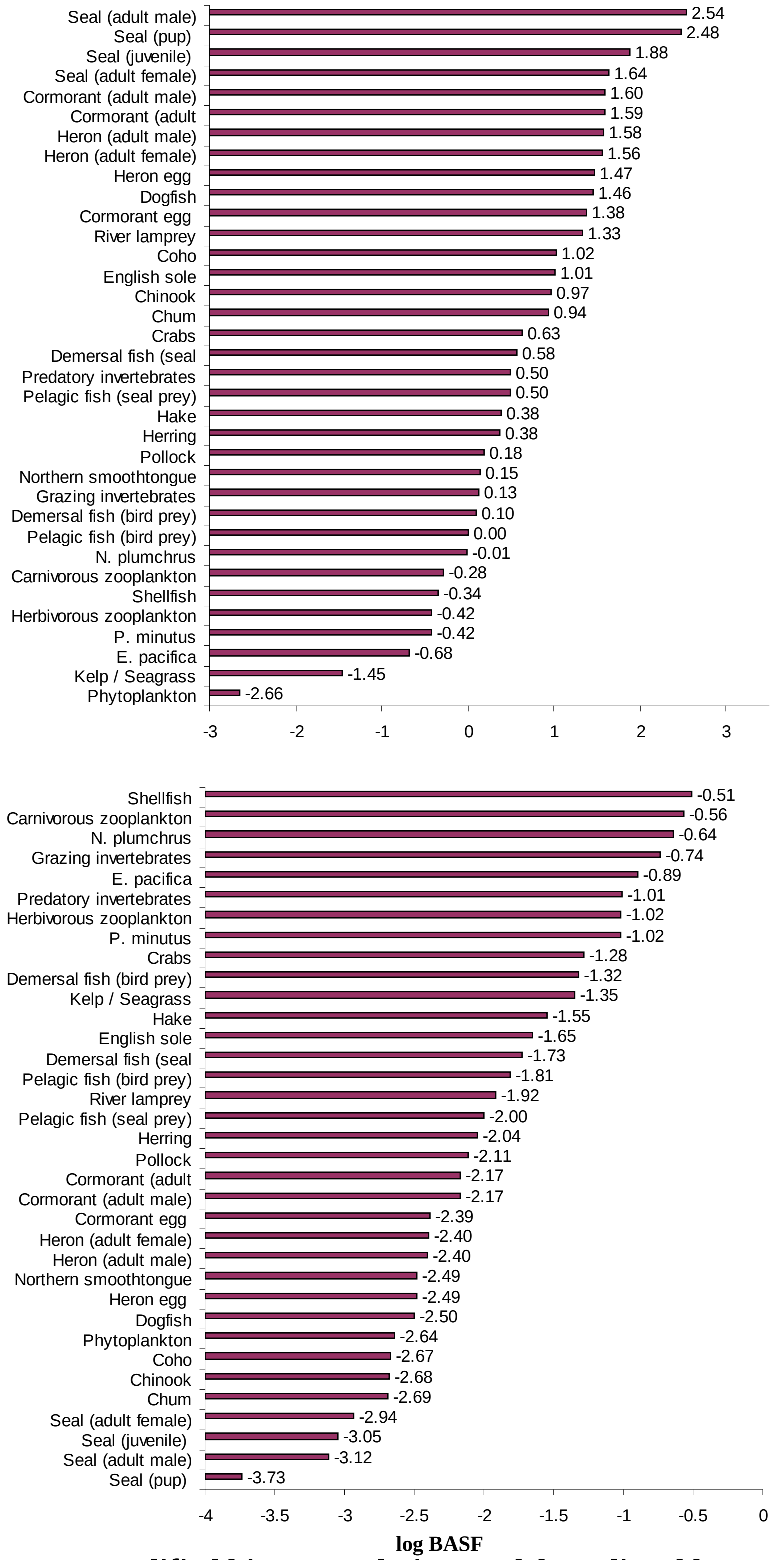

Figure 5-1. Modified bioaccumulation model predicted log-BSAFs for hexachlorobenzene (top) and fluorene (bottom).

Data were sorted by descending order.

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6.0 Modified Bioaccumulation Model Output Comparisons

Model-predicted concentrations of toxics in biota are compared to measured values in Puget Sound biota tissue samples. Model-predicted concentrations are also compared to various criteria designed to protect biota and human health.

6.1 Modified Bioaccumulation Model Output Compared to Puget Sound Tissue Samples

Ecology provided E & E with data sets that contained measured tissue toxics concentrations for some SMS compounds and organisms found in the bioaccumulation model's food web. A summary of these data along with model-predicted concentrations based on SQS input values are presented below (Table 6-1). The table does not include model-predicted concentrations for SMS compounds for which there were no empirical tissue data relevant to the food web's biota (predicted concentrations for all modeled SMS compounds can be found in Tables 5-1 through 5-5).

There are several "classes" of compounds with SQS compound-specific criteria. For example, there are 5 different phenols, 6 phthalates, and 16 PAHs. The sources of these toxics are varied. When compared to measured Puget Sound sediment compound-specific concentrations, the modified bioaccumulation model predicted concentrations are above the median measured value for some toxics and below the median for others (this is discussed in more detail in the following paragraph). The median value is defined as the concentration at which half the measured concentrations are greater than and half less than the median value. This suggests that there could be some bias in the model depending on the actual sediment concentration. This evaluation relied on tissue samples collected from numerous areas in Puget Sound which represent the entire spectrum of contaminated sediments. Some areas are relatively uncontaminated, other areas, such as certain urban embayments or estuaries like the Lower Duwamish Waterway may be contaminated by several different toxics at elevated levels.

Modified bioaccumulation model predictions (using SQS values) for the chlorinated benzenes are generally lower than the median observed tissue concentrations, though some predicted values do fall within reported tissue ranges. Hexachlorobenzene is one exception in which model predictions are substantially higher than observed values. Modified bioaccumulation model-predicted PAH concentrations are mostly higher than observed tissue concentrations, in some cases by as much as two orders of magnitude. Conversely, phthalates and phenols predictions tend to be lower than reported median tissue concentrations, though some fell within measured ranges. In theory and holding that all model assumptions are valid, instances in which model-predicted concentrations exceeded empirical concentrations indicate that the SQS are higher than sediment concentrations from areas where the biota used for these comparisons were sampled. Conversely, the SQS criteria represent less-contaminated conditions for model-predicted concentrations falling below measured toxics levels. Ecology is in the process of updating its historic sediment quality information system database and incorporating sediment data into its

Environmental Information Management System. Once completed, it may prove useful to compare actual sediment concentrations to SQS on a spatial basis.

While there may be some utility in comparing bioaccumulation model-predicted concentrations derived from the SQS to observed tissue concentrations, comparisons for the sake of determining the model's ability to accurately predict concentrations are inappropriate for several reasons. First and most obviously, the model utilized SQS values as input and not actual sediment data. As such, observed and predicted tissue concentrations would only be similar if site sediment contamination levels were comparable to SQS values. Second, the summary statistics provided on the following pages for observed tissue concentrations are from nine data files, containing many different studies which themselves include hundreds of different sampling locations. Across this many locations one would expect to find substantial variability not only in sediment contaminant concentrations but also in physical parameters that can substantially affect predicted model concentrations. For example, total organic carbon sediment concentrations and organic carbon sediment density are key variables in deriving water contaminant concentrations from sediment data and are known to vary substantially within Puget Sound (Michelsen and Bragdon-Cook 1993). Finally, there is extreme variability in much of the observed data, with values for a single compound and species ranging by as much as three orders of magnitude. Likewise, much of the data contained within these data files were flagged with some type of qualifier. For example, one of the datasets used for this analysis contained qualifiers for 689 of the 722 data points. Accurate observed tissue concentrations are essential for determining the quality of model output and need to be paired with sediment data from the same site. Qualifiers within all the provided datasets included:

B - Analyte detected in sample & blank, reported result without blank correction
E – Estimates above calibration range
J – Analyte identified, result estimated
L – Value likely less than reported
N – Tentatively identified analyte
NB – Tentatively identified analyte, reported result is without blank correction
U – Analyte not detected at or above reported limit
UJ – Analyte not detected at or above reported estimate

Table 6-1. Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
1,2,4- Trichlorobenzene	crab	21	499.7	570	57	580	17.9
	demersal (fillet, skin on)	3	576.7	580	570	580	3.6
	demersal (whole organism)	53	287.2	290	40	580	
	english sole (fillet, skin on)	8	505	575	290	580	7.5
	english sole (whole organism)	22	445.5	570	290	580	
	grazing invertebrate	13	50.5	50	50	56	10.1
	predatory invertebrate	12	61.1	56.5	49	100	13.2
	shellfish	26	52	40	39	100	8.4
	herring	-	-	-	-	-	*3.0*
	chinook	-	-	-	-	-	*3.5*
	seal (pup)	-	-	-	-	-	*174.6*
1,2 - Dichlorobenzene	crab	21	499.7	570	57	580	47.1
	demersal (fillet, skin on)	3	576.7	580	570	580	9.9
	demersal (whole organism)	53	287.2	290	40	580	
	english sole (fillet, skin on)	8	505	575	290	580	19.8
	english sole (whole organism)	22	445.5	570	290	580	
	grazing invertebrate	17	60.5	50	50	150	28.1
	predatory invertebrate	12	63.6	53	49	110	34.6
	shellfish	32	62	49.5	39	150	24.2
	herring	-	-	-	-	-	*7.3*
	chinook	-	-	-	-	-	*7.9*
	seal (pup)	-	-	-	-	-	*287.0*
1,4 - Dichlorobenzene	crab	21	499.7	570	57	580	63.9
	demersal (fillet, skin on)	56	302.7	580	40	580	13.3
	demersal (whole organism)	3	576.7	290	570	580	
	english sole (fillet, skin on)	8	505	575	290	580	26.8
	english sole (whole organism)	22	445.5	570	290	580	
	grazing invertebrateebrate	12	84.8	50	49	210	37.8
	predatory invertebrate	14	52.9	50	49	58	47.0
	shellfish	35	86.9	50	39	300	32.4
	herring	-	-	-	-	-	*10.1*
	chinook	-	-	-	-	-	*11.0*
	seal (pup)	-	-	-	-	-	*347.7*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	*taxonomic group*	*n*	*mean*	*median*	*min*	*max*	
			(ppb, ng/g, ug/kg)				*(ng/g)*
2,4 - Dimethylphenol	crab	21	1045.7	1200	120	1200	19.2
	demersal (fillet, skin on)	3	1200	1200	1200	1200	4.8
	demersal (whole organism)	53	580.9	570	79	1200	
	english sole (fillet, skin on)	8	1042.5	1200	570	1200	8.2
	english sole (whole organism)	22	915.9	1200	570	1200	
	grazing invertebrate	12	59.4	50	49	100	14.0
	predatory invertebrate	9	55.9	50	49	83	16.0
	shellfish	30	70.4	77.5	50	100	12.5
	herring	-	-	-	-	-	*2.9*
	chinook	-	-	-	-	-	*2.0*
	seal (pup)	-	-	-	-	-	*2.2*
2 - Methylnaphthalene	crab	20	0.62	0.48	0.31	1.3	103.9
	demersal (fillet, skin on)	3	1.6	2	0.94	2	78.0
	demersal (whole organism)	54	134	6.4	1.7	400	
	english sole (fillet, skin on)	9	1.8	1.9	0.96	2.8	47.1
	english sole (whole organism)	21	3.8	3.2	1.6	10	
	grazing invertebrate	6	50	50	50	50	273.9
	predatory invertebrate	12	55	50	49	83	172.7
	shellfish	33	36.4	50	0.41	100	356.4
	herring	-	-	-	-	-	*17.1*
	chinook	-	-	-	-	-	*4.4*
	seal (pup)	-	-	-	-	-	*0.5*
2 - Methylphenol	crab	21	1045.7	1200	120	1200	46.7
	demersal (fillet, skin on)	3	1200	1200	1200	1200	11.4
	demersal (whole organism)	53	580.5	580	79	1200	
	english sole (fillet, skin on)	8	1042.5	1200	570	1200	19.5
	english sole (whole organism)	22	915.9	1200	570	1200	
	grazing invertebrate	11	50.5	50	49	56	33.3
	predatory invertebrate	17	60.7	56	49	100	38.2
	shellfish	8	70.1	61	50	100	29.8
	herring	-	-	-	-	-	*6.9*
	chinook	-	-	-	-	-	*5.4*
	seal (pup)	-	-	-	-	-	*14.3*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.
n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	*taxonomic group*	*n*	*mean*	*median*	*min*	*max*	
			(ppb, ng/g, ug/kg)				*(ng/g)*
4 - Methylphenol	crab	21	1045.7	1200	120	1200	449.6
	demersal (fillet, skin on)	3	1200	1200	1200	1200	112.0
	demersal (whole organism)	53	577	580	20	1500	
	english sole (fillet, skin on)	8	1042.5	1200	570	1200	190.8
	english sole (whole organism)	22	915.9	1200	570	1200	
	grazing invertebrate	2	50	50	50	50	326.0
	predatory invertebrate	6	67.5	53	50	100	374.0
	shellfish	9	57.7	57	49	83	291.0
	herring	-	-	-	-	-	*68.1*
	chinook	-	-	-	-	-	*47.6*
	seal (pup)	-	-	-	-	-	*156.7*
Acenaphthene	crab	20	0.5	0.7	0.13	0.89	39.0
	demersal (fillet, skin on)	3	4.4	5	2.8	5.3	30.5
	demersal (whole organism)	54	136.8	13	4.6	400	
	english sole (fillet, skin on)	9	3.8	3.5	2	6.6	17.6
	english sole (whole organism)	21	8.2	8.1	3.5	22	
	grazing invertebrate	6	50	50	50	50	108.8
	predatory invertebrate	20	56.9	50	49	100	66.3
	shellfish	25	29.6	2.6	0.82	100	147.8
	herring	-	-	-	-	-	*6.5*
	chinook	-	-	-	-	-	*1.6*
	seal (pup)	-	-	-	-	-	*0.2*
Acenaphthylene	crab	20	0.6	0.72	0.13	0.72	260.7
	demersal (fillet, skin on)	3	0.32	0.26	0.26	0.44	166.7
	demersal (whole organism)	54	132.3	1.3	0.38	400	
	english sole (fillet, skin on)	9	0.6	0.7	0.26	1	119.5
	english sole (whole organism)	21	1.7	1.8	0.56	2.8	
	grazing invertebrate	6	50	50	50	50	557.3
	predatory invertebrate	14	58.9	53	49	99	396.9
	shellfish	31	33.6	49	0.56	100	643.0
	herring	-	-	-	-	-	*42.3*
	chinook	-	-	-	-	-	*11.6*
	seal (pup)	-	-	-	-	-	*0.8*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Anthracene	crab	20	0.35	0.23	0.09	0.9	184.8
	demersal (fillet, skin on)	3	0.58	0.51	0.41	0.82	180.6
	demersal (whole organism)	54	132.5	1.9	0.59	400	
	english sole (fillet, skin on)	9	1.03	1	0.4	1.7	72.1
	english sole (whole organism)	21	3.5	2.9	0.89	9	
	grazing invertebrate	6	50	50	50	50	729.4
	predatory invertebrate	11	62.2	57	49	100	368.6
	shellfish	34	35.9	50	1.8	100	1559.4
	herring	-	-	-	-	-	*33.4*
	chinook	-	-	-	-	-	*7.1*
	seal (pup)	-	-	-	-	-	*0.4*
Benz[a]anthracene	crab	20	0.52	0.72	0.08	0.72	21.4
	demersal (fillet, skin on)	3	0.18	0.13	0.06	0.34	13.4
	demersal (whole organism)	54	132.1	1.6	0.15	400	
	english sole (fillet, skin on)	9	0.41	0.5	0.17	0.72	1.7
	english sole (whole organism)	21	1.6	1.4	0.35	3.6	
	grazing invertebrate	6	50	50	50	50	72.4
	predatory invertebrate	18	52.2	50	49	58	53.9
	shellfish	12	75.7	74	50	100	100.7
	herring	-	-	-	-	-	*4.2*
	chinook	-	-	-	-	-	*0.3*
	seal (pup)	-	-	-	-	-	*0.02*
Benzo(a)pyrene	crab	20	0.66	0.72	0.18	0.72	17.9
	demersal (fillet, skin on)	3	0.46	0.5	0.37	0.5	10.7
	demersal (whole organism)	54	132.1	1.2	0.13	400	
	english sole (fillet, skin on)	9	0.51	0.5	0.18	0.72	1.1
	english sole (whole organism)	21	1.1	1.1	0.49	1.8	
	grazing invertebrate	13	59.6	56	50	99	59.3
	predatory invertebrate	8	52.5	50	49	58	45.8
	shellfish	40	113.3	50	3	500	66.0
	herring	-	-	-	-	-	*3.5*
	chinook	-	-	-	-	-	*0.2*
	seal (pup)	-	-	-	-	-	*0.02*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

		Puget Sound Tissue Study Data					Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Benzo(g,h,i)perylene	crab	20	0.66	0.72	0.22	0.72	4.0
	demersal (fillet, skin on)	3	0.34	0.36	0.16	0.5	2.1
	demersal (whole organism)	54	132	0.87	0.16	400	
	english sole (fillet, skin on)	9	0.46	0.5	0.2	0.72	0.1
	english sole (whole organism)	21	0.68	0.7	0.21	1.2	
	grazing invertebrate	8	43.8	50	25	50	12.7
	predatory invertebrate	14	60	53	49	100	10.4
	shellfish	29	47.6	50	25	100	8.1
	herring	-	-	-	-	-	*0.7*
	chinook	-	-	-	-	-	*0.02*
	seal (pup)	-	-	-	-	-	*0.003*
Benzofluoranthenes	grazing invertebrate	6	50	50	50	50	151.1
	predatory invertebrate	6	53.3	53	49	58	112.7
	shellfish	6	75.7	74	50	100	208.6
	herring	-	-	-	-	-	*8.7*
	chinook	-	-	-	-	-	*0.6*
	seal (pup)	-	-	-	-	-	*0.04*
Benzoic acid	crab	21	10457.1	12000	1200	12000	632.3
	demersal (fillet, skin on)	3	7466.7	5700	4700	12000	148.2
	demersal (whole organism)	53	5443.2	5700	800	54000	
	english sole (fillet, skin on)	8	5925	6000	5300	6500	250.0
	english sole (whole organism)	22	5213.6	5800	1900	6500	
	grazing invertebrate	10	1017	500	490	5600	436.8
	predatory invertebrate	18	1931.7	500	490	11000	502.1
	shellfish	21	1939.1	500	340	11000	397.4
	herring	-	-	-	-	-	*88.2*
	chinook	-	-	-	-	-	*93.9*
	seal (pup)	-	-	-	-	-	*1181.6*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Benzyl alcohol	crab	21	712	570	12	1200	44.6
	demersal (fillet, skin on)	3	433.3	570	180	580	9.6
	demersal (whole organism)	53	339.8	400	24	2100	
	english sole (fillet, skin on)	8	575	575	570	580	18.6
	english sole (whole organism)	22	370.5	570	79	610	
	grazing invertebrate	9	50	50	50	50	27.4
	predatory invertebrate	12	297.3	53	49	1600	33.2
	shellfish	28	154	40	39	1600	24.0
	herring	-	-	-	-	-	*6.8*
	chinook	-	-	-	-	-	*7.3*
	seal (pup)	-	-	-	-	-	*70.3*
Bis (2-ethylhexyl) Phthalate	crab	21	779	67	66	7200	0.83
	demersal (fillet, skin on)	3	67	67	67	67	0.31
	demersal (whole organism)	53	2429.3	2100	66	5000	
	english sole (fillet, skin on)	8	799.8	98.5	67	3600	0.004
	english sole (whole organism)	22	1770.4	591.5	66	7200	
	grazing invertebrate	6	50	50	50	50	2.54
	predatory invertebrate	23	508.7	78	50	9000	2.15
	shellfish	32	464.4	99.5	50	9000	1.22
	herring	-	-	-	-	-	*0.02*
	chinook	-	-	-	-	-	*0.001*
	seal (pup)	-	-	-	-	-	*0.0002*
Butyl benzyl phthalate	crab	21	956.2	1200	120	1200	2.6
	demersal (fillet, skin on)	3	1200	1200	1200	1200	2.5
	demersal (whole organism)	53	10765.9	1200	57	4000	
	english sole (fillet, skin on)	8	1042.5	1200	570	1200	0.9
	english sole (whole organism)	22	842.7	1200	290	1200	
	grazing invertebrate	6	50	50	50	50	10.7
	predatory invertebrate	12	52.8	50	49	65	5.5
	shellfish	33	54.7	50	39	100	27.0
	herring	-	-	-	-	-	*0.5*
	chinook	-	-	-	-	-	*0.1*
	seal (pup)	-	-	-	-	-	*0.005*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Chrysene	crab	20	0.54	0.72	0.13	0.8	21.5
	demersal (fillet, skin on)	3	0.39	0.51	0.14	0.53	13.5
	demersal (whole organism)	54	131.9	3.5	0.49	400	
	english sole (fillet, skin on)	9	0.41	0.5	0.12	0.72	1.7
	english sole (whole organism)	21	2.4	2	0.5	9	
	grazing invertebrate	6	50	50	50	50	72.7
	predatory invertebrate	14	60.6	56.5	49	100	54.0
	shellfish	31	52.2	50	20	100	102.0
	herring	-	-	-	-	-	*4.2*
	chinook	-	-	-	-	-	*0.3*
	seal (pup)	-	-	-	-	-	*0.02*
Di-n-octyl phthalate	crab	21	2194.8	2900	290	2900	0.68
	demersal (fillet, skin on)	3	2900	2900	2900	2900	0.25
	demersal (whole organism)	53	2164.9	1500	290	4000	
	english sole (fillet, skin on)	8	2550	2900	1500	2900	0.003
	english sole (whole organism)	22	1933.6	2900	290	2900	
	grazing invertebrate	13	55.1	50	49	99	2.09
	predatory invertebrate	13	63.3	60	49	100	1.77
	shellfish	25	50.2	40	39	100	1.00
	herring	-	-	-	-	-	*0.01*
	chinook	-	-	-	-	-	*0.0003*
	seal (pup)	-	-	-	-	-	*0.0002*
Di-n-butyl phthalate	crab	21	385.5	400	31	580	98.1
	demersal (fillet, skin on)	3	936.7	1200	410	1200	92.9
	demersal (whole organism)	53	717	290	57	2300	
	english sole (fillet, skin on)	8	467.5	420	160	1200	29.7
	english sole (whole organism)	22	786.4	1200	290	1200	
	herring	-	-	-	-	-	*18.8*
	chinook	-	-	-	-	-	*3.4*
	seal (pup)	-	-	-	-	-	*0.2*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.
n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Dibenzo (a,h) anthracene	crab	20	0.66	0.72	0.13	0.72	1.7
	demersal (fillet, skin on)	3	0.57	0.5	0.5	0.71	0.9
	demersal (whole organism)	54	132.2	0.72	0.14	400	
	english sole (fillet, skin on)	9	0.5	0.5	0.24	0.72	0.1
	english sole (whole organism)	21	0.48	0.5	0.12	0.72	
	grazing invertebrate	6	50	50	50	50	5.4
	predatory invertebrate	20	56.5	50	49	99	4.4
	shellfish	25	29.6	1.7	0.63	100	3.6
	herring	-	-	-	-	-	*0.3*
	chinook	-	-	-	-	-	*0.01*
	seal (pup)	-	-	-	-	-	*0.001*
Dibezofuran	crab	20	0.29	0.17	0.09	0.83	340.3
	demersal (fillet, skin on)	3	2.33	2.3	1.6	3.1	68.7
	demersal (whole organism)	54	134.4	6.6	2.2	400	
	english sole (fillet, skin on)	9	1.7	1.6	0.92	2.9	142.0
	english sole (whole organism)	21	3.8	3.7	1.6	9.5	
	grazing invertebrate	13	58.8	50	50	100	189.4
	predatory invertebrate	6	53.3	53	49	58	252.5
	shellfish	32	33.9	49.5	0.61	100	156.0
	herring	-	-	-	-	-	*58.8*
	chinook	-	-	-	-	-	*69.5*
	seal (pup)	-	-	-	-	-	*7062.4*
Diethyl phthalate	crab	21	747.2	1200	21	1200	80.3
	demersal (fillet, skin on)	3	1200	1200	1200	1200	74.3
	demersal (whole organism)	53	333.9	170	18	1200	
	english sole (fillet, skin on)	8	931.1	1200	99	1200	34.1
	english sole (whole organism)	22	830	1200	100	1200	
	grazing invertebrate	8	79.8	50	50	280	285.8
	predatory invertebrate	16	60.9	56.5	49	100	151.0
	shellfish	50	87.4	61	9.5	500	501.3
	herring	-	-	-	-	-	*13.9*
	chinook	-	-	-	-	-	*3.2*
	seal (pup)	-	-	-	-	-	*0.2*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Dimethyl phthalate	crab	21	497.3	570	7.6	580	1318.2
	demersal (fillet, skin on)	3	576.7	580	570	580	333.8
	demersal (whole organism)	53	351.3	400	9.9	2900	
	english sole (fillet, skin on)	8	505	575	290	580	525.4
	english sole (whole organism)	22	445.5	570	290	580	
	grazing invertebrate	6	50	50	50	50	992.0
	predatory invertebrate	19	131.5	50	49	500	1107.8
	shellfish	36	94.5	50	39	500	914.4
	herring	-	-	-	-	-	*183.8*
	chinook	-	-	-	-	-	*157.1*
	seal (pup)	-	-	-	-	-	*1.1*
Fluoranthene	crab	20	0.62	0.5	0.18	3	47.2
	demersal (fillet, skin on)	3	2.1	1.8	1.4	3.1	39.5
	demersal (whole organism)	54	134.4	7.9	2.3	400	
	english sole (fillet, skin on)	9	1.3	1.4	0.82	1.7	9.9
	english sole (whole organism)	21	4.9	4	2.3	11	
	grazing invertebrate	15	35	25	25	50	182.5
	predatory invertebrate	64	986.3	745	25	3500	109.4
	shellfish	90	666.4	360	25	3500	465.7
	herring	-	-	-	-	-	*9.2*
	chinook	-	-	-	-	-	*1.3*
	seal (pup)	-	-	-	-	-	*0.1*
Fluorene	crab	20	0.29	0.175	0.08	0.98	32.4
	demersal (fillet, skin on)	3	2.1	1.6	1.4	3.3	29.6
	demersal (whole organism)	54	133	6.5	1.6	400	
	english sole (fillet, skin on)	9	1.2	1.3	0.69	2.1	13.9
	english sole (whole organism)	21	2.9	2.7	1.2	6.3	
	grazing invertebrate	6	50	50	50	50	113.0
	predatory invertebrate	15	56.4	56	49	83	60.4
	shellfish	30	34.4	26.8	0.81	100	192.3
	herring	-	-	-	-	-	*5.6*
	chinook	-	-	-	-	-	*1.3*
	seal (pup)	-	-	-	-	-	*0.1*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Hexachlorobenzene	chinook	48	0.37	0.39	0.06	0.74	95.6
	chum	4	0.27	0.21	0.04	0.61	88.3
	coho	7	0.64	0.62	0.57	0.74	107.3
	crab	21	3.3	1.5	0.65	7.2	43.4
	demersal (fillet, skin on)	3	7.2	7.2	7.2	7.2	12.9
	demersal (whole organism)	55	19.5	1.5	1	570	
	english sole (fillet, skin on)	8	41.8	7.2	1.1	290	104.9
	english sole (whole organism)	23	7.9	7.2	4.1	10	
	grazing invertebrate	23	27.5	33	1.2	58	13.7
	predatory invertebrate	12	63.75	56.5	49	140	32.1
	shellfish	56	57.9	33	0.38	300	4.7
	herring	-	-	-	-	-	*24.5*
	seal (pup)	-	-	-	-	-	*3056.5*
Hexachlorobutadiene	crab	21	499.7	570	57	580	128.6
	demersal (fillet, skin on)	3	576.7	580	570	580	24.4
	demersal (whole organism)	53	287.2	290	40	580	
	english sole (fillet, skin on)	8	505	575	290	580	63.9
	english sole (whole organism)	22	445.5	570	290	580	
	grazing invertebrate	10	123	50	50	360	59.0
	predatory invertebrate	11	51.8	50	49	58	97.8
	shellfish	40	110.1	53	39	500	41.0
	herring	-	-	-	-	-	*30.1*
	chinook	-	-	-	-	-	*51.5*
	seal (pup)	-	-	-	-	-	*3748.0*
Indeno(1,2,3-cd)pyrene	crab	20	0.65	0.72	0.21	0.72	4.1
	demersal (fillet, skin on)	3	0.31	0.32	0.11	0.5	2.0
	demersal (whole organism)	54	132	0.91	0.12	400	
	english sole (fillet, skin on)	9	0.46	0.5	0.19	0.72	0.1
	english sole (whole organism)	21	0.71	0.71	0.16	1.4	
	grazing invertebrate	10	50	50	50	50	12.8
	predatory invertebrate	16	56	56	49	83	10.6
	shellfish	10	75.2	74	49	100	7.8
	herring	-	-	-	-	-	*0.7*
	chinook	-	-	-	-	-	*0.02*
	seal (pup)	-	-	-	-	-	*0.003*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

		Puget Sound Tissue Study Data					Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
HPAH	grazing invertebrate	6	50	50	50	50	628.6
	predatory invertebrate	6	53.3	53	49	58	469.2
	shellfish	6	75.7	74	50	100	863.1
	herring	-	-	-	-	-	*36.2*
	chinook	-	-	-	-	-	*2.4*
	seal (pup)	-	-	-	-	-	*0.2*
LPAH	grazing invertebrate	6	50	50	50	50	2516.7
	predatory invertebrate	6	53.3	53	49	58	1532.6
	shellfish	6	75.7	74	50	100	3418.1
	herring	-	-	-	-	-	*149.6*
	chinook	-	-	-	-	-	*37.6*
	seal (pup)	-	-	-	-	-	*3.9*
N-nitrosodiphenylamine	crab	21	499.7	570	57	580	225.2
	demersal (fillet, skin on)	3	576.7	580	570	580	47.2
	demersal (whole organism)	53	353.9	400	40	2900	
	english sole (fillet, skin on)	8	505	575	290	580	94.6
	english sole (whole organism)	22	445.5	570	290	580	
	grazing invertebrate	6	50	50	50	50	134.2
	predatory invertebrate	6	53.3	53	49	58	165.5
	shellfish	11	134.9	100	300	250	115.6
	herring	-	-	-	-	-	*35.0*
	chinook	-	-	-	-	-	*38.0*
	seal (pup)	-	-	-	-	-	*2864.1*
Naphthalene	crab	20	1.8	1.9	1.4	2.2	883.2
	demersal (fillet, skin on)	3	2.2	1.6	1.3	3.7	349.4
	demersal (whole organism)	54	134.4	8.1	2.4	400	
	english sole (fillet, skin on)	9	3.1	3.5	1.7	4.1	399.2
	english sole (whole organism)	21	5.7	5.5	2.6	12	
	grazing invertebrate	6	50	50	50	50	1063.5
	predatory invertebrate	14	54.2	50	49	83	1011.5
	shellfish	31	35.6	50	0.57	100	1019.6
	herring	-	-	-	-	-	*139.2*
	chinook	-	-	-	-	-	*50.4*
	seal (pup)	-	-	-	-	-	*10.5*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Abbreviations: LPAH = low molecular weight polycyclic aromatic hydrocarbons, HPAH = molecular weight polycyclic aromatic hydrocarbons

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

			Puget Sound Tissue Study Data				Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Pentachlorophenol	crab	21	628.3	3.3	3.3	5700	124.7
	demersal (fillet, skin on)	3	5.6	6.7	3.3	6.7	47.9
	demersal (whole organism)	53	1990.3	1200	1.3	5700	
	english sole (fillet, skin on)	8	1453.2	7.7	3.3	5800	56.2
	english sole (whole organism)	22	1524.3	803.4	1.1	5800	
	grazing invertebrate	31	218.1	250	111.5	500	145.2
	predatory invertebrate	32	188.2	113.3	65	1500	140.1
	shellfish	72	310.8	170	64.8	1500	138.2
	herring	-	-	-	-	-	*19.6*
	chinook	-	-	-	-	-	*7.3*
	seal (pup)	-	-	-	-	-	*0.1*
Phenanthrene	crab	20	0.77	0.49	0.31	5.9	82.3
	demersal (fillet, skin on)	3	3.6	1.9	1.7	7.3	80.5
	demersal (whole organism)	54	134.8	11	1.9	400	
	english sole (fillet, skin on)	9	1.5	1.6	0.82	2.4	31.9
	english sole (whole organism)	21	4.2	3.3	1.9	13	
	grazing invertebrate	18	54.2	50	49	83	325.8
	predatory invertebrate	6	53.3	53	49	58	164.6
	shellfish	27	37.5	19	4	100	702.7
	herring	-	-	-	-	-	*14.9*
	chinook	-	-	-	-	-	*3.1*
	seal (pup)	-	-	-	-	-	*0.2*
Phenol	crab	21	1302	1500	43	1500	441.3
	demersal (fillet, skin on)	3	1500	1500	1500	1500	115.8
	demersal (whole organism)	53	653.8	720	17	1500	
	english sole (fillet, skin on)	8	1302.5	1500	710	1500	171.6
	english sole (whole organism)	22	1145	1500	710	1500	
	grazing invertebrate	12	50	50	50	50	347.7
	predatory invertebrate	12	389.3	99.5	49	1500	380.7
	shellfish	37	137.4	65	18	520	325.4
	herring	-	-	-	-	-	*59.2*
	chinook	-	-	-	-	-	*51.1*
	seal (pup)	-	-	-	-	-	*299.9*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

Table 6-1 (continued). Summary statistics for Puget Sound tissue data by SMS compound and organism/taxonomic group and the modified bioaccumulation model-predicted biota concentrations.

n = number organisms for the given chemical. Tissue data reported as ppb or equivalent. SMS compounds not included in the empirical datasets were not listed. Selected higher taxa (*italicized*) not included in the empirical datasets are listed for reference.

		Puget Sound Tissue Study Data					Modeled ouput
compound	***taxonomic group***	***n***	***mean***	***median***	***min***	***max***	
			(ppb, ng/g, ug/kg)				*(ng/g)*
Pyrene	crab	20	0.42	0.28	0.16	2.5	408.1
	demersal (fillet, skin on)	3	0.89	1	0.48	1.2	379.6
	demersal (whole organism)	54	133.1	4.3	1.1	400	
	english sole (fillet, skin on)	9	0.56	0.54	0.33	0.91	116.5
	english sole (whole organism)	21	3.1	2.8	1.2	7.7	
	grazing invertebrate	26	34.5	25	11	50	1657.7
	predatory invertebrate	16	60.6	57	25	100	896.1
	shellfish	39	46.3	49	11	130	4420.7
	herring	-	-	-	-	-	*78.7*
	chinook	-	-	-	-	-	*13.6*
	seal (pup)	-	-	-	-	-	*0.7*

Units: ppb = parts per billion, ng/g = nanograms per gram, ug/kg = micrograms per kilograms

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6.2 Comparison of Modified Bioaccumulation Model-Predicted Toxics Concentrations in Puget Sound Water and Biota to Water Quality and Tissue Residue Criteria

Introduction

In previous sections, E & E described how it modified and used the Food Web Bioaccumulation Model developed by Condon (2007) to simulate the flux of toxics from sediment to biota and then compared model output to Puget Sound tissue samples. The model employs the well-established bioaccumulation equation that equates the rate of change in toxic concentration in an aquatic organism (for example, mussel, fish, or seal) with the sum of the fluxes into and out of the organism. The bioaccumulation mass balance is repeatedly applied to biota in successive trophic levels to simulate the biomagnifications of toxics from sediment to primary producers (plants) to secondary producers (herbivores) to forage species (carnivores and omnivores) to top predators (seals or marine birds). E & E used the modified bioaccumulation model and the Washington Sediment Management Standards (SMS) Sediment Quality Standard levels (SQS) to predict toxin water and biota concentrations in a food web applicable to Puget Sound. That is, the modified bioaccumulation model assumes that sediment contaminants are the maximum allowed by the SQS, and then projects how much of each contaminant would enter the water and how much would bioaccumulate in various organisms under various conditions.

The purpose of the current effort is to evaluate whether the SMS effectively protect marine life and human health from bioaccumulative effects. The evaluation compares concentrations the modified model predicts will be in water and organisms based on the SQS levels in marine sediments to various criteria that have been established based on toxicity and bioaccumulation effects on organisms. This will allow Ecology to determine whether SQS values result in water and tissue contaminant concentrations that fall below exposure thresholds established by these various criteria.

Approach and Rationale

Comparing model-predicted toxics concentrations to results derived from empirical studies is complicated by several factors including variability in study methods (for example, delivery method of study compound), experimental endpoints, and environmental conditions. Observers differ in how they characterize effects and examine the toxicity of compounds in terms of their LOEL/LOEC (lowest observable effects level/concentration), NOEL/NOEC (no observable effects level/concentration), LD_{50}/LC_{50} (dose or concentration lethal to 50% of the subject population), ED_{50}/EC_{50} (dose or concentration producing a defined response in 50% of the test population), and MATC (maximum acceptable toxicant concentration). The effects themselves also vary across studies, and include measures such as mortality, development, growth, enzymatic activity, cellular processes, and many others. The variability among studies commonly results in wide ranges of concentration levels for a single compound and effect. Additionally, comparisons can be hampered by lack of available empirical data for specific species and because freshwater and marine organisms can differ in their sensitivity to a specific contaminant, comparisons across media are not reliable.

To provide the most useful assessment possible, E & E adopted an approach using single studies, reviews, and databases to compare model predictions to effect-based standards and criteria over several levels of assessment. Specifically, model-predicted water and biota concentrations are compared to standards at multiple levels including: water quality criteria for human health, water criteria for protection of marine life, tissue residue guidelines for piscivorous wildlife using marine habitats, and tissue residue guidelines for protection of human health. While data for some SMS compounds are not available, this approach maximizes the number of SMS compounds that could be compared with at least one analysis level. This is particularly important because data for many of the species used in the model's food web are lacking, and often the type and level of effects for a particular contaminant vary across species.

MacDonald et al. (1999) provided one of the most comprehensive toxicity benchmarks reviews and was relied upon as the primary source for general comparisons. The review included quality criteria and guidelines from around the world and within multiple jurisdictions, though for human health tissue guidelines, most of the available criteria originated from the United States Environmental Protection Agency (US EPA). Benchmarks were included in MacDonald (1999) only after they met all three of the following criteria: (1) methods used to derive benchmarks were evident, (2) the source of the benchmark was apparent, and, most importantly, (3) *the benchmarks were effect based*. Additional criteria and data sources used to compare the modified bioaccumulation model's output include: the ECOTOXicology database system (EPA 2007), the National Recommended Water Quality Criteria (EPA 2002 & 2006), the US EPA's Toxicity and Residue database, and the United States Army Corp of Engineers' (USACE 2007) Environmental Residue-Effects Database (ERED), which digitized the work of Jarvinen and Ankley (1999). The databases above are comprised of peer reviewed empirical research and, with the exception of USACE's ERED, are updated routinely. For each comparison using the above references (described below), values are reported only for marine and estuarine waters and organisms, though in some instances threshold levels were inclusive of both fresh and marine waters.

Recently, more specialized means to determine tissue contaminant thresholds for the protection of both human and wildlife health have been developed. Studies employing these methods focus on region-wide or even site-specific conditions, and while they may vary in their assumptions, are often more stringent than even the lower ranges provided by MacDonald et al. (1999). These methods seek to provide tissue-level thresholds based on fish consumption rates and human health risks assessments and are back-calculated using accepted risk levels for carcinogenic and/or non-carcinogenic effects. As a point of reference, comparisons are provided here between modified bioaccumulation model-predicted biota concentrations and tissue concentration thresholds (or equivalent) from: Lower Duwamish Waterway Remedial Investigation (US EPA and Ecology 2007), Portland Harbor Remedial Investigation and Feasibility Study (Lower Willamette Group 2007), Guidance for Assessing Bioaccumulative Chemicals of Concern in Sediment (Oregon Department of Environmental Quality 2007), and the Northwest Regional Sediment Evaluation Framework (USACE and US EPA 2006)/Regional Sediment Evaluation Team (RSET). *Most of the above references are in draft or interim form, may undergo further review, and are subject to change. In the case of RSET's total tissue levels, these criteria have not yet been published and were provided by RSET team members.* The above references establish thresholds for only a few of the SMS compounds and therefore provide a limited opportunity for comparison with model-predicted biota concentrations. For all comparisons, readers should consult the original publications for more information on the equations used to calculate threshold tissue levels, ingestion scenarios, and other relevant assumptions.

Modified Bioaccumulation Model Output Comparisons

The comparisons described below assume that the modified bioaccumulation model accurately predicts water and tissue contaminant concentrations for each of the SMS compounds. Implicit in this assumption is that all the chemical and environmental properties, metabolic transformation rates, and food web assumptions used in the model are reasonable. Comparisons based on water concentration outputs are likely to be more valid than those based on tissue concentrations because model-predicted water concentrations rely on fewer assumptions. The relationship between sediment toxics concentrations and tissue toxics concentrations (flux from sediment to biota) is extremely complex, is often not fully understood, and is dependent on more factors than just food web relationships and the solubility of compounds in water and lipids. Again, data and criteria are not available for all SMS compounds.

Bioaccumulation model output compared to water quality criteria for human health

Model-predicted water contaminant concentrations are compared to water quality benchmarks developed for the protection of human health (Table 6-2). These benchmarks represent safe water concentration thresholds, below which bioaccumulation by marine animals is not expected to pose a significant threat to humans through ingestion of such animals. Comparisons are made to both the highest and lowest available benchmarks reported in MacDonald et al. (1999), as well as to the EPA’s (2002 & 2006) criteria (organism consumption only, excludes contact with water). In general, there are few exceedances of the ranges presented in MacDonald et al., and only PCBs exceed criteria set by the EPA.

Bioaccumulation model output compared to water criteria for the protection of marine life

Model-predicted water contaminant concentrations are compared to water quality benchmarks developed for the protection of marine life (Table 6-3). Because the model assumes steady state conditions, predicted water contaminant concentrations are relevant to both acute and chronic exposure limits. These benchmarks represent safe water concentration thresholds, below which exposure is not expected to pose significant health risks. Comparisons are made to both acute and chronic exposure levels where both are available, as well as to the lowest effect level recorded in the EPA’s ECOTOXicology database system. In no instances do model-predicted water concentrations exceed acute criteria levels and only in three cases are chronic exposure levels exceeded.

Bioaccumulation model output compared to tissue level concentration limits for the protection of marine life

Model-predicted fish tissue contaminant concentrations are compared to critical tissue level concentrations (Oregon Department of Environmental Quality 2007) developed for the protection of marine life (Table 6-4). The comparison includes both the lowest and highest predicted concentrations from all the fish species included in the model’s food web as well as shellfish and crab concentrations. These benchmarks represent safe tissue concentration thresholds, below which significant health effects to the aquatic organisms whose tissues contain these chemicals are not expected to occur. SQS values resulted in model-predicted biota concentration that exceed safe limits for three of the five compounds for which there are criteria.

Predicted PCB concentrations for low and high fish values and for crabs exceed critical tissue levels.

Bioaccumulation model output compared to residue guidelines for piscivorous wildlife using marine habitats

Model-predicted fish tissue contaminant concentrations are compared to tissue residue benchmarks developed for the protection of wildlife feeding primarily on fishes (Tables 6-5a and 6-5b). These benchmarks represent safe tissue concentration thresholds, below which ingestion is not expected to result in adverse effects. The comparison includes both the lowest and highest predicted concentrations from all the fish species included in the model's food web and, where applicable, shellfish and crab concentrations. The lack of available standards results in very few comparisons between model-predicted tissue concentrations and tissue residue criteria. However, as with comparisons to other criteria, SQS-based PCB concentrations exceed tissue residue criteria and acceptable tissue level guidelines.

Bioaccumulation model output compared to tissue residue guidelines for the protection of human health

Model-predicted fish tissue contaminant concentrations are compared to tissue residue benchmarks and target tissue levels developed for protection of human health (Tables 6-6a through 6-6c). These benchmarks represent safe tissue concentration thresholds, below which ingestion by humans is not expected to pose a significant health risk. Benchmarks listed in Table 6-6a represent the lowest available criteria from Mac Donald (1999). Tables 6-6b and 6-6c used target tissue levels reported for the most conservative (protective) excess cancer risk (usually 1×10^{-6}) provided by the referenced studies. Comparisons are made to fish commonly used as a source of food from the model's food web (chum, Coho, and Chinook salmon and herring, hake, pollock, and English sole), as well as shellfish and crabs where applicable. While most model-predicted concentrations do not exceed criteria reported in MacDonald et al. (1999, Table 6-6a), there are numerous exceedances of regionally specific and site-specific criteria (Tables 6-6b & 6-6c). In some cases both the carcinogenic and noncarcinogenic levels are surpassed.

Table 6-2. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound waters and marine water quality criteria derived for human health.
Upper and lower criteria represent the range of guidelines reported in MacDonald et al. (1999). EPA values are from the National Recommended Water Quality Criteria (2002). Shaded cells indicate an exceedance of the model predicted concentration relative to the applicable standard.

	Model predicted H_2O concentrations (ppb)	Water quality criteria (ppb)		
		lower	*upper*	*EPA*
PAHs				
Acenaphthene	0.0473	0.02	2700	990
Anthracene	0.1719	110,000	110,000	40000
Benz(a)anthracene	0.0030	0.049	0.49	0.018
Benzo(a)pyrene	0.0017	0.0006	0.49	0.018
Chrysene	0.0030	0.049	0.49	0.018
Dibenzo(a,h)anthracene	0.0001	0.0053	0.49	0.018
Fluoranthene	0.0214	9.4	370	140
Fluorene	0.0348			5,300
Indeno(1,2,3-CD)pyrene	0.0001	0.049	0.49	0.018
Naphthalene	1.8466	1	1	
Pyrene	0.2628	11000	11000	4,000
Phthalates				
Bis (2-ethylhexyl) phthalate	0.000005	1	59000	2.2
Butyl benzyl phthalate	0.0020	5,200	5,200	1,900
Diethyl phthalate	0.0847	21,000	1,800,000	44,000
Dimethyl phthalate	44.63	530,000	3,700,000	1,100,000
Di-N-Butyl phthalate	0.0675	2,100	12,000	4,500
Phenol				
2,4-Dimethylphenol	0.1672	0.4	2300	850
2-Methylphenol	0.6879	0.4	0.4	
4-Methylphenol	4.1266	0.1	0.1	
Pentachlorophenol	0.2709	0.83	82	3
Phenol	19.98	4,600,000	4,600,000	1,700,000
Chlorinated Benzens				
1,2,4 Trichlorobenzene	0.0019	940	2700	940
1,2-Dichlorobenzene	0.0437	0.25	17000	17,000
1,4-Dichlorobenzene	0.0309	2,600	3,400	2,600
Hexachlorobenzene	0.00001	0.00012	0.17	0.00029
Other Contaminants				
Hexachlorobutadiene	0.0013	0.3	1300	18
N-Nitrosodiphenylamine	0.2023	2.8	160	6
Total PCBs	0.0001	0.00007	0.00044	0.000064

Table 6-3. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound waters, marine water quality criteria derived for the protection of marine life, and the lowest observed effect levels (LOEL) and corresponding effects class.

Acute and chronic values are the most conservative (lowest) criteria reported in MacDonald et al. (1999). LOEL values are the lowest reported concentrations from all available studies in the EPA's ECOTOXicology database system. The observed effect class is reported in the adjacent cells. Shaded cells indicate an exceedance of the model predicted concentration relative to the applicable standard and or LOEL.

	Model predicted	Water quality criteria		ECOTOX database	
	H_2O concentrations	*acute*	*chronic*	*LOEL*	*effect*
		~ all values ppb ~			
PAHs					
2-Methylnaphthalene	0.1298	38	4.2		
Acenaphthene	0.0473	970	710	25	reproductive
Anthracene	0.1719	300		3	genetic
Benz(a)anthracene	0.0030	300			
Benzo(a)pyrene	0.0017	300	0.01	6.88	enzymatic
Benzo(g,h,i)perylene	0.0001	300			
Chrysene	0.0030	300	0.1		
Fluoranthene	0.0214	40	16	0.81	growth
Fluorene	0.0348			10.8	mortality
Indeno(1,2,3-CD)pyrene	0.0001	300			
Naphthalene	1.8466	2,350	1	0.000085	behavioral
Phenanthrene	0.0760	7.7	4.6	1	development
Pyrene	0.2628	300		0.91	growth
Phthalates					
Bis (2-ethylhexyl) phthalate	0.000005	2,944	3.4		
Butyl benzyl phthalate	0.0020	2,944	3.4		
Diethyl phthalate	0.0847			10,000	development
Dimethyl phthalate	44.63	2,944	3.4		
Di-N-Butyl phthalate	0.0675	2,944	3.4	1,887	mortality
Phenol					
2,4-Dimethylphenol	0.1672	210	170	197	mortality
2-Methylphenol	0.6879			12,000	multiple
4-Methylphenol	4.1266			5,000	multiple
Pentachlorophenol	0.2709	13	7.9	20	reproductive
Phenol	19.98	5,800		100	behavior
Chlorinated Benzens					
1,2,4 Trichlorobenzene	0.0019	160	5.4		
1,2-Dichlorobenzene	0.0437	1,970	42	1,000	growth
1,4-Dichlorobenzene	0.0309	1,970			
Hexachlorobenzene	0.00001	160	129		
Other Contaminants					
Hexachlorobutadiene	0.0013	32	0.3		
N-Nitrosodiphenylamine	0.2023	3,300,000			
Total PCBs	0.00012	10	0.0001		

ECOTOX query criteria were set to saltwater only; animals only; taxon= crustacean, fish, mollusks, worms; concentration endpoint = EC/EDxx, LOEL/LOEC, MATC. All other criteria set to default values.

Table 6-4. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound fishes, shellfish, and crabs and critical tissue levels for protection of organisms whose tissues contain the listed contaminants.

Critical tissue levels are from Oregon Department of Environmental Quality 2007. Fish (low) and fish (high) are the lowest and highest predicted concentrations in all Puget Sound fishes modeled. Shaded cells indicate an exceedance of the model-predicted concentration relative to the critical tissue level.

	Model predicted contaminant biota concentrations (ppb)				**Critical Tissue Level (ppb)**
	fish (low)	*fish (high)*	*shellfish*	*crabs*	
Fluoranthene	1.3	39.5	465.7	47.2	19,000
Pentachlorophenol	0.35	56.00	138.21	124.68	87
Pyrene	13.3	379.6	4,420.7	408.1	1,000
Hexachlorobenzene	12.9	296.0	4.7	43.4	32,000
Total PCBs	1,195	33,983	209	2,600	930

Table 6-5a. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound fish and residue criteria derived for the protection of piscivorous *wildlife* utilizing marine habitats.

Fish (low) and fish (high) are the lowest and highest predicted concentrations in all Puget Sound fishes modeled. Tissue residue criteria values (MacDonald et al. 1999) are presented for both carcinogenic and non-carcinogenic effects. Light shaded cells indicate an exceedance of the carcinogenic criteria only. Darker cells indicate exceedances of both the carcinogenic and non-carcinogenic criteria.

	Model predicted contaminant concentrations in fish (ppb)		**Tissue residue criteria (ppb) *effect type***	
	low	*high*	*carcinogenic*	*non-carcinogenic*
Pentachlorophenol	0.35	56		2000
Hexachlorobenzene	10.3	296	200	330
Total PCBs	1,195	33,983	110	110

Table 6-5b. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound fish, shellfish, and crabs and residue criteria derived for the protection of piscivorous *mammals* utilizing marine habitats.

Fish (low) and fish (high) are the lowest and highest predicted concentrations in all Puget Sound fishes modeled. Acceptable tissue levels (Oregon Department of Environmental Quality 2007 & US EPA and Ecology 2007) are presented for individuals and populations. Shaded cells indicate an exceedance of the model predicted concentration relative to the applicable standard.

	Model predicted contaminant biota concentrations (ppb)				**Acceptable Tissue Level (ppb)**	
	fish (low)	*fish (high)*	*shellfish*	*crabs*	*individual*	*population*
Fluoranthene	1.3	39.5	465.7	47.2	190,000	950,000
Pentachlorophenol	0.4	56.0	138.2	124.7	180	1,800
Pyrene	13.3	379.6	4,421	408.1	9,500,000	47,000,000
Total PCBs	1,195	33,983	208.8	2,600	540*	

**** Reported in US EPA and Ecology 2007, all other values from Oregon Department of Environmental Quality 2007***

Table 6-6a. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound shellfish, crabs, and fishes* used for human consumption and tissue residue criteria derived for protection of human health.
Fish (low) and fish (high) are the lowest and highest predicted concentrations in Puget Sound fishes modeled. Tissue residue criteria values are the most conservative (lowest) criteria reported in MacDonald et al. (1999). Shaded cells indicate an exceedance of the model-predicted concentration relative to the applicable standard.

	Model predicted organism concentrations (ppb)				Tissue residue criteria (ppb)
	shellfish	*crabs*	*fish (low)*	*fish (high)*	
PAHs					
Acenaphthene	147.8	39.0	1.6	19.1	650,000
Anthracene	1559.4	184.8	6.9	101.6	3,200,000
Benz(a)anthracene	100.7	21.4	0.3	3.6	150
Benzo(a)pyrene	66.0	17.9	0.2	3.5	2
Chrysene	102.0	21.5	0.3	4.2	15,000
Fluoranthene	465.7	47.2	1.3	17.4	430,000
Indeno(1,2,3-CD)pyrene	7.8	4.1	0.02	0.3	150
Naphthalene	1019.6	883.2	48.4	399.2	430,000
Pyrene	4420.7	408.1	13.3	189.3	320,000
Phthalates					
Bis (2-ethylhexyl) phthalate	1.2	0.8	0.0	0.0	7,700
Butyl benzyl phthalate	27.0	2.6	0.1	1.3	2,200,000
Diethyl phthalate	501.3	80.3	3.1	43.8	8,600,000
Di-N-Butyl phthalate	1057.0	98.1	3.3	47.3	1,100,000
Di-N-Octyl phthalate	1.0	0.7	0.0003	0.01	220,000
Phenol					
2,4-Dimethylphenol	12.5	19.2	1.6	8.2	220,000
2-Methylphenol	29.8	46.7	3.9	19.5	540,000
4-Methylphenol	291.0	449.6	38.0	190.8	54,000
Pentachlorophenol	138.2	124.7	7.0	56.2	900
Phenol	325.4	441.3	38.0	171.6	6,500,000
Chlorinated Benzens					
1,2,4 Trichlorobenzene	8.4	17.9	1.5	7.5	110,000
1,2-Dichlorobenzene	24.2	47.1	3.7	19.8	970,000
1,4-Dichlorobenzene	32.4	63.9	5.1	26.8	4,500
Hexachlorobenzene	4.7	43.4	15.6	107.2	67
Other Contaminants					
Benzyl Alcohol	24.0	44.6	3.5	18.6	3,200,000
Bezoic Acid	397.4	632.3	51.5	250.0	43,000,000
Dibenzofuran	156.0	340.3	29.8	142.0	43,000
Hexachlorobutadiene	41.0	128.6	15.8	63.9	1,400
N-Nitrosodiphenylamine	115.6	225.2	17.7	94.6	22,000
Total PCBs	208.8	2600.1	1753.5	14929.1	2,000

* Fish from the Puget Sound food web included in this analysis (based on those species likely to be consumed): herring, hake, pollock, english sole and chum, coho and chinook salmon.

Table 6-6b. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound fishes* used for human consumption and target tissue levels derived for protection of human health.

Fish (low) and fish (high) are the lowest and highest predicted concentrations in Puget Sound fishes used for consumption. Light shaded cells indicate an exceedance by the highest model predicted concentration relative to CEL (carcinogenic effect level) and NCEL (non-carcinogenic effect level) values. Darker cells indicate exceedances by both the lowest and highest predicted concentrations.

	Model predicted fish conc. (ppb)		Target tissue levels (ppb)		
	fish (low)	*fish (high)*	*CEL*	*NCEL*	*source*
Fluoranthene	1.3	17.4	-	51,900	5
			-	15,800	6
			-	4,720	7
			-	160,000	8
			-	20,000	9
Pyrene	13.3	189.3	-	38,900	5
			-	11,900	6
			-	3,540	7
Bis (2-ethylhexyl) phthalate	0.001	0.02	82	9,900	1
			160	19,000	2
			670	80,000	3
			230	65,000	4
Pentachlorophenol	7.0	56.2	25.2	38,900	5
			3.3	11,900	6
			0.98	3,540	7
Hexachlorobenzene	15.6	107.2	0.72	390	1
			1.40	760	2
			5.80	3,200	3
			2.00	2,600	4
			1.89	1,040	5
			0.25	316	6
			0.07	94	7
			5.80	3,200	8
			0.72	390	9
Total PCBs	1753.5	14929.1	0.6	10	1
			1.1	19	2
			4.7	80	3
			1.6	65	4
			0.4	17	10

* Fish from the Puget Sound food web included in this analysis (based on those species likely to be consumed): herring, hake, pollock, english sole and chum, coho and chinook salmon.

1: Portland Harbor RI/FS, nontribal adult , 142 g/day consumed
2: Portland Harbor RI/FS, nontribal adult , 73.5 g/day consumed
3: Portland Harbor RI/FS, nontribal adult , 17.5 g/day consumed
4: Portland Harbor RI/FS, native american adult , 175 g/day consumed total, 21.7 g/day resident species
5. RSET, general coastal population, 54 mg/kg day
6. RSET, high end recreational / mid level subsistence, 177 mg/kg day
7. RSET, high end tribal subsistence, 593 mg/kg day
8. OR DEQ, general / recreational
9. OR DEQ, subsistence / tribal
10. Lower Duwamish RI, adult tribal, RME (reasonable maximum exposure)

Table 6-6c. Modified bioaccumulation model-predicted contaminant concentrations in Puget Sound shellfish and crabs and target tissue levels derived for protection of human health (Lower Willamette Group 2007).

Light-shaded cells indicate an exceedance by model-predicted contaminant concentrations for either shellfish or crabs relative to CEL (carcinogenic effect level) and NCEL (non-carcinogenic effect level) values. Darker cells indicate exceedances by both shellfish and crab predicted contaminant concentrations.

	Model predicted biota concentrations ppb		**Target tissue levels (ppb) - *ingestion rate* -**			
			18 g/day		3.3 g/day	
	shellfish	*crabs*	*CEL*	*NCEL*	*CEL*	*NCEL*
Benz(a)anthracene	100.7	21.4	12	-	68	-
Benzo(a)pyrene	66.0	17.9	1.2	-	6.8	-
Dibenzo(a,h)anthracene	3.6	1.7	1.2	-	6.8	-
Indeno(1,2,3-CD)pyrene	7.8	4.1	12	-	68	-
Pentachlorophenol	138.2	124.7	76	120,000	410	640,000
Total PCBs	208.8	2600.1	4.5	78	25	420

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7.0 Conclusions and Discussion

This section addresses how "protective" the current SQS criteria are for bioaccumulatives based on modified bioaccumulation model-generated toxics concentrations within the food web and evaluates the efficacy of the model in describing the flux of toxics from sediments to biota and the food chain in Puget Sound. The model identified some instances (Section 6.2 and Tables 6.2 through 6.6) where toxics concentrations at the SQS level exceeded criteria derived to protect both human and wildlife receptors. While the model's predictions appear to be reasonable based on available verification, caution should be exercised when interpreting these results and applying them to regulatory issues because of the uncertainty associated with the model's assumptions. In light of these uncertainties, the modified bioaccumulation model's assumptions are briefly discussed, as are suggestions for better evaluating the model's accuracy.

SMS Evaluations

Using modified bioaccumulation model-predicted toxics concentrations and contaminant standards derived for the protection of human and wildlife health to evaluate the protectiveness of the SMS yielded mixed results. Most of the SQS levels result in water contaminant concentrations that generally fall below the most conservative water criteria (Tables 6-2 and 6-3) reviewed in MacDonald (1999). Likewise, comparisons between model-predicted biota contaminant concentrations and tissue residue guidelines yield very few exceedances (Tables 6-5a and 6-6a). This is true even though predicted concentrations are evaluated against standards that were selected because they are the most conservative (most stringent) of all the criteria reviewed. However, at least one compound from each contaminant group exceeds criteria from one of the four comparisons provided in MacDonald (1999). While some exceedances are smaller and likely within the model's range of error (resulting from the underlying assumptions), other model-predicted concentrations exceed criteria by two to three orders of magnitude.

Evaluations of model-predicted biota concentrations are not as favorable when compared to more recent efforts to derive tissue target levels. While a lack of standardization across methods (partially because of site or region specificity) resulted in target tissue levels sometimes spanning as much as three orders of magnitude, most of the SMS compounds for which there are available standards exceed at least one target (Tables 6-4, 6-5b, 6-6b and 6-6c). Included in these exceedances are PAHs and phenols. In most cases, these compounds are not expected to bioaccumulate substantially and are not problematic when compared to criteria from MacDonald (1999). Of the contaminants that exceed at least one criterion, total PCBs may be the greatest concern. Total PCBs exceed at least one threshold level in every comparison and often do so for both low and high fish groups as well as crabs and shellfish (Fish [low] and fish [high] are the lowest and highest predicted concentrations in Puget Sound fishes used for consumption.). PCBs exceed criteria even in comparisons against the lower fish consumption scenarios (Table 6-6b).

Given the trend toward deriving regional and site specific criteria which tend to be more stringent than generalized targets, it seems unlikely that the current SMS will meet these higher standards. While these area specific methods have not resulted in comparison values for all the SMS compounds, there are substantially more model-predicted exceedances than for the more numerous comparisons provided by MacDonald (1999). It therefore seems plausible that as more regional and site specific thresholds are developed for the remaining SMS compounds, there will be more instances in which the current sediment standards are shown to be under-protective.

Uncertainty

Assumptions are incorporated into all models because rarely are complex systems and relationships fully understood and in many instances there is a lack of empirical data for key variables. Assumptions may not perfectly match real world conditions and as a result, add some degree of uncertainty to model results and predictions. The modified bioaccumulation model used in this study retains all the assumptions of Condon's model (2007); bioaccumulation and environmental partitioning equations, environmental physiochemical properties and biota parameters are unchanged from Condon and readers should consult Condon (2007) for a full description. Environmental and biological parameters derived by Condon (2007) and used in this model are provided in Appendix C. Assumptions apart from those in Condon were necessary for this study and have been discussed in sections four and five of this document. Key assumptions and related uncertainties are briefly repeated below. The absence of empirical data and field observations prohibits the modified bioaccumulation model's predictions from being fully verified and limits the certainty surrounding the assumptions used in this model.

- Condon's (2007) original model used a series of equations to estimate bioaccumulation of PCBs in the marine food web of the SOG. The modified bioaccumulation model presented herein retains the bioaccumulation and environmental partitioning (air and water) equations and all assumptions relating to these equations (see Condon 2007 for a complete discussion). Implicit in the use of these equations in the modified bioaccumulation model is that they work with the same precision across the range chemical properties found in SMS compounds, which can vary substantially. For example, Kow values for modeled SMS compounds span seven orders of magnitude at 9.5°C while Kow values modeled by Condon spanned only three orders of magnitude. This assumption has not been tested and needs to be verified given that physiochemical properties are one of the main drivers in estimating environmental and biota contaminant concentrations from sediment input data.

- Kow and Koa coefficients are an important component of the equations the model uses to estimate biota and environmental contaminant concentrations; they are key factors in the bioavailability of a given substance. Kow and Koa values are empirically derived using gas chromatography retention times and energy of phase transfer for octanol to water and octanol to air. Even though standardized methods are used to determine Kow and Koa, values for these coeffcients do vary in the literature. Likewise, there has been little research on the dependence of these coefficients on temperature, though the general conclusion is that the variability of Kow/Koa coefficients over the range of temperatures found in the environment is small. Because of the complex methods needed to determine Kow and Koa coefficients, they are not available for many compounds, including some used in this modeling exercise. For SMS compounds without empirically derived Kow and Koa coefficients, E & E assumed a value (Table 4-2) based on molecular weight and the relationship between Kow and Koa for compounds where both Kow and Koa are known. For the purposes of this study, E & E had to assume these same relationships for both polar and non-polar compounds, though there appear to be no studies that address the relationship of Kow and Koa for polar compounds and no mechanism to test this assumption for polar compounds. Therefore there is an unknown level of uncertainty related to Kow and Koa coefficients for some SMS compounds, and this uncertainty is greatest for polar compounds. The SMS criteria included three general compound categories (total PCBs, LPAHs and HPAHs). Kow and Koa coefficients are metrics of single compounds and not of composite groups. To predict bioaccumulation of total PCBs, LPAHs, and HPAHs, we used the median value of molecular weights, Kows, and Koas for compounds within each group as model inputs. Uncertainty here is not therefore related to a lack of available data but rather to the effects of applying a single compound metric to a composite group.

While it is impossible to determine the amount of error associated with the Kow and Koa coefficients used in this study, it is possible to examine the degree to which error could potentially affect model predicted concentrations. To test this, a model run was devised for two hypothetical compounds; one compound (compound A) with the lowest Kow/Koa coefficient from the SMS and one (compound B) having the highest used coefficient (see Table 4-2). For both compounds, sediment concentrations of 1000 ppb and metabolic transformation rates of zero at all trophic levels were assumed. Kow and Koa coefficients were adjusted to 10 and 20 percent below and 10 and 20 percent above their original values and the resulting model predicted contaminant concentrations were evaluated at several trophic levels (Table 7-1). The effects range from minimal to several orders of magnitude and are dependent on both starting Kow and Koa values and trophic level.

Table 7-1. Model predicted concentrations based on hypothetical Kow and Koa error levels.

See above text for a full description.

	Compound A				
	original Kow/Koa	minus 10%	minus 20%	plus 10%	plus 20%
	concentration, ppb				
Water	4.32E+00	7.81E+00	1.41E+01	2.39E+00	1.32E+00
Air	4.24E+01	6.24E+01	9.19E+01	2.88E+01	1.96E+01
Phytoplankton	6.54E+00	1.00E+01	1.62E+01	4.62E+00	3.55E+00
Shellfish	4.20E+02	4.49E+02	5.01E+02	4.05E+02	3.96E+02
Chinook	1.28E+02	1.30E+02	1.35E+02	1.27E+02	1.27E+02
English sole	3.26E+02	3.35E+02	3.51E+02	3.22E+02	3.20E+02
Seal (adult male)	1.28E+03	1.24E+03	1.20E+03	1.33E+03	1.38E+03

	Compound B				
	original Kow/Koa	minus 10%	minus 20%	plus 10%	plus 20%
	concentration, ppb				
Water	3.89E-06	2.64E-05	1.79E-04	5.74E-07	8.47E-08
Air	1.97E-07	1.98E-06	1.98E-05	1.97E-08	1.96E-09
Phytoplankton	4.21E-01	1.37E+00	2.05E+00	7.40E-02	1.12E-02
Shellfish	2.59E+02	1.12E+03	9.21E+02	3.51E+01	5.02E+00
Chinook	3.17E+03	6.64E+04	6.76E+04	2.23E+01	1.96E-01
English sole	3.79E+03	8.66E+04	9.46E+04	5.41E+01	1.09E+00
Seal (adult male)	2.05E+05	2.52E+06	2.33E+06	5.20E+03	1.99E+02

- Many pollutants are substantially metabolized, making metabolism an important elimination pathway. Condon's model assumed PCB metabolic elimination (Km) rates of zero for SOG lower trophic levels (through fish) and used derived rates of metabolic elimination for birds and seals. However, many SMS compounds are more completely metabolized than PCBs, even at lower trophic levels. As such, the modified bioaccumulation model used published and tested PAH Km values (Stevenson 2003). For most other SMS compounds, there was very little published research related to metabolic transformation rates. Based on the chemical properties of phthalates and phenols in relation to PAHs, as well as on prior research on and discussion of phenols (Call 1980; Environment Canada 2000) and phthalates (Gobas et al. 2002; Mackintosh et al. 2004), we assumed PAH Km values for all phenol and phthalate compounds. As there is a lack of empirical data, it is not known how much uncertainty is associated with this assumption. Given that many phenols and phthalates are not expected to substantially bioaccumulate, assuming PAH Km values for these two compound classes is likely more valid than assuming that no metabolism takes place. However, for all other compounds, literature is not readily available to either determine Km values or infer reasonable assumptions; therefore, it was necessary to assume Km values of zero.

- The modified bioaccumulation model food web and the Stevenson (2003) food web are not identical; the Dungeness crab occupies the top trophic level in the Stevenson model. To determine Km values for the modified Condon model, organisms or organism groups were assigned the most appropriate category available in the Stevenson model (Table 4-3). If a group from the Condon food web could be described by more than one of the general categories from Stevenson (2003), the group was assigned the lower Km value (conservative approach). Likewise, because Km values for PAHs in the Stevenson model generally increase with increasing trophic level, all fish and higher organisms in the modified bioaccumulation model were assigned the greatest Km value from the Stevenson model (fish: Km=2). This is a conservative assumption because higher vertebrates are known to more readily metabolize PAHs.

- The modified bioaccumulation model used the same food web as Condon's (2007), which was developed for the Strait of Georgia and based on empirical data. However, in Condon's model, PCB concentration data were input (not predicted) for herring and salmon (chum, Coho and Chinook) because these fishes are migrants and tend to feed mostly in the open ocean. Because empirical data are not available for each SMS compound for each species, the modified bioaccumulation model assumes a closed system for Puget Sound (herring and salmon are treated as if they feed only in Puget Sound) and predicts concentrations for all the species in the food web. The closed system assumption is more likely to result in over – than under – predicted tissue concentrations for these species and for those in higher trophic levels feeding on these species because concentrations of SMS compounds are likely to be lower in the open ocean than in Puget Sound. The degree to which concentrations for these species may be over-predicted cannot be established without empirical data from tissue samples.

- Treating Puget Sound as a closed system necessitated formulating dietary composition values for herring and salmon. This was a somewhat subjective process given differences among populations and age classes and the requirement that herring and salmon prey had to consist of organisms contained in the SOG food web. Diet compositions were assumed for herring and salmon (Table 4-1) based on selected research (James & Unwin 1996; Pauly & Christensen 1996; Schweigert et al. 2007; Zacolokin et al. 2007) and best professional judgment.

- As noted above, the equations in Condon's (2007) model were retained for this study. Included in these equations was the following method for calculating BSAFs:

$$BSAF = \frac{C_B}{C_S}$$

where C_B is the chemical concentration in the organism and C_S is the chemical concentration in the sediment.

While the above equation yielded reasonable BSAFs estimates when compared to published BSAFs, more precise approximations can be achieved by considering tissue lipid content and sediment organic carbon concentrations. Note also that BSAFs from the above equation are not unitless because the numerator's units are wet weight based while the denominator's are based on dry weight concentrations.

Recommendations

There are several uncertainties relating to assumptions used in the modified bioaccumulation model that need further evaluation. Most of the model's uncertainties result from a lack of empirical data for key input variables; and unfortunately, remedies appear to be limited. For example, complex methods are needed to empirically measure Kow and Koa coefficients and it would be impractical to do so for SMS compounds for which there are currently no data. It would also be impractical to determine species specific metabolic transformation rates for each of the SMS compounds. Instead, to test the assumptions in the modified bioaccumulation model and to assess whether the model accurately predicts contaminant concentrations in Puget Sound marine organisms, the model needs to be evaluated against high quality datasets with temporally and spatially paired tissue and sediment data. Ideally these datasets would be from multiple locations, spanning the range of environmental conditions found in Puget Sound, and would contain important, site-specific parameters such as sediment organic carbon concentration. Only by inputting known sediment concentrations and comparing predicted tissue concentrations to known tissue concentrations from the same location can an accurate assessment be made of this model's ability to accurately reproduce concentrations for non-PCB compounds.

Some of the uncertainty surrounding the model's predictions could be reduced by employing a more specialized food web. The current food web includes a range of trophic levels from primary producers to top level predators. Covering such a range required that many species be categorized in and treated as organism groups. Limiting the food web to lower trophic levels would allow for better resolution among organisms. Ideally such a food web would include species (particularly shellfish and fish) that humans consume but would eliminate migrant species whose contamination levels are in part determined by environmental conditions outside of Puget Sound.

Finally, future iterations of the modified bioaccumulation model should include a BSAF equation with lipid normalized tissue and total organic carbon normalized sediment components. As BSAF determinations are used in risk analyses and as one criterion for developing sediment quality standards, it is imperative that BSAFs accurately and completely as possible represent bioavailability and the potential for bioaccumulation. While the method currently used to estimate BSAFs resulted in values that mostly fell within published ranges, more precise approximations can be achieved by considering tissue lipid content and total organic carbon concentrations in the sediment. For example:

$$BSAF = \frac{\left(\dfrac{C_B}{L_B}\right)}{\left(\dfrac{C_S}{OC_S}\right)}$$

where C_B is the chemical concentration in the organism;
L_B is the lipid fraction of the organism;
C_S is the chemical concentration in the sediment, and
OC_S is the sediment's total organic carbon concentration.

BSAFs from this and the equation utilized in the model, while generally agreeing, can differ by an order of magnitude (Table 7-2). Note that the equation above results in BSAFs that are unitless because dry weight sediment concentrations are normalized with dry weight organic content and wet weight biota concentrations are normalized with the wet lipid fraction. Using the above equation with the modified bioaccumulation model predicted biota contaminant concentrations resulted in BSAFs that better agreed with published BSAF ranges than did the equation used both in Condon (2007) and the modified bioaccumulation model (Table 7-3).

Table 7-2. Bioaccumulation model-predicted and lipid/organic-carbon-normalized BSAFs for selected SMS contaminants and Puget Sound biota.
The alternative (alt.) BSAFS were calculated using the normalized equation above**.**

	Pyrene *BSAF*		**Pentachlorophenol** *BSAF*		**Total PCBs** *BSAF*		**Hexachlorobenzene** *BSAF*	
	model	*alt.*	*model*	*alt.*	*model*	*alt.*	*model*	*alt.*
Shellfish	1.64E-01	3.69E-01	3.84E-01	8.62E-01	6.47E-01	1.45E+00	4.57E-01	1.03E+00
Herring	2.93E-03	1.58E-03	5.45E-02	2.94E-02	7.56E+00	4.07E+00	2.40E+00	1.29E+00
Seal (pup)	2.69E-05	1.75E-06	3.92E-04	2.55E-05	4.94E+01	3.22E+00	2.99E+02	1.95E+01

model units = ng/g wet wt in biota per ng/g dry wt in sediment
alt values are unitless

Table 7-3. Log BSAF statistics from published data, modified bioaccumulation model predictions and a tissue and sediment normalized equation.

Dungeness crab data were summarized in Stevenson 2003. *Macoma* data are from USACE's BSAF database and were only included for those compounds having three or more records. Shaded cells indicate modified bioaccumulation model-predicted and tissue/sediment normalized BSAFs falling outside observed ranges. The alternate BSAFS were calculated using the previously described normalizing equation.

Chemical	**Dungeness crabs**			**All crabs**	
	mean	*min*	*max*	*model*	*alternate*
Anthracene	-2.76	-4.31	-0.66	-1.51	-1.55
Benz(a)anthracene	-3.99	-6.25	-1.75	-2.14	-2.19
Benzo(a)pyrene	-4.24	-6.20	-2.69	-2.17	-2.22
Chrysene	-3.61	-5.54	-1.10	-2.14	-2.19
Fluoranthene	-3.43	-4.90	-1.27	-1.96	-2.01
Phenanthrene	-3.47	-5.30	-1.26	-1.51	-1.56
Pyrene	-3.61	-4.95	-1.49	-1.82	-1.87
	Macoma species			**Shellfish**	
	mean	*min*	*max*	*model*	*alternate*
Benz(a)anthracene	-0.63	-1.59	-0.21	-1.47	-1.11
Benzo(g,h,i)perylene	-1.70	-1.96	-1.46	-2.01	-1.66
Benzo(a)pyrene	-0.71	-1.82	-0.07	-1.61	-1.25
Chrysene	-0.55	-1.60	-0.21	-1.46	-1.11
Fluoranthene	-0.06	-2.05	0.58	-0.97	-0.62
Hexachlorobenzene	0.23	-0.16	0.40	-0.34	0.01
Indeno(1,2,3-CD)pyrene	-1.77	-2.15	-1.60	-2.07	-1.72
Naphthalene	-0.39	-1.46	0.03	-0.42	-0.07
Phenanthrene	-1.15	-1.40	-0.94	-0.58	-0.23
Pyrene	-0.52	-1.70	-0.28	-0.78	-0.43

min = minimum
max = maximum

Modified Bioaccumulation Model Efficacy

Using the single box, ecologically based model employed in this study can produce informative output and useful comparisons. Modifying and using Condon's bioaccumulation model was clearly useful in understanding how non-PCB compounds flux from sediment to biota and in seeing they do so differently depending on their sediment concentrations and chemical properties. The modified model performed satisfactorily, reproducing Condon's (2007) results when tasked with his input data and calculating compound- and species-specific BSAFs that were in line with other published studies.

However, the degree to which results from generalized models can be relied upon for regulatory and management decisions is unclear. The potential negative aspects to using a single box model are the ecological, physiochemical, and other uncertainties resulting from modeling assumptions, as well as the un-captured variability in site conditions and surrounding land uses resulting from generalized models. While a broad analysis is a useful first step in helping to identify problem areas or deficiencies in current standards, specialized models that are able to focus on specific chemical classes or on smaller locations may be able to capture variability in physical parameters and demographics, both of which are crucial in defining exposure parameters.

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Appendix A

Review of Available Sediment-Water Flux Models

The objective of this task was to identify and briefly describe models currently being used to predict the flux of toxics to/from sediments into the water column and models used to estimate the impacts of sediment dredging.

Summary of Sediment-Water Flux Models

Brief summaries of the models identified as potentially viable for use in estimating the flux of toxics from contaminated sediment sites to the waters of Puget Sound are presented below.

Davis Model

The Davis model (Davis 2004) has been described as a simple one-box mass budget model presented as a first step toward a quantitative understanding of the long-term fate of polychlorinated biphenyls (PCBs) in San Francisco Bay.

This model was used to describe PCB fluxes across the entire bay. Because the Condon (2007) model was used to model PCB fluxes across the entire Strait of Georgia, it may also be considered a “one-box” model. Although the Davis model is described as a conservation of mass or “mass budget” model, this is simply another term for a mass balance model, like the Condon model.

Unlike the Condon (2007) bioaccumulation model, the Davis model addresses only the physical and chemical fluxes of PCBs. Other than the physical mixing of sediments by biota (bioturbation), biological processes are not part of this model. Davis used trends in PCB concentrations in water and sediment to infer similar trends in concentrations of PCBs in the food web.

In a sense, the Condon model has several compartments within its one box; examples include sediment, plankton, benthos, fish, birds, and seals. The Davis model has only two compartments, sediment and water; each compartment was assumed to be homogeneously mixed with no spatial variability in PCB concentrations.

Davis evaluated five major processes that could lead to addition or removal of PCBs from water or sediment:

- external loading,
- outflow to the ocean,
- volatilization to the atmosphere,
- burial in deep sediment, and
- degradation by biotic or abiotic processes.

Davis also evaluated processes that result in transfer of PCBs between water and sediment:

- diffusion of dissolved PCBs and
- deposition and re-suspension of PCBs bound to sediment particles.

Davis used the model to predict the amounts of PCBs that would be lost from the bay over different time periods under a series of PCB regulatory management scenarios and the subsequent changes in the mean water and sediment PCB concentrations. He accomplished this by using the four basic components of any contaminant mass budget model for an aquatic ecosystem:

1. contaminant concentrations in each of the compartments of the ecosystem,
2. trends in concentrations over time,
3. rates of contaminant loss from the system, and
4. rate of external loading to the system.

Because there were considerable data on PCB concentrations in bay water, sediment, and bivalves, data were readily available for the first two components (numbers 1 and 2 above). Estimates of potential future loading (component 4) were input into the model. Davis combined information on other properties of the bay (e.g., flow of water out of the bay) and properties of PCBs (e.g., octanol-water partition coefficients) to estimate the time that would be necessary for PCB concentrations to be reduced to levels at which biota would not be impacted.

Davis Model's Capabilities as a Sediment Flux model

As noted above, the Davis model describes the fate of PCBs in the water and sediment of the San Francisco Bay ecosystem (Figure A-1). Inputs and outputs from the water and sediment compartments are quantitatively estimated using the model. Each compartment (water and sediment) is assumed to be completely homogeneous (well-mixed). Because sediments occur over depth and do not undergo the same mixing phenomena as water, the sediment layer is conceptually divided into an active sediment layer and an inactive buried sediment layer. PCBs in the active layer undergo exchange with the water column and food webs. The depth of this layer is dependent on bioturbation and mixing driven by tides and storms. Anthropogenic mixing, such as anchor drag, propeller wash, and dredging-related activities, are not addressed. The inactive (buried) sediment layer is too deep below the bottom surface to exchange PCBs with either the active sediment layer or the water column.

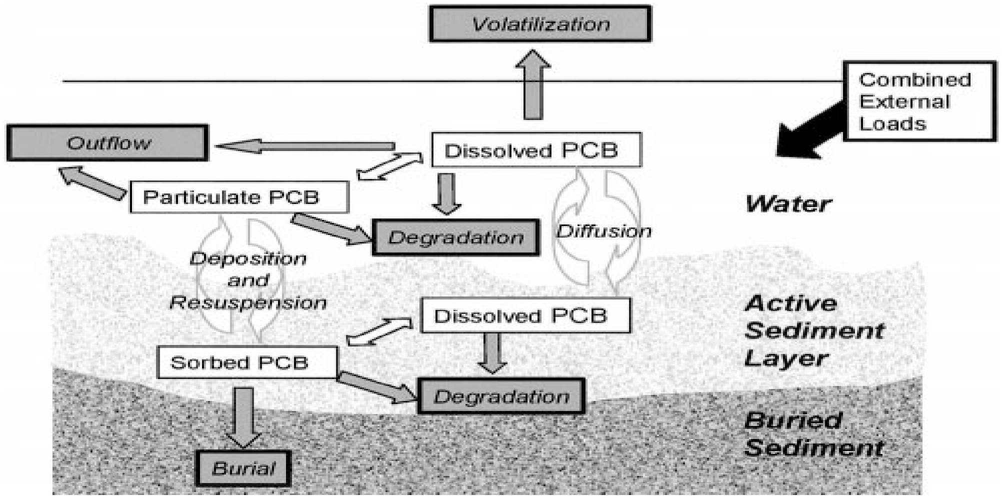

Figure A-1. Diagram of polychlorinated biphenyl (PCB) fate in San Francisco Bay (USA) showing processes included in the model.

Flux of toxics from water to sediment

Inputs to the water column include external loads, re-suspension of sorbed PCBs from sediment, and diffusion of dissolved PCBs from sediment. The Davis model accounts for external loading as a total quantity entering the water column. Examples of potential loading sources include PCB-contaminated atmospheric deposition, wastewater discharges, and buried sediment erosion. Outputs from the water compartment include volatilization to the atmosphere, flow of particulate and dissolved PCBs out of the bay, deposition of particulate PCBs to the active sediment layer, diffusion of dissolved PCBs to the active sediment layer, and degradation of particulate and dissolved PCBs.

Flux of toxics to sediment from water and flux of toxics within the sediment column

Inputs to the active sediment layer include deposition of particulate PCBs from the water column and diffusion of dissolved PCBs from the water column. Outputs from the active sediment layer include re-suspension of sorbed PCBs to the water column, diffusion of dissolved PCBs to the water column, burial of sorbed PCBs as inaccessible deep sediment, and degradation of sorbed and dissolved PCBs in sediment. The model does not include losses from the water column and active sediment layer due to bioaccumulation in the food web.

Burial flux (loss from the active sediment layer)

Burial flux was crudely estimated from empirical data collected during a sediment budget study and bathymetric data. These data highlight a limitation of this box model, which does not account for erosional remobilization of PCBs from buried sediment although some areas within the bay were identified as depositional and others as erosional, with a mean burial rate of zero.

Anthropogenic impacts

The model does not have any specific functions for simulating anthropogenic impacts. However, it is possible to alter the input parameters to artificially account for the impacts, for example, changing the rates of solids settling, water-to-sediment diffusion, solids re-suspension, and sediment-to-water diffusion.

Natural disturbances

The Davis model relies on linking a separate hydrodynamic model to the sediment flux model to simulate the flux of PCBs due to movement of water. The model's capability to simulate chemical transport under natural disturbances such as high flow flood events depends mainly on the choice of the hydrodynamic model. The model does not address sediment transport as bed load.

Integration of model into a hydrodynamic model

The Davis model includes two compartments, water and sediment. Each compartment includes terms that address the transport of PCBs to and from each compartment. The model also addresses the flux between the sediment and water compartments.

Sensitivity for key input data

Sensitivity analysis identified degradation half-life in sediment, outflow from the bay, octanol-water partition coefficient, average PCB concentration in sediment, and depth of the active sediment layer as the most influential input parameters in the Davis model. A number of other moderately important parameters include organic carbon content of suspended solids, sediment burial mass transfer coefficient, and Henry's law constant.

WASP Model

Unlike the Condon and Davis models, which were developed for specific purposes, the Water Quality Analysis Simulation Program (WASP) was developed as a flexible model that users may adapt as necessary to meet specific model output goals. Therefore, this discussion of the WASP model focuses more on modeling parameters than do discussions of the Condon and Davis models.

The WASP system consists of two stand-alone computer programs, DYNHYD and WASP, which can be run in conjunction with one another or separately. The hydrodynamics program, DYNHYD, simulates the movement of water, while the water quality program, WASP, simulates the movement and interaction of pollutants within the water. Other water movement models, for example the Puget Sound Box Model described in the Conceptual Model Letter Report, may be linked to WASP.

As is true for the Davis model, the basic principle underlying both the hydrodynamics and water-quality program for WASP is conservation of mass.

The WASP box model includes a set of expanded control volumes, or "segments," that together represent the physical configuration of the water body. The network may subdivide the water body laterally and vertically as well as longitudinally. Segments in WASP may be one of four types: epilimnion layer (warm surface water), hypolimnion layer (cool deep water), upper benthic layer, and lower benthic layer.

WASP permits the modeler to structure three-dimensional models with specification of time-variable exchange coefficients, advective flows, waste loads, and water quality boundary conditions, and permits tailored structuring of the kinetic (addition/removal) processes, all within the larger modeling framework, without having to write or rewrite large sections of computer code.

WASP is structured to permit easy substitution of kinetic subroutines into the overall package to form problem-specific models. WASP comes with two such models, TOXI for toxic chemicals and EUTRO for conventional water quality analytes (for example, nitrate or phosphate).

WASP Sediment Transport

Sediment size fractions, or solids types, are simulated using the TOXI program. Simulations may incorporate total solids as a single variable, or, alternatively, represent from one to three solids types or fractions. The three solids types may represent sand, silt, and clay, or organic solids and inorganic solids. The user defines each solid type by specifying its settling and erosion rates and its organic content.

WASP performs a simple mass balance on each solid variable in each compartment based on specified water column advection and dispersion rates, along with settling, deposition, erosion, burial, and bed load rates. Mass balance computations are performed in benthic compartments as well as water column compartments. Bulk densities or benthic volumes are adjusted throughout the simulation.

Sediment loading derives primarily from watershed erosion and bank erosion. These can be measured or estimated and input into each segment as a point source load. If available, suspended sediment data at local gage stations can be extrapolated to provide area-wide loading estimates. Alternatively, daily runoff loads can be simulated with a watershed model and read in directly from an appropriately formatted non-point source-loading file.

Overview of WASP Model for Toxics

TOXI simulates the transport and transformation of one-to-three chemicals and one-to-three types of particulate material. The three chemicals may be independent or they may be linked with reaction yields, such as a parent compound-daughter product sequence.

In an aquatic environment, toxic chemicals may be transferred between phases and may be degraded by any of a number of chemical and biological processes. Simplified transfer processes defined in the model include sorption and volatilization. Transformation processes include biodegradation, hydrolysis, photolysis, and oxidation. Sorption is treated as an equilibrium reaction. Transformation processes are described by first-order rate equations.

WASP uses a mass balance equation to calculate sediment and chemical mass and concentrations for every segment in a specialized network that may include surface water, underlying water, surface bed, and underlying bed. In a simulation, sediment is advected and dispersed among water segments, settled to and eroded from benthic segments, and moved between benthic segments through net sedimentation, erosion, or bed load.

Simulated chemicals undergo several physical or chemical reactions as specified by the user in the input dataset. Chemicals are advected and dispersed among water segments, and exchanged with surficial benthic segments by dispersive mixing. Sorbed chemicals settle through water column segments and deposit to or erode from surficial benthic segments. Within the bed, dissolved chemicals migrate downward or upward through percolation and porewater diffusion. Sorbed chemicals migrate downward or upward through net sedimentation or erosion. Rate constants and equilibrium coefficients must be estimated from field or literature data in simplified toxic chemical studies.

Some limitations should be kept in mind when applying TOXI. First, chemical concentrations should be near trace levels, that is, below half the solubility or 10^{-5} molar. At higher concentrations, the assumptions of linear partitioning and transformation begin to break down. Chemical density may become important, particularly near the source such as in the case of a spill. Large concentrations can affect key environmental characteristics, such as pH or bacterial populations, thus altering transformation rates.

WASP's capabilities as a sediment flux model

Structurally, the WASP program includes six mechanisms for describing transport. These "transport fields" consist of advection and dispersion in the water column; advection and dispersion in the pore water; settling, re-suspension, and sedimentation of up to three classes of solids; and evaporation or precipitation. Through those mechanisms, WASP provides many capabilities for simulating different processes.

Flux of toxics to sediment from water

Transport of toxics to sediment from water involves two forms of chemicals: dissolved and sorbed. Dissolved chemicals in water column and benthic segments interact with sediment particles and dissolved organic carbon (DOC) to form five phases: dissolved, DOC-sorbed, and sediment-sorbed (with three possible phases corresponding to three sediment types). Dissolved chemicals in the water column are advected and dispersed among water segments, and exchanged with surficial benthic segments by diffusive mixing. Sorbed or particulate fractions may settle through water column segments and deposit to surficial benthic segments. Settling velocities should set within the range of Stokes' velocities corresponding to suspended particle size distribution. Deposition velocity of solid variables is calculated as the product of the Stokes settling velocity and the probability of deposition.

Flux of toxics within the sediment column

In WASP, dissolved chemicals within the sediment column may migrate through advection and porewater diffusion. Dissolved fractions may be input by the user. In TOXI, these are recomputed from sorption kinetics for each time step.

Burial flux

In WASP, movement of sediment in the bed is governed by one of two options. In the first option, bed segment volumes remain constant and sediment concentrations vary in response to deposition and scour. No compaction or erosion of the segment volume is allowed to occur. In the second option, the bed segment volume is compacted or eroded as sediment is deposited or scoured. Sediment concentration in the bed remains constant. In both cases, estimation of sedimentation velocity of the upper and lower bed is based on mass balance.

Flux of toxics from sediment to water

As with flux of toxics from water to sediment, transport of toxics to water from sediment involves two forms of chemicals, dissolved and sorbed. Dissolved chemicals in the sediment column are advected and dispersed between water column and sediment column. Sorbed chemicals can be transported by scour and/or erosion from surficial benthic segments. The scour velocity depends upon shear stress, bed sediment size and cohesiveness, and the state of consolidation of surficial benthic deposits. The erosion rates, however, are not programmed as a function of sediment shear strength and water column shear stress, as is commonly the case. Therefore the TOXI sediment model should be considered descriptive, not predictive, and must be calibrated to site data.

Anthropogenic impacts

WASP does not explicitly account for anthropogenic impacts. However, WASP provides quite a bit of flexibility in specifying input parameters. Anthropogenic impacts can be considered in different ways. For example, time variable setting, deposition, scour, sedimentation velocities, exchange coefficients, and waste loads can be specified for each type of solid in accordance with different anthropogenic activities.

Natural disturbances

WASP relies on a hydrodynamics program to simulate the movement of water. Therefore, its ability to simulate chemical transport under natural disturbances such as those caused by currents depends mainly on the choice of the hydrodynamic model. While DYNHYD is delivered with WASP, other hydrodynamic programs have also been linked with WASP.

Integration of the model into a hydrodynamic model

When linking WASP with other hydrodynamic programs, factors that must be considered include the format of input files for WASP and the consistency between the model grids.

WASP sensitivity analysis

A sensitivity analysis was conducted using a toxic fate and transport model of the Thea Foss Waterway, based on the WASP model originally developed for the City of Tacoma. The contaminants considered were bis (2-ethylhexyl) phthalate, dibenz (a,h) anthracene, phenanthrene, and pyrene. Examination of the input data, data sources, and methods used for data development showed that: (1) the predicted sediment contaminant concentrations are very sensitive to the partition coefficient, resulting in a high level of uncertainty; (2) boundary conditions and tidal and seasonal dynamics of the waterway and its storm water inputs (suspended sediment and contaminants) affect sediment transport; and (3) coarse grid resolution may cause high numerical diffusion and lower predicted contaminant concentrations in the sediment.

DAVIS and WASP Model Comparisons

The Davis model is a simple one-box mass budget model presented as a first step toward a quantitative understanding of the long-term fate of PCBs. WASP is a dynamic compartment mass budget model that can be used to analyze a variety of water quality problems. Table A-1 compares the two models.

Table A-1. Davis and WASP Model Comparison

Comparison Items		**Model**	
		Davis	**WASP**
Simulations	**Flux of toxics to sediment from water**	Yes	Yes
	Flux of toxics within the sediment column	Yes	Yes
	Burial flux	Yes	Yes
	Flux of toxics from sediment to water	Yes	Yes
	Anthropogenic impacts	No	No
	Natural disturbances	Yes (if combined with dynamic model)	Yes (if combined with dynamic model)
Linked hydrodynamic model		Yes, e.g., Box model	Yes, e.g., DYNHYD
Water systems applied		Lake, estuary	Stream, river, lake, reservoir, estuary
Model conceptual philosophy		Deterministic	Deterministic
Model Type		Lumped	Distributed
Sediment dynamics		No	Yes
Properties of source code		EXCEL/VBA	FORTRAN
Numerical solution method		Stepwise	Finite-difference

ABC Model

The Aquatic Biogeochemical Cycling (ABC) Model was developed by scientists at the University of Washington primarily as a regional planning, teaching, and communications tool. The model was designed specifically to simulate nutrient and plankton dynamics in the water column and for incorporation into or with a physical circulation model. ABC is a simple flux-based model designed specifically for Puget Sound and similar Pacific Northwest aquatic ecosystems. The model simulates nitrogen- and phosphorus-based inorganic nutrients, dissolved oxygen, dissolved and particulate organic matter, and three types of phytoplankton and zooplankton. One of the more valuable facets of ABC is its use in “what-if scenarios” answering questions such as, “What would be the impact of climate change on the water properties that influence Puget Sound marine resources and the health of the ecosystem?” Work is in progress to add a sediment component to the model.

This discussion of the ABC model is limited since sediments are currently not addressed, and therefore its utility is limited for this project.

Ecology Water Quality Models for Puget Sound

Ecology has developed basin-wide and sub-basin models to describe oceanographic features of Puget Sound. These are summarized below.

HOBO Model

The Hammersley Inlet Oakland Bay Oceanographic Model (HOBO) has been used to model faecal coliform bacteria concentrations for National Pollutant Discharge Elimination System (NPDES) permitting. The model is based on a primitive, three-dimensional hydrodynamic computer equation model (Environmental Fluid Dynamic Code (EFDC)) driven by empirical data collected at the model boundaries (for example, meteorological conditions at the air-sea boundary). Although all the capabilities of EFDC were not utilized, this open-source, public domain modeling system does include surface water modeling, including hydrodynamic, water quality, and sediment-contaminant simulation capabilities. HOBO has been used to determine the flushing characteristics of Oakland Bay and Hammersley Inlet in Puget Sound to assist the City of Shelton and the Washington Department of Health in evaluating the potential impacts from the proposed expansion of the city’s wastewater treatment plant.

SPASM Model

The South Puget Sound Area Synthesis Model (SPASM) is also a three-dimensional EFDC-based hydrodynamic and water quality model. SPASM has been used to model nutrients and eutrophication based on total maximum daily loads (TMDLs). TMDLs are the amounts of toxic pollutants a waterbody can “handle” without violating state water quality standards. Eutrophication is the increase in chemical nutrients, typically inorganic compounds containing nitrogen or phosphorus, in an ecosystem that results in an increase in primary productivity (excessive plant growth and subsequent decay) and further impacts including dangerous reductions of dissolved oxygen levels and severe reductions in water quality and acute or chronic impacts to fish and other biota. SPASM has been used to identify potential "hot-spots" in South Puget Sound likely to be negatively impacted by eutrophication.

Neither SPASM nor HOBO is applicable for determining the flux of contaminants to and from Puget Sound sediments or as a bioaccumulation model.

Dredging-Related Models

Dredging of marine sediment and dredge spoils disposal into the marine environment require assessment of the levels of contaminants in the sediment to be dredged and evaluation of the disposal impacts. Procedures for evaluation of sediments to be dredged are provided in Puget Sound Dredged Disposal Analysis (PSDDA) guidance manuals. Several models are available for evaluation of dredging and dredge spoil disposal; representative models are described below.

SSFATE

The Suspended Sediment Fate (SSFATE) model was developed by Applied Science Associates in association with the United States Army Corps of Engineers. The model is used to predict transport, dispersal, and settling of dredged material in the water column at dredging sites. SSFATE may be customized to address various dredging scenarios using different dredging methods in a variety of hydrodynamic settings. Model outputs include depositional footprint and time-variable estimates of the suspended sediment concentrations in the water column.

DREDGE

DREDGE is one component of the United States Army Corps of Engineers Automated Dredging and Disposal Alternatives Modeling System (ADDAMS). DREDGE was developed to assist decision makers with a priori assessments of potential environmental impacts from proposed dredging operations. The model is used to estimate the rate of bottom sediment suspension into the water column resulting from hydraulic or mechanical dredging operations and to estimate the suspended sediment concentration that would result. DREDGE is also used to estimate the potential particulate and dissolved concentrations of toxics in the water column based in initial sediment concentrations and equilibrium partitioning theory.

Conclusion

Two sediment-water flux models, the Davis model used to describe the long-term fate of PCBs in San Francisco Bay and WASP, have been discussed above. Neither model addresses bioaccumulation. Ecology's Puget Sound Box Model for Analysis and the Food Web can accommodate input from either of these two models. Between the Davis and WASP models, WASP offers the greatest flexibility. It also addresses some factors, such as flocculation, not addressed by the Davis model.

Several marine water models were presented above. The Aquatic Biogeochemical Cycling (ABC) Model, Hammersley Inlet Oakland Bay Oceanographic Model (HOBO), and South Puget Sound Area Synthesis Model (SPASM) address toxics in water but do not address sediment or bioaccumulation and so are not applicable.

Two dredging-related models, the Suspended Sediment Fate (SSFATE) model and the Automated Dredging and Disposal Alternatives Modeling System (ADDAMS) DREDGE Model, provide support specifically for dredging and dredge spoils disposal and thus are not applicable.

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Appendix B

Puget Sound Sediment-Water Flux Studies Summary Report

The objective of this task was to identify studies conducted in Puget Sound that could be used to provide empirical data on the flux of toxics between the marine sediment and water of Puget Sound. These data would assist in calibrating sediment-to-water flux models. The task included literature searches for:

- Sediment-water toxics flux studies conducted in Puget Sound and
- Studies characterizing the sediment and interstitial porewater at contaminated sites that might provide data appropriate for estimating the flux of toxics to and from contaminated sediments in Puget Sound.

Summary of Existing Flux Studies

This Sediment-Water Flux Studies Summary Report identifies, provides brief summaries of, and evaluates the utility of the relevant Puget Sound flux studies identified. Data utility is based on the applicability of the studies for calibration of a sediment-water flux model.

An Evaluation of Contaminant Flux Rates from Sediments of Sinclair Inlet, Washington, Using a Benthic Flux Sampling Device

Naval Command, Control and Ocean Surveillance Center, Tech. Doc. 2434, February 1993

Study Purpose

The purpose of this study was to demonstrate the Benthic Flux Sampling Device (BFSD) on site to determine the mobility of toxics in Sinclair Inlet (Puget Sound) sediments near the Puget Sound Naval Shipyard.

Summary

Flux rate measurements were performed at seven shipyard and three reference sites in Sinclair Inlet. Sediment samples were also collected and analyzed for each site. The BFSD is a remotely operated device for *in situ* measurement of the contaminant flux rate into or out of sediment. Flux is measured by isolating a known volume of water above a known sediment surface area. Time series water samples, collected into Teflon bottles, were analyzed following retrieval of the BFSD. The BFSD allowed light to enter, maintained an oxic environment, and maintained circulation within the sealed system. Ancillary *in situ* measurements of dissolved oxygen and other parameters provided data to support the flux data.

Data

Metals flux was measured at all sites. Two sites also included PAH and PCB measurements.

Utility

The study successfully documented the flux of several metals from sediment to water. No flux was measured for several metals. Similarly, releases of certain PAHs were measured together with no flux for several toxics; the uptake of one PAH from the water into the sediment was also measured. No PCB flux was measured.

Interpretation of the data was limited by small sample volumes and low ambient water concentrations which controlled the analytical detection limits for all toxics, but especially for the PCBs.

Sediment Flux Assessment of Sinclair and Dyes Inlets

E & E found only limited information on a second BFSD flux study in Puget Sound. Sampling was conducted at seven stations in Sinclair Inlet and two stations in Dyes Inlet during spring 2000. Analytes included conventional water quality parameters and metals.

In addition to flux studies, E & E identified several pore water studies that may assist in evaluating the flux of toxics between the marine sediments and waters of Puget Sound.

USEPA Rhone-Poulenc (Rhodia) Sediment & Porewater Investigation

August/September 2004

Study Purpose

The purpose of this study was to determine if contaminants of concern were present in groundwater, intertidal sediment, and/or subtidal sediment of the Duwamish Waterway adjacent to a facility with known soil, groundwater, and sediment contamination.

Summary

Pore water was collected using seepage meters installed at four locations within the subtidal zone of the Duwamish Waterway near Slip 6. Sediment samples were also collected at these four locations. Seepage meters consisted of inverted plastic buckets pushed into the sediment; trapped water was allowed to escape and the system sealed after some period of equilibration, and water samples from within the bucket above the sediment were drawn into polyethylene bags.

Data

Analytical data were presented for only two seepage meters, and only for mercury, copper, and zinc.

Utility

While these data appear to have met the data needs of the project, the limited number of toxics analyzed, questions about sampling design (for example, sealing the seepage meter system could shift the sediment redox potential from oxic to anoxic), and other issues do not support use of the data in evaluating toxics flux to and from marine sediments in Puget Sound. This was a study of groundwater seepage into a freshwater/estuarine environment, not into a marine environment; this difference would affect metals partitioning in particular.

USEPA Site Inspection Report Lower Duwamish River (RK 2.5 to 11.5)

April 1999, by Roy F. Weston

Study Purpose

The purpose of this study was to provide a screening level evaluation of sediment quality in the Duwamish River.

Summary

Porewater samples were collected at 15 stations within the Duwamish River. Sediment samples were also collected at these 15 locations. The report does not specify how the pore water samples were collected, but the text indicates that multiple whole sediment samples were collected and then combined in a polyethylene bucket and that some manner of water extraction was subsequently employed to isolate the pore water sample for later analysis.

Data

Analytical data were presented for all 15 locations. Analytes included metals and organotins.

Utility

While these data appear to have met the data needs of the project, the limited number of toxics, questions regarding sampling design (for example, porewater collection methods), and other issues do not support use of the data in evaluating toxics flux to/from marine sediments in Puget Sound. However, if additional information about the study could be obtained, these data could be re-evaluated as they might be useful for metals.

Great Western International - Supplemental Remedial Investigation and Feasibility Study.

October 2000, Terra Vac, Edmonds, Washington, and Floyd & Snider, Inc., Seattle, Washington for GW International, Seattle, Washington.

South Myrtle Street Embayment Study

Study Purpose

The purpose of this study was to determine if groundwater was discharging to the South Myrtle Street embayment of the Lower Duwamish Waterway through seeps or through broad areas of groundwater upwelling through the South Myrtle Street embayment sediments. The goal was to gather information that would both distinguish between the two types of discharge (seeps and generalized upwelling) and identify the areas where significant discharge is occurring, so that the discharge points could be sampled during other remedial investigation activities using conventional sampling protocols.

Summary

Three separate sampling events took place between October and December 1998 to measure and map the distribution of chlorinated ethenes in sediment pore water:

- Sampling of sediments in the South Myrtle Street embayment using a series of passive screening devices (GORE-SORBERS®).
- Sampling of seep-face sediment in the South Myrtle Street embayment and along the LDW main channel using several GORE-SORBERS®.
- Sampling of seep water discharging to the South Myrtle Street embayment and to the LDW main channel as part of the annual sampling.

Data

Chlorinated ethenes were measured in the pore water samples.

Utility

While these data appear to have met the data needs of the project, the limited number of toxics, questions regarding sampling design (for example, the pore water collection methodology was based on *in situ* passive soil gas sample collection techniques), and other issues do not support use of the data in evaluating toxics flux to and from marine sediments in Puget Sound. This was a study of groundwater seepage into a freshwater/estuarine environment, not a marine environment; this difference would affect metals partitioning in particular.

Summary of Information on Sediment-Water Toxics Flux Studies in Puget Sound

Qualitative and quantitative data exist on toxics in marine sediments and provide information on the nature and extent of contamination in Puget Sound sediments. However, few studies appear to have been conducted that measured the flux of toxics between the sediment and water.

As noted above, some sediment flux toxics data have been identified and could be used to assist in evaluating a sediment flux model.

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Appendix C

Environmental and Biological Parameters

Table C-1. Environmental parameters from Condon (2007).
These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Model parameter	Value	Units
Concentration of particulate organic carbon in water	5.66E-07	kg/L
Concentration of dissolved organic carbon in water	1.32E-06	kg/L
Concentration of suspended solids	1.55E-05	kg/L
Mean annual water temperature	9.50E+00	^{o}C
Mean annual air temperature	1.03E+01	^{o}C
Salinity	3.00E+01	g/kg
Density of organic carbon in sediment	9.00E-01	kg/L
Organic carbon content of sediment	2.69E-02	unitless
Dissolved oxygen concentration @ 90% saturation	7.50E+00	mg O_2/L
Setschenow proportionality constant	1.80E-03	L/cm^3
Ideal gas law constant (Rgaslaw)	8.31E+00	K
Absolute temperature	2.73E+02	K
Molar concentration of seawater @ 35 ppt	5.00E-01	mol/L
Organic carbon burial rate	1.10E-02	gC/cm^2/yr
Primary production rate of organic carbon	5.52E-01	gC/cm^2/yr

Values rounded to two decimal places.

Table C-2. General biological parameters from Condon (2007).
These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Organisms	Model parameter	Value	Units
All	Non-lipid organic matter – octanol constant	3.50E-02	Unitless
Fish	Growth rate factor	7.00E-04	Unitless
Invertebrates	Growth rate factor	3.50E-04	Unitless
Scavengers	Particle scavenging efficiency	1.00E+00	Unitless
Poikilotherms	Metabolic transformation rate	0.00E+00	d^{-1}
Homeotherms	Mean homeothermic biota temperature	3.75E+01	°C
Homeotherms	Density of lipids	9.00E-01	kg/L
Poikilotherms	Ew constant A	1.85E+00	Unitless
Zooplankton	Dietary absorption efficiency of lipid	7.20E-01	Unitless
Zooplankton	Dietary absorption efficiency of non-lipid organic matter	7.20E-01	Unitless
Zooplankton	Dietary absorption efficiency of water	5.50E-01	Unitless
Invertebrates (except zooplankton)	Dietary absorption efficiency of lipid	7.50E-01	Unitless
Invertebrates (except zooplankton)	Dietary absorption efficiency of non-lipid organic matter	7.50E-01	Unitless
Invertebrates (except zooplankton)	Dietary absorption efficiency of water	5.50E-01	Unitless
Fish	Dietary absorption efficiency of lipid	9.00E-01	Unitless
Fish	Dietary absorption efficiency of non-lipid organic matter	5.00E-01	Unitless
Fish	Dietary absorption efficiency of water	5.50E-01	Unitless
Birds	Dietary absorption efficiency of lipid	9.50E-01	Unitless
Birds	Dietary absorption efficiency of non-lipid organic matter	7.50E-01	Unitless
Birds	Dietary absorption efficiency of water	8.50E-01	Unitless
Seals	Dietary absorption efficiency of lipid	9.70E-01	Unitless
Seals	Dietary absorption efficiency of non-lipid organic matter	7.50E-01	Unitless
Seals	Dietary absorption efficiency of water	8.50E-01	Unitless
Fish, birds, adult seals	Non-lipid organic matter fraction in biota	2.00E-01	Unitless
All feeding Poikilotherms	ED constant A	8.50E-08	Unitless
All feeding Poikilotherms	ED constant B	2.00E+00	Unitless
Birds	ED constant A	3.00E-09	Unitless
Birds	ED constant B	1.04E+00	Unitless
Seals	ED constant A	1.00E-09	Unitless
Seals	ED constant B	1.03E+00	Unitless
Homeotherms	Lung uptake efficiency	7.00E-01	Unitless

Values rounded to two decimal places.

Table C-3. Plant parameters from Condon (2007).

These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Model parameter	Units	Phytoplankton	Kelp / Seagrass
Wet weight of the organism	kg	0.00E+00	0.00E+00
Lipid fraction in plant	Unitless	9.00E-04	8.00E-04
Non-lipid organic carbon fraction in plant	Unitless	6.00E-04	6.20E-02
Water fraction in plant	Unitless	9.99E-01	9.37E-01
Growth rate constant	d^{-1}	1.25E-01	1.25E-01
Aqueous phase resistance constant	d^{-1}	6.00E-05	6.00E-05
Organic phase resistance constant	d^{-1}	5.50E+00	5.50E+00

Values rounded to two decimal places.

Table C-4. Invertebrate parameters from Condon (2007).
These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Model parameter	**Units**	Herbivorous zooplankton	Grazing invertebrates	Carnivorous zooplankton	Predatory invertebrates	*E. pacifica*
Wet weight of the organism	kg	7.10E-08	5.00E-02	3.23E-07	1.00E+00	4.03E-05
Lipid fraction in biota	Unitless	3.96E-02	1.50E-02	3.68E-02	2.00E-02	1.59E-02
Non-lipid organic matter fraction in biota	Unitless	1.46E-01	1.85E-01	1.33E-01	1.80E-01	1.56E-01
Water fraction in biota	Unitless	8.14E-01	8.00E-01	8.30E-01	8.00E-01	8.28E-01
Dietary absorption efficiency of lipid	Unitless	7.20E-01	7.50E-01	7.20E-01	7.50E-01	7.50E-01
Dietary absorption efficiency of non-lipid organic matter	Unitless	7.20E-01	7.50E-01	7.20E-01	7.50E-01	7.50E-01
Dietary absorption efficiency of water	Unitless	5.50E-01	5.50E-01	5.50E-01	5.50E-01	5.50E-01
ED constant A	Unitless	8.50E-08	8.50E-08	8.50E-08	8.50E-08	8.50E-08
ED constant B	Unitless	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00
		N. plumchrus	*P. minutus*	Shellfish	Crab	
Wet weight of the organism	kg	4.54E-06	8.84E-08	8.06E-03	5.37E-01	
Lipid fraction in biota	Unitless	1.22E-01	3.96E-02	1.20E-02	3.00E-02	
Non-lipid organic matter fraction in biota	Unitless	6.36E-02	1.46E-01	1.88E-01	1.70E-01	
Water fraction in biota	Unitless	8.14E-01	8.14E-01	8.00E-01	8.00E-01	
Dietary absorption efficiency of lipid	Unitless	7.20E-01	7.20E-01	7.50E-01	7.50E-01	
Dietary absorption efficiency of non-lipid organic matter	Unitless	7.20E-01	7.20E-01	7.50E-01	7.50E-01	
Dietary absorption efficiency of water	Unitless	5.50E-01	5.50E-01	5.50E-01	5.50E-01	
ED constant A	Unitless	8.50E-08	8.50E-08	8.50E-08	8.50E-08	
ED constant B	Unitless	2.00E+00	2.00E+00	2.00E+00	2.00E+00	

Values rounded to two decimal places.

Table C-5. Fish parameters from Condon (2007).

These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Model parameter	**Units**	Herring	Pelagic fish (seal prey)	Pelagic fish (bird prey)	River lamprey	Demersal fish (seal prey)
Wet weight of the organism	kg	5.95E-02	4.49E-02	4.92E-03	1.43E-02	1.81E-01
Lipid fraction in biota	Unitless	4.99E-02	3.86E-02	1.53E-02	1.25E-01	2.51E-02
Non-lipid organic matter fraction in biota	Unitless	2.00E-01	2.00E-01	2.00E-01	2.00E-01	2.00E-01
Water fraction in biota	Unitless	7.50E-01	7.61E-01	7.85E-01	6.75E-01	7.75E-01
Dietary absorption efficiency of lipid	Unitless	9.00E-01	9.00E-01	9.00E-01	9.00E-01	9.00E-01
Dietary absorption efficiency of non-lipid organic matter	Unitless	5.00E-01	5.00E-01	5.00E-01	5.00E-01	5.00E-01
Dietary absorption efficiency of water	Unitless	5.50E-01	5.50E-01	5.50E-01	5.50E-01	5.50E-01
Fraction of respiration that involves sed. associated pore water	Unitless	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.00E-02
ED constant A	Unitless	8.50E-08	8.50E-08	8.50E-08	8.50E-08	8.50E-08
ED constant B	Unitless	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00

		Demersal fish (bird prey)	Chum	Coho	Chinook	Pacific hake
Wet weight of the organism	kg	4.72E-03	3.96E+00	3.50E+00	3.63E+00	3.74E-01
Lipid fraction in biota	Unitless	1.63E-02	4.83E-02	6.39E-02	5.43E-02	5.20E-02
Non-lipid organic matter fraction in biota	Unitless	2.00E-01	2.00E-01	2.00E-01	2.00E-01	2.00E-01
Water fraction in biota	Unitless	7.84E-01	7.52E-01	7.36E-01	7.46E-01	7.48E-01
Dietary absorption efficiency of lipid	Unitless	9.00E-01	9.00E-01	9.00E-01	9.00E-01	9.00E-01
Dietary absorption efficiency of non-lipid organic matter	Unitless	5.00E-01	5.00E-01	5.00E-01	5.00E-01	5.00E-01
Dietary absorption efficiency of water	Unitless	5.50E-01	5.50E-01	5.50E-01	5.50E-01	5.50E-01
Fraction of respiration that involves sed. associated pore water	Unitless	5.00E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
ED constant A	Unitless	8.50E-08	8.50E-08	8.50E-08	8.50E-08	8.50E-08
ED constant B	Unitless	2.00E+00	2.00E+00	2.00E+00	2.00E+00	2.00E+00

		Northern smooth-tongue	Dogfish	Pollock	English sole
Wet weight of the organism	kg	7.50E-04	2.00E+00	7.97E-02	7.40E-02
Lipid fraction in biota	Unitless	4.99E-02	1.00E-01	2.16E-02	4.00E-02
Non-lipid organic matter fraction in biota	Unitless	2.00E-01	2.00E-01	2.00E-01	2.00E-01
Water fraction in biota	Unitless	7.50E-01	7.00E-01	7.78E-01	7.60E-01
Dietary absorption efficiency of lipid	Unitless	9.00E-01	9.00E-01	9.00E-01	9.00E-01
Dietary absorption efficiency of non-lipid organic matter	Unitless	5.00E-01	5.00E-01	5.00E-01	5.00E-01
Dietary absorption efficiency of water	Unitless	5.50E-01	5.50E-01	5.50E-01	5.50E-01
Fraction of respiration that involves sed. associated pore water	Unitless	0.00E+00	0.00E+00	0.00E+00	5.00E-02
ED constant A	Unitless	8.50E-08	8.50E-08	8.50E-08	8.50E-08
ED constant B	Unitless	2.00E+00	2.00E+00	2.00E+00	2.00E+00

Values rounded to two decimal places.

Table C-6. Bird parameters from Condon (2007).

These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Model parameter	Units	Double crested cormorant (adult male)	Double crested cormorant (adult female)	Great blue heron (adult male)	Great blue heron (adult female)
Wet weight of the organism	kg	2.50E+00	2.40E+00	2.58E+00	2.20E+00
Lipid fraction in biota	Unitless	7.50E-02	7.50E-02	7.50E-02	7.50E-02
Non-lipid organic matter fraction in biota	Unitless	2.00E-01	2.00E-01	2.00E-01	2.00E-01
Water fraction in biota	Unitless	7.25E-01	7.25E-01	7.25E-01	7.25E-01
Dietary absorption efficiency of lipid	Unitless	9.50E-01	9.50E-01	9.50E-01	9.50E-01
Dietary absorption efficiency of non-lipid organic matter	Unitless	7.50E-01	7.50E-01	7.50E-01	7.50E-01
Dietary absorption efficiency of water	Unitless	8.50E-01	8.50E-01	8.50E-01	8.50E-01
Lung uptake efficiency	Unitless	7.00E-01	7.00E-01	7.00E-01	7.00E-01
Growth rate constant	d^{-1}	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Activity Factor	Unitless	3.00E+00	3.00E+00	3.00E+00	3.00E+00
ED constant A	Unitless	3.00E-09	3.00E-09	3.00E-09	3.00E-09
ED constant B	Unitless	1.04E+00	1.04E+00	1.04E+00	1.04E+00
		Double crested Cormorant (egg)	Great Blue Heron (egg)		
No. clutches per year	clutch/yr	1.00E+00	1.00E+00		
No. eggs per clutch	eggs	4.00E+00	4.00E+00		
Wet weight of egg	kg	4.49E-02	7.10E-02		
Lipid content of egg	Unitless	4.62E-02	6.28E-02		
NLOM content of egg	Unitless	1.15E-01	1.20E-01		
Water content of egg	Unitless	8.39E-01	8.17E-01		

Values rounded to two decimal places.

Table C-7. Seal parameters from Condon (2007).
These values were retained for use in the modified bioaccumulation model. See Condon (2007) for discussion and references.

Model parameter	**Units**	Harbor seal (adult male)	Harbor seal (adult female)	Harbor seal (1 yr old)	Harbor seal (pup)
Wet weight of the organism	kg	8.70E+01	6.48E+01	3.33E+01	2.39E+01
Lipid fraction in biota	Unitless	4.30E-01	1.50E-01	1.16E-01	4.13E-01
Non-lipid organic matter fraction in biota	Unitless	2.00E-01	2.00E-01	2.46E-01	1.51E-01
Water fraction in biota	Unitless	3.70E-01	6.50E-01	6.38E-01	4.36E-01
Dietary absorption efficiency of lipid	Unitless	9.70E-01	9.70E-01	9.70E-01	9.70E-01
Dietary absorption efficiency of non-lipid organic matter	Unitless	7.50E-01	7.50E-01	7.50E-01	7.50E-01
Dietary absorption efficiency of water	Unitless	8.50E-01	8.50E-01	8.50E-01	8.50E-01
Lung uptake efficiency	Unitless	7.00E-01	7.00E-01	7.00E-01	7.00E-01
Growth rate constant	d^{-1}	7.50E-05	1.00E-05	1.00E-03	2.50E-02
Activity Factor	Unitless	2.50E+00	2.50E+00	2.50E+00	1.50E+00
ED constant A	Unitless	1.00E-09	1.00E-09	1.00E-09	1.00E-09
ED constant B	Unitless	1.03E+00	1.03E+00	1.03E+00	1.03E+00
Additional seal parameters					
Proportion of population reproducing	Unitless	9.00E-01			
Weight of fetus	kg	1.12E+01			
Lipid content of fetus	Unitless	1.10E-01			
NLOM content of fetus	Unitless	2.00E-01			
Water content of fetus	Unitless	6.90E-01			
Lipid content of milk	Unitless	4.93E-01			
NLOM content of milk	Unitless	1.17E-01			
Water content of milk	Unitless	3.90E-01			

Values rounded to two decimal places.