DEVELOPMENT, EVALUATION, AND APPLICATION OF A FOOD WEB BIOACCUMULATION MODEL FOR PCBS IN THE STRAIT OF GEORGIA, BRITISH COLUMBIA

by

Colm David Condon
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Name:	**Colm David Condon**
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Examining Committee:

Dr. Frank A.P.C. Gobas
Senior Supervisor
Professor

School of Resource and Environmental Management
Simon Fraser University

Dr. Peter S. Ross
Adjunct Professor

Simon Fraser University

Date Approved:

ABSTRACT

In an effort to enhance the understanding of persistent organic pollutant (POP) bioaccumulation in the Strait of Georgia, I developed, parameterized, and tested a mechanistic bioaccumulation model for polychlorinated biphenyls (PCBs) in the Strait of Georgia. Review of the literature required to support the model uncovered significant gaps in the empirical dataset. These gaps limit the usefulness of the model as a management tool; however, enough data were available to support analysis of the current sediment quality guideline for PCBs in British Columbia. This analysis suggests that the guideline is inadequate to protect top predators in the Strait of Georgia and may not meet the Ministry of Environment's protection objectives. I recommend that research be directed at improving the empirical database required for bioaccumulation modelling in the Strait of Georgia and that bioaccumulation models similar to that developed here be used when deriving sediment quality guidelines for other POPs.

Keywords: bioaccumulation; biomagnification; PCBs; Strait of Georgia; food web; sediment quality guidelines

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GLOSSARY

TERM	DEFINITION	REFERENCE
Bioaccumulation	The process by which the chemical concentration within an organism achieves a level that exceeds that in its environment as a result of chemical uptake through all possible routes of exposure (e.g., dietary, dermal, respiratory).	Gobas & Morrison, 2000
Bioaccumulation factor	The ratio of the chemical concentration in the organism to the chemical concentration in the water. The concentration can be expressed on a wet weight, dry weight, or lipid weight basis.	Gobas & Morrison, 2000
Biomagnification	The process in which the chemical concentration in an organism achieves a level that exceeds that in the organism's diet, due to dietary absorption.	Gobas & Morrison, 2000
Biota-sediment accumulation factor	The ratio of the chemical concentration in an organism to the chemical concentration in the sediment in which the organism resides.	Gobas & Morrison, 2000
Ecological risk assessment	Ecological risk assessment is a process that evaluates the likelihood that adverse ecological effects are occurring or may occur as a result of exposure to one or more stressors	US EPA, 1992
Equilibrium	A condition where the chemical's potentials (also chemical activities and fugacities) are equal in the environmental media. At equilibrium, chemical concentrations in static environmental media remain constant over time.	Gobas & Morrison, 2000
Fugacity capacity	The proportionality constant that indicates the ability of a media to absorb a solute and varies with the nature of the chemical and the	Mackay, 1991

	medium, the temperature, pressure, and concentration.	
Lowest observed adverse effect limit	The lowest concentration or dose in a test which produced an observable adverse effect.	US EPA, 2006
No observed adverse effect limit	The maximum concentration or dose in a test which produces no observed adverse effects.	US EPA, 2006
Octanol-air partition coefficient	The ratio of a chemical's solubility in octanol vs. air.	Derived from Mackay, 1991
Octanol-water partition coefficient	The ratio of a chemical's solubility in octanol vs. water.	Mackay, 1991
Persistent organic pollutant	A chemical possessing three primary attributes: persistence, tendency to bioaccumulate, and toxicity	Wania & Mackay 1999
Steady-state	A condition where the total flux of chemical into an organism equals the total flux out with no net change in mass or concentration of the chemical.	Gobas & Morrison, 2000
Trophic position	A measure of an organism's trophic status in a food web which, by providing non-integer quantities, considers the effects of omnivory, cannibalism, feeding loops, and scavenging on food web structure.	Vander Zanden & Rasmussen, 1996

LIST OF ACRONYMS

BAF	Bioaccumulation factor
BC	British Columbia
BSAF	Biota-sediment accumulation factor
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
DSL	Domestic Substances List
dw	Dry weight
ERA	Ecological risk assessment
GB	Georgia Basin
GBAP	Georgia Basin Action Plan
K_{OA}	Octanol-air partition coefficient
K_{OW}	Octanol-water partition coefficient
LOAEL	Lowest observed adverse effects level
MB	Model bias
MOE	BC Ministry of Environment
NLOM	Non-lipid organic matter
NOAEL	No observed adverse effects level
OC	Organic carbon
PBDEs	Polybrominated diphenyl ethers
PCBs	Polychlorinated biphenyls
ΣPCBs	Total polychlorinated biphenyls
POPs	Persistent organic pollutants
SoG	Strait of Georgia

SQG	Sediment Quality Guideline
SQT	Sediment Quality Target
TP	Trophic position
TRV	Toxicity reference value
ww	Wet weight

1 INTRODUCTION

1.1 Background

The Strait of Georgia (SoG), which lies in south-western British Columbia (BC) within the Georgia Basin (GB) (Figure 1-1), is home to a rich and complex food web and one of the largest estuaries in North America.

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Figure 1-1 Map of the Strait of Georgia and surrounding area

The SoG is also home to approximately eight million surrounding residents who, through their various commercial and recreational activities, exert considerable stress on the SoG ecosystem. One of the contributing stressors is the presence of persistent organic pollutants (POPs) that originate locally, regionally, and globally. POPs of particular concern include polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), polychlorinated dibenzo-p-dioxins (PCDDs), and others. Many of the 209 highly stable, persistent PCB congeners, for instance, are known to bioaccumulate up aquatic food webs and are believed to disrupt endocrine function, suppress the immune system, and impair reproduction in a wide range of biota including fish, marine mammals, birds, and humans [Van den Berg *et al.*, 1998; Newsted *et al.*, 1995; Ross *et al.*, 2000].

Recent SoG monitoring studies have detected high levels of PCBs in wild and farmed salmon [Hites *et al.*, 2004], double-crested and pelagic cormorant eggs [Harris *et al.*, 2005], great blue heron eggs [Harris *et al.*, 2003], harbour seals [Ross *et al.*, 2004], and orcas [Ross *et al.*, 2000]. In fact, PCB levels are so high in southern resident and transient orcas (an average of 150 and 250 mg/kg lipid, respectively) that these organisms are considered among the most PCB-contaminated cetaceans in the world [Ross *et al.*, 2000]. Studies have also detected high concentrations of PBDEs, polybrominated biphenyls (PBBs), and polychlorinated naphthalenes (PCNs) in transient and resident orcas [Rayne *et al.*, 2004].

1.2 Risk Management

The investigation and management of potential risks to SoG wildlife associated with exposure to POPs is a key concern for two institutions: the Georgia Basin Action Plan (GBAP) and the BC Ministry of Environment (MOE). The roles of each are discussed below.

1.2.1 Georgia Basin Action Plan

The Georgia Basin Action Plan (GBAP) is a multi-partnered initiative (i.e., including various federal, provincial, and municipal government agencies, non-governmental organizations, private corporations, etc.) that is working to improve sustainability in the Georgia Basin [Environment Canada, 2005]. Among the GBAP's many goals is the aim of improving the capacity of environmental managers to make decisions by advancing scientific understanding [Environment Canada, 2005]. For example, to help environmental managers manage POP-exposure risks to GB wildlife, Environment Canada (EC) is funding the development of mass balance models aimed at improving scientific understanding of POP-pollution dynamics in the SoG. These models will simulate the flux of POPs into and out of the environmental media of the SoG over time and relate POP concentrations in environmental media to POP concentrations in, and associated risks to, resident wildlife of the SoG.

The POP mass balance models are expected assist environmental risk managers in a number of ways. For example, they will help them to (i) set POP emissions targets that meet desired ecological risk endpoints (e.g., no more than 10% of the harbour seal population with PCB body burdens that exceed their effects threshold for PCBs); (ii) predict the response time of the SoG to POP reduction strategies; (iii) identify which POPs on the Domestic Substances List (DSL) should be targeted for management or virtual elimination (as per Environment Canada, 2004); (iv) prioritize research aimed to better achieve GBAP objectives; etc.

1.2.2 Ministry of Environment

The BC Ministry of Environment (MOE) manages the exposure of wildlife to chemicals primarily by setting environmental quality guidelines. BC's ambient sediment quality guidelines (SQGs), for instance, "apply province-wide and are safe levels of substances for the protection of a given water use, including drinking water, aquatic life, recreation and agricultural uses" [MOE, 2006].

Currently, SQGs exist for only two POPs: PCBs and PAHs. SQGs for dioxins and furans are under development, and SQGs for other POPs are expected in the coming years. The SQG for ΣPCBs is based on a combination of (i) PCB exposure and effects data from laboratory studies conducted primarily on freshwater fish and invertebrates, (ii) the application of simple equilibrium partitioning equations, and (iii) the application of uncertainty factors [Nagpal, 1992]. Given that little, if any, SoG-specific data was used to derive the SQG for ΣPCBs, and given the high potential for PCB biomagnification in the SoG food web (note its complexity in Table 3-1) and the high concentrations of PCBs in SoG wildlife (particularly orcas), it is unclear whether the current SQG for ΣPCBs is sufficient to meet the MOE's protection objectives.

1.3 Project Objectives

To help improve POP-associated risk management in BC, I have conducted a research project with the following objectives:

1. Develop, parameterize, and test a food web bioaccumulation model for PCBs that estimates biota sediment accumulation factors (BSAFs) for a set of resident organisms of the SoG. This model is intended to form all or part of the biological component of a broader fate model for PCBs in the SoG. It is also intended to serve as a foundation for the biological component of mass balance models developed in the future for other POPs (including PBDEs). I elected to use PCBs in this initial food web model because empirical datasets for PCBs (e.g., congener properties, environmental and biological concentrations, etc.), which are necessary for performance analysis and application, are much more comprehensive for PCBs than for other POPs. In addition, PCBs are easier to model than some other POPs because they are poorly (or not) metabolized by fish, invertebrates, algae, and other lower-trophic organisms. not metabolized by lower-trophic organisms.

2. Use this model to

- characterize the risks to top predators of the SoG associated with current levels of PCB exposure,

- characterize the level of protection offered to top predators of the SoG by the current SQG for ΣPCBs,

- propose a new SQG for ΣPCBs which meets the MOE's protection goals, and

- propose sediment quality targets (SQTs) for ΣPCBs which protect top predators of the SoG to various risk-related endpoints (e.g., not more than 5% of cormorant eggs above the no observed adverse effects level (NOAEL), 5% of seal pups above the effects threshold, etc.).

3. Use the literature review required for the model to identify PCB bioaccumulation data gaps and make research recommendations aimed at narrowing these gaps.

1.4 Overview

A conceptual overview of the food web bioaccumulation model is presented below (Figure 1-2). Rounded-corner white boxes indicate major inputs; grey boxes indicate calculation routines; and sharp-corner white boxes indicate major outputs. The model can be viewed as having three basic components. The first is the bioaccumulation calculation component, where I convert measured, congener-specific concentrations of PCBs in SoG sediments, herring, and salmon to predicted, congener-specific PCB-BSAFs for 31 organisms/organism groups in the SoG. The second is the model performance analysis component, where I compare model predicted BSAFs to empirically derived BSAFs. The third is the model application component, where, upon satisfactory completion of the model performance analysis, I use the model to address various issues of environmental management interest.

The following paper details each of the components introduced above. The bioaccumulation routines used to predict organism BSAFs are described in the bioaccumulation theory section. The methods used to derive the BSAF, performance analysis, and application results are described, in turn, in the methods section. And the results of the BSAF, performance analysis, and application phases are described and discussed, in turn, in results and discussion section.

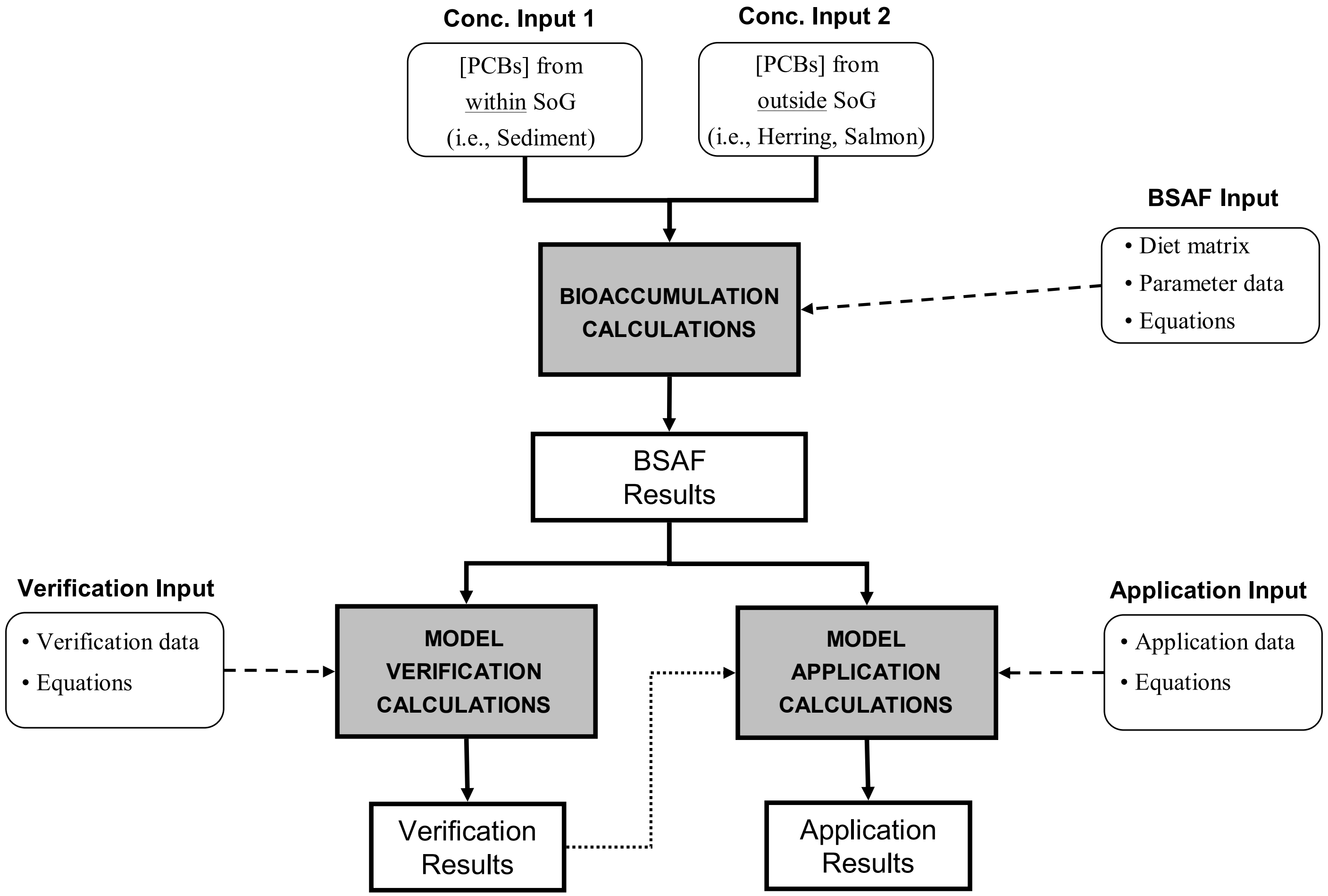

Figure 1-2 An overview of the principal components of the food web bioaccumulation model for PCBs in the SoG

2 BIOACCUMULATION THEORY

2.1 Overview

The ultimate aim of the model's bioaccumulation equations is to generate congener-specific BSAFs (g/g) for resident organisms and organism groups in the SoG. BSAFs relate sediment and organism concentrations as per the following equation:

$$C_B = BSAF * C_S \tag{1}$$

where C_B (ng/g-ww) is the PCB congener concentration in the biological organism, and C_S (ng/g-dw) is the PCB congener concentration in sediment.

To derive BSAFs, the model converts, through the application of literature derived mass-balance equations, empirical PCB congener concentrations in SoG sediment to predicted PCB congener concentrations in SoG organisms. This approach has been applied successfully in a number of other systems including San Francisco Bay, Lake Ontario, and Kitimat Arm [Gobas & Arnot, 2005; Gobas *et al*., 1998; Morrison *et al*., 1997; Stevenson, 2003; etc.]. Sections 3.2 to 3.5 (below) describe the bioaccumulation equations. I divide the description into (i) a general bioaccumulation equation for marine phytoplankton, algae, invertebrates, and fish and (ii) a general bioaccumulation equation for birds and seals. The derivation of equations is not included (refer to Arnot & Gobas, 2004 and Gobas & Arnot, 2005 for these details) except where I have developed equations specific to this system.

2.2 Bioaccumulation Description – Water Breathers & Plants

The concentration of a given PCB congener in marine phytoplankton and algae depends on a balance between the rate of congener uptake via passive diffusion and the rates of congener loss via passive diffusion, growth, and metabolism (Figure 2-1).

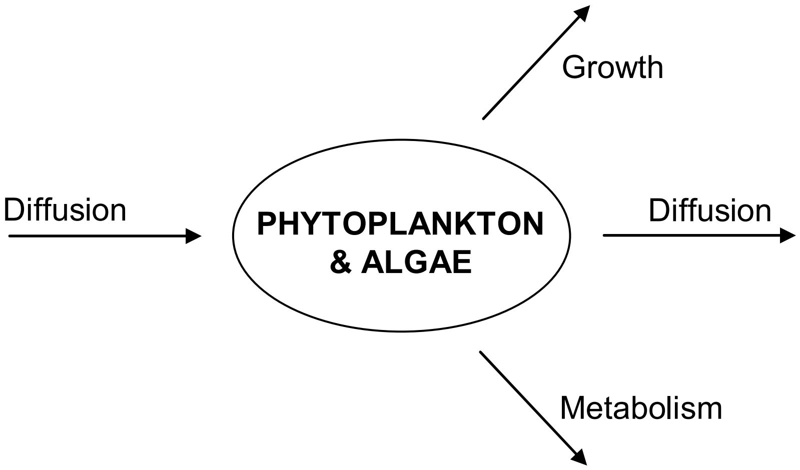

Figure 2-1 PCB uptake and elimination pathways for phytoplankton and algae

Similarly, the concentration of a given PCB congener in marine fish and invertebrates depends on a balance between the rates of congener uptake via dietary ingestion and water respiration and the rates of congener loss via growth, respiration, metabolism, and faecal egestion (Figure 2-2).

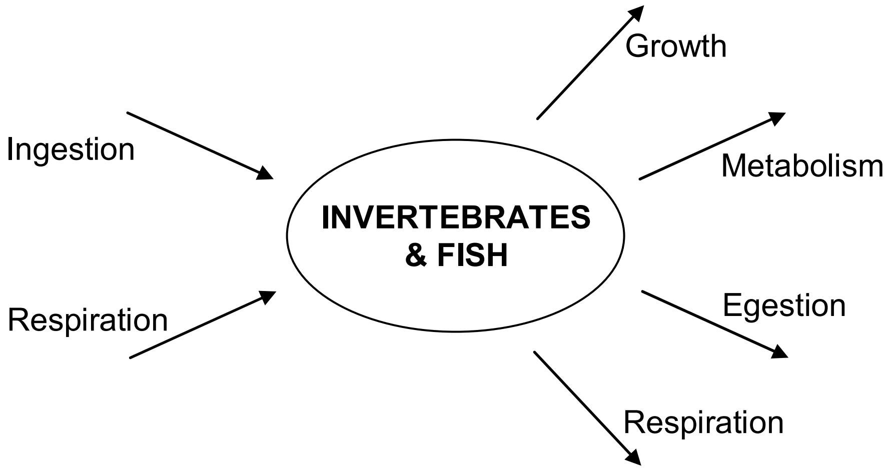

Figure 2-2 PCB uptake and elimination pathways for invertebrates and fish

These PCB-congener uptake and loss processes can be expressed mathematically to predict the change in congener mass in an organism over time in phytoplankton, algae, invertebrates, and fish as follows:

$$dM_{Bj}/dt = \{W_B \bullet (k_{1j} \bullet [m_O \bullet \phi \bullet C_{WT,O} + m_P \bullet C_{WD,S}] + k_{Dj} \bullet \Sigma(P_i \bullet C_{D,i}))\} - (k_{2j} + k_{Ej} + k_{Mj} + k_{Gj}) \bullet M_B \qquad [2]$$

Where M_{Bj} (ng) is the mass of the PCB congener j in the organism B at time t, and W_B (kg) is the wet weight of the organism at time t (see next page for individual parameter definitions).

In order to simplify the modelling exercise, I assumed that PCB congener concentrations in organisms of the SoG are at steady-state (i.e., they do not change over time). This assumption is considered valid for POP models in complex systems [Wania & Mackay, 1999] and has been applied successfully in other systems [Gobas & Arnot, 2004; Russell et al., 1999]. Furthermore, since the rate of change in PCB concentrations in the SoG is likely slow, SoG organisms probably have enough time to achieve a dynamic equilibrium with their surroundings.

Assuming steady-state (i.e., $dM_B/dt = 0$), equation 2 rearranges to predict the PCB congener concentration in an organism as follows:

$$C_{Bj} = \{k_{1j} \bullet (m_O \bullet \phi \bullet C_{WT,O} + m_P \bullet C_{WD,S}) + k_{Dj} \bullet \sum P_i \bullet C_{D,j,i}\} / (k_{2j} + k_{Ej} + k_{Gj} + k_{Mj}) \qquad [3]$$

Where

C_{Bj} = concentration of congener j in the organism (ng/g wet weight)
k_{1j} = rate of congener j uptake via respiration (d^{-1})
m_O = fraction of the respiratory ventilation that involves overlying water (unitless)
m_P = fraction of the respiratory ventilation that involves pore water (unitless)
ϕ_j = fraction of congener j in overlying water that can be absorbed (unitless)
$C_{WT,O,j}$ = total concentration of congener j in overlying water (ng/mL)
$C_{WD,S,j}$ = freely dissolved concentration of congener j in pore water (ng/mL)
k_{Dj} = rate of congener j uptake via dietary ingestion (d^{-1})
P_i = fraction of the diet consisting of prey item i (unitless)
$C_{D,j,i}$ = concentration of congener j in prey item i (g/kg)
k_{2j} = rate of congener j elimination via respiration (d^{-1})
k_{Ej} = rate of congener j elimination via egestion (d^{-1})
k_{Mj} = rate of congener j elimination via metabolic transformation (d^{-1})
k_{Gj} = rate of congener j elimination via growth (d^{-1})

For phytoplankton and algae, k_D, k_E, and k_M are assumed to equal zero and equation 3 simplifies to the following:

$$C_{Bj} = k_{1j} \bullet C_{WD,j,S} / k_{2j} + k_{Gj} \qquad [4]$$

Values for model parameters m_O, m_P, and Pi were entered directly into the model. Values for variables k_1, k_D, k_2, k_E, k_G, ϕ, $C_{WT,O}$, and $C_{WD,S}$ were derived as detailed below.

Note that the variable equations below apply to PCB congeners. To derive ΣPCB concentrations (used for SQGs and risk estimation calculations), the concentrations of all the congeners in an organism are added up, as per the following equation:

$$C_{B\Sigma} = \sum_{j=1}^{n} C_{Bj} \tag{5}$$

Where $C_{B\Sigma}$ (ng/g) is the ΣPCB concentration in organism B.

Respiratory Uptake (k_1) – Phytoplankton and Algae

The rate of respiratory chemical uptake by phytoplankton and algae, k_1 (d^{-1}), is calculated as follows:

$$k_1 = (A_P + (B_P / K_{OW}))^{-1} \tag{6}$$

Where A_P (unitless) and B_P (unitless) are constants describing the resistance to PCB uptake through the aqueous and organic phases, respectively, of the phytoplankton or algae.

Respiratory Uptake (k_1) – Invertebrates and Fish

The rate of respiratory chemical uptake by invertebrates and fish, k_1 (L/kg/d), is calculated as follows:

$$k_1 = E_W \bullet G_V / W_B \tag{7}$$

Where E_W (unitless) is the diffusive transfer efficiency at the respiratory surface, G_V (L/d) is the water ventilation rate across the respiratory membrane, and W_B (kg) is the wet weight of the organism. The diffusive transfer efficiency, E_W, is congener specific and derived as follows:

$$E_W = (E_M + (155 / K_{OW}))^{-1} \qquad [8]$$

Where E_M (unitless) is the maximum gill uptake efficiency and K_{OW} (unitless) is the octanol-water partition coefficient for a given congener. The water ventilation rate, G_V, is derived as follows:

$$G_V = 1400 \bullet W_B^{0.65} / C_{OX} \qquad [9]$$

Where C_{OX} ($mg\text{-}O_2 \cdot L^{-1}$) is the dissolved oxygen concentration in the water.

Respiratory Elimination (k_2) – Phytoplankton and Algae

The rate of respiratory chemical elimination in phytoplankton and algae, k_2 (d^{-1}), is related to respiratory uptake by the following equation:

$$k_2 = k_1 / K_{PW} \qquad [10]$$

Where K_{PW} (unitless) is the plant-water partition coefficient. K_{PW} is estimated as follows:

$$K_{PW} = v_{LP} \bullet K_{OW} + v_{NP} \bullet 0.35 \bullet K_{OW} + v_{WP} \qquad [11]$$

Where v_{LP}, v_{NP}, v_{WP} (unitless) are the lipid, NLOC (non-lipid organic carbon), and water compositions of the phytoplankton / algae. The value 0.35 is the NLOC proportionality constant which implies that sorption affinity of NLOC for PCBs is 35% that of octanol.

Respiratory Elimination (k_2) –Invertebrates and Fish

The rate of chemical elimination via respiration in invertebrates and fish, k_2 (d^{-1}), is related to respiratory uptake as follows:

$$k_2 = k_1 / K_{BW} \qquad [12]$$

Where K_{BW} (unitless) is the biota-water partition coefficient. Partitioning between biota and water of the SoG is a function of the fraction of lipid, non-lipid organic matter (NLOM), and water in the organism as described by the following equation:

$$K_{BW} = v_{LB} \bullet K_{OW} + v_{NB} \bullet \beta \bullet K_{OW} + v_{WB} \qquad [13]$$

Where v_{LB}, v_{NB}, and v_{WB} (unitless) are the lipid, NLOM, and water fraction of the organism, respectively, and β (unitless) is the NLOM proportionality constant which relates the PCB sorption capacity of NLOM to lipids. A β value of 0.035 was used (see parameterization section below) implying that sorption affinity of NLOM for PCBs is 3.5% that of octanol.

Dietary Uptake (k_D) – Invertebrates and Fish

The rate at which PCBs are absorbed from the diet, k_D (d^{-1}) is estimated as follows:

$$k_D = E_D \bullet G_D / W_B \qquad [14]$$

Where E_D (unitless) is the dietary chemical transfer efficiency, G_D (kg/d) is the feeding rate, and W_B (kg) is the wet weight of the organism. E_D was estimated using the following two-phase resistance model:

$$E_D = (E_DA \bullet K_{OW} + E_DB)^{-1} \qquad [15]$$

Where E_DA and E_DB are species-specific constants (see parameterization section for values). The feeding rates, G_D, for filter feeders and detritovores are estimated respectively as

$$G_D = G_V \bullet V_{SS} \bullet \sigma \qquad [16]$$

$$G_D = 0.22 \bullet W_B^{0.85} \bullet e^{(0.06 \bullet Tw)} \qquad [17]$$

Where G_V (L/d) is the water ventilation rate (described above), V_{SS} (kg/L) is the concentration of suspended solids in the water, σ (unitless) is the particle scavenging efficiency, and T_W (K) is the water temperature.

Faecal Elimination (k_E) – Invertebrates and Fish

The rate of chemical elimination by egestion, k_E (d^{-1}), is derived as follows:

$$k_E = G_F \bullet E_D \bullet K_{GB} / W_B \qquad [18]$$

Where G_F (kg-faeces/kg-organism/d) is the faecal egestion rate, E_D (unitless) is the dietary chemical transfer efficiency (described above), K_{GB} (unitless) is the gut-biota partition coefficient, and W_B (kg) is the wet weight of the organism. G_F is estimated as follows:

$$G_F = \{(1 - \varepsilon_L) \bullet v_{LD} + (1 - \varepsilon_N) \bullet v_{ND} + (1 - \varepsilon_W) \bullet v_{WD}\} \bullet G_D \qquad [19]$$

Where ε_L, ε_N, and ε_W (unitless) are the dietary absorption efficiencies of lipid, NLOM, and water, respectively; v_{LD}, v_{ND}, and v_{WD} (unitless) are lipid, NLOM, and water composition of the diet, respectively; and G_D (kg/d) is the feeding rate (described above).

The gut-biota partition coefficient, K_{GB} (unitless), is estimated as follows:

$$K_{GB} = Z_{GUT} / Z_{ORG} \quad [20]$$

Where Z_{GUT} (mol/m^3-Pa) is the fugacity capacity (or chemical sorptive capacity) of the organism's gut contents, and Z_{ORG} (mol/m^3-Pa) is the fugacity capacity of the organism. Z_{GUT} is estimated from the following equation:

$$Z_{GUT} = v_{LG} \bullet Z_L + v_{NG} \bullet \beta \bullet Z_L + v_{WG} \bullet Z_W \quad [21]$$

Where v_{LG}, v_{NG}, and v_{WG} (unitless) are the lipid, NLOM, and water contents, respectively, of the organism's gut contents; Z_L and Z_W (mol/m^3-Pa) are the fugacity capacities of lipid and water, respectively; and β (unitless) is the NLOM proportionality constant. The sum of the v_{LG}, v_{NG}, and v_{WG} approach 1 and are estimated as follows:

$$v_{LG} = (1 - \varepsilon_L) \bullet v_{LD} / \{(1 - \varepsilon_L) \bullet v_{LD} + (1 - \varepsilon_N) \bullet v_{ND} + (1 - \varepsilon_W)\, v_{WD}\} \quad [22]$$

$$v_{NG} = (1 - \varepsilon_N) \bullet v_{ND} / \{(1 - \varepsilon_L) \bullet v_{LD} + (1 - \varepsilon_N) \bullet v_{ND} + (1 - \varepsilon_W)\, v_{WD}\} \quad [23]$$

$$v_{WG} = (1 - \varepsilon_W) \bullet v_{WD} / \{(1 - \varepsilon_L) \bullet v_{LD} + (1 - \varepsilon_N) \bullet v_{ND} + (1 - \varepsilon_W)\, v_{WD}\} \quad [24]$$

Z_L and Z_W are estimated by the following equations:

$$Z_L = K_{OA} / R \bullet T \quad [25]$$

$$Z_W = Z_L / K_{OW} \quad [26]$$

Where K_{OA} (unitless) is the octanol-air partition coefficient, R (Pa-m^3/mol K) is the ideal gas constant, and T (K) is the water temperature (lower trophic organisms) organism temperature (seals and birds).

The fugacity capacity of the organism, Z_{ORG}, is estimated as follows:

$$Z_{ORG} = v_{LB} \bullet Z_L + v_{NB} \bullet \beta \bullet Z_L + v_{WB} \bullet Z_W \quad [27]$$

Where v_{LB}, v_{NB}, and v_{WB} (unitless) are the lipid, NLOM, and water composition of the organism, respectively, and Z_L and Z_W (mol/m^3-Pa) are the fugacity capacities of lipid and water, respectively (described above).

Growth Dilution (k_G) – All Lower Trophic Organisms

The rate of chemical dilution by growth, k_G (d^{-1}), for phytoplankton and algae is input directly (see parameter section) and for invertebrates and fish is derived from the following equation:

$$k_G = GRF \bullet W_B^{-0.2} \tag{28}$$

Where GRF (unitless) is the species-specific growth rate factor.

Metabolic Elimination (k_M) – All Lower Trophic Organisms

The rate of chemical elimination via metabolism, k_M (d^{-1}), is assumed to be zero for lower trophic organisms.

2.3 Bioaccumulation Description – Birds and Seals

The concentration of a given PCB congener in marine birds and seals depends on the balance between the rates of chemical uptake via dietary ingestion and air respiration and the rates of chemical loss via respiration, growth, metabolism, faecal egestion, gestation (females only) and lactation (female seals only) (Figure 2-3).

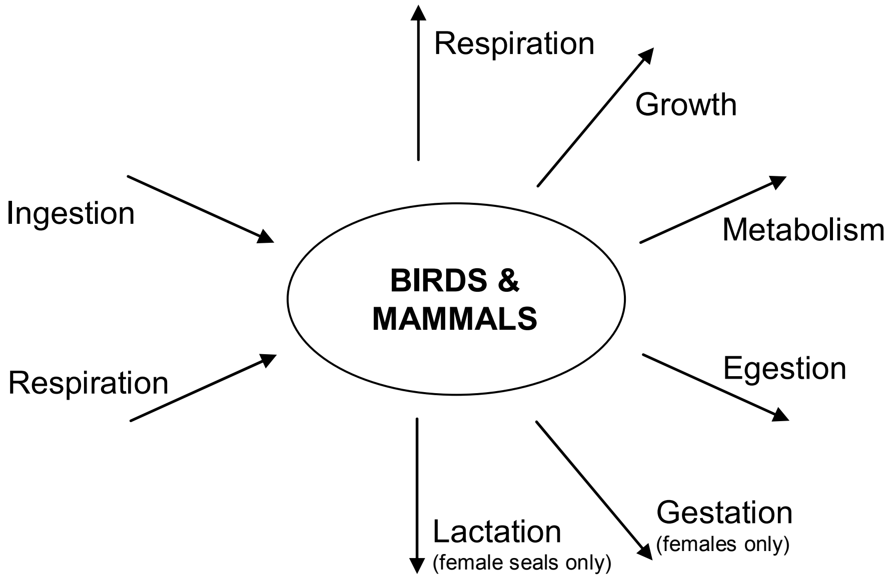

Figure 2-3 PCB uptake and elimination pathways for birds and seals

These PCB congener uptake and loss processes can be expressed mathematically to predict the change in congener mass in an organism over time as follows:

$$dC_{Bj}/dt = k_{1j} \bullet C_{AG,j} + k_{Dj} \bullet \Sigma(P_i \bullet C_{D,i,j}) - (k_{2j} + k_{Ej} + k_{Uj} + k_{Gj} + k_{Rj} + k_{Lj} + k_{Mj}) \bullet C_{Bj} \quad [29]$$

Where dC_{Bj}/dt is the rate of change of the PCB congener j concentration in the organism B. Assuming steady-state (i.e., $dC_{Bj}/dt = 0$), equation 29 rearranges as follows:

$$C_{Bj} = (k_{1j} \bullet C_{AG,j} + k_{Dj} \bullet \Sigma(P_i \bullet C_{D,I,j})) \; / \; (k_{2j} + k_{Ej} + k_{Uj} + k_{Gj} + k_{Rj} + k_{Lj} + k_{Mj}) \quad [30]$$

Where

C_{Bj} = concentration of congener j in the organism (ng/g wet weight)
$C_{AG,j}$ = concentration of congener j in the gas phase (ng/mL)
k_{1j} = rate of congener j uptake via inhalation (d^{-1})
k_{Dj} = rate of congener j uptake via dietary ingestion (d^{-1})
P_i = fraction of the diet consisting of prey item i

$C_{D,i,j}$ = concentration of congener j in prey item i (ng/g)
k_{2j} = rate of congener j elimination via exhalation (d^{-1})
k_{Ej} = rate of congener j elimination via faecal egestion (d^{-1})
k_{Uj} = rate of congener j elimination via urinary excretion (d^{-1})
k_{Gj} = rate of congener j elimination via growth dilution (d^{-1})
k_{Mj} = rate of congener j elimination via metabolic transformation (d^{-1})
k_{Rj} = rate of congener j elimination via reproduction (d^{-1})
k_{Lj} = rate of congener j elimination via lactation (seals only) (d^{-1})

The value for parameter Pi is entered directly into the model. Values for variables k_1, k_D, k_2, k_E, k_U, k_G, k_M, k_R, k_L, and C_{AG} are derived from the equations detailed below. Note that the variable equations below apply to PCB congeners. ΣPCB concentration values are derived using equation 5.

Respiratory Uptake (k_1)

The rate of respiratory chemical uptake by seals and birds, k_1 (d^{-1}), is derived as follows:

$$k_1 = E_A \bullet G_A / W_B \qquad [31]$$

Where E_A (unitless) is the chemical transfer efficiency at the respiratory surface, G_A (L/d) is the respiration rate, and W_B (kg) is the wet weight of the organism. The respiration rates, G_A, for seals and birds are calculated as follows:

$$G_A = 480 \bullet W_B^{0.75} \bullet AF \text{ [\textit{for seals}]} \qquad [32]$$

$$G_A = 0.4089 \bullet W_B^{0.77} \bullet 1000 \bullet AF \text{ [\textit{for birds}]} \qquad [33]$$

Where AF (unitless) is the species-specific activity factor.

Respiratory Elimination (k_2)

The rate of respiratory chemical elimination by seals and birds, k_2 (d^{-1}), is derived as follows:

$$k_2 = Z_{AIR} / Z_{ORG} \qquad [34]$$

Where Z_{AIR} (mol/m^3-Pa) is the fugacity capacity (or chemical sorptive capacity) of air, and Z_{ORG} (mol/m^3-Pa) is the fugacity capacity of the organism (described above). Z_{AIR} is estimated as follows:

$$Z_{AIR} = 1 / RGL \bullet T_B \qquad [35]$$

Where RGL (m^3 Pa/mol K) is the ideal gas constant and T_B (K) is the organism temperature.

Dietary Uptake (k_D)

The rate of dietary chemical uptake, k_D (d^{-1}), is derived from the following equation:

$$k_D = E_D \bullet G_D / W_B \qquad [36]$$

Where E_D (unitless) is the dietary chemical transfer efficiency, G_D (kg/d) is the feeding rate, and W_B (kg) is the wet weight of the organism. The feeding rate, G_D, for seals and cormorants is estimated as follows:

$$G_D = G_DA \bullet W_B \qquad [37]$$

Where G_DA is a species and age specific constant. G_D for herons was estimated as follows [Sample & Suter, 1994]:

$G_D = 10 \wedge (0.966 \bullet \mathrm{Log}(W_B) - 0.640)$ [38]

Faecal Elimination (k_E)

The rate of chemical elimination by egestion, k_E (d^{-1}), for seals and birds is derived in the same way as that for invertebrates and fish (see above).

Urinary Elimination (k_U)

The rate of chemical elimination by urination, k_U (d^{-1}), is derived as follows:

$k_U = (G_U / W_B) \bullet E_D \bullet (Z_W / Z_{ORG})$ [39]

Where G_U (L / d) is the urination rate, W_B (kg) is the wet weight of the organism, E_D (unitless) is the chemical transfer efficiency (described above), and Z_W and Z_{ORG} (mol/m^3-Pa) are the fugacity capacities of water and the organism, respectively (described above). The urination rates, G_U, for seals and birds are calculated as follows:

$G_U = 0.33 \bullet G_F$ (seals) [40]

$G_U = 0.2 \bullet G_F$ (birds) [41]

Where G_F (kg-faeces/kg-organism/d) is the faecal egestion rate (described above).

Growth Dilution (k_G)

The rate of chemical elimination by growth dilution for seals and birds is based on empirical data (see parameterization section).

Reproductive Elimination (k_R) – Seals

The rate of PCB elimination via reproduction, k_R (d^{-1}), is derived for adult female seals from the following equation:

$$k_R = (Z_F / Z_M) \bullet (W_F / W_M) \bullet P_R \bullet (1 / 365) \qquad [42]$$

Where Z_F and Z_M (mol/m^3-Pa) are the fugacity capacities of the foetus and mother, respectively; W_F and W_M (kg) are the wet weights of the foetus and mother, respectively; and P_R (unitless) is the proportion of the seal population reproducing. Z_F and Z_M are estimated with the Z_{ORG} equation (see above).

Reproductive Elimination (k_R) – Birds

The rate of PCB elimination via reproduction, k_R (d^{-1}), is derived for female birds from the following equation:

$$k_R = (Z_E / Z_M) \bullet (W_E / W_M) \bullet (NEC / NCY \bullet 365) \qquad [43]$$

Where Z_E and Z_M (mol/m^3-Pa) are the fugacity capacities of the egg and mother, respectively; W_E and W_M (kg) are the wet weights of the egg and mother, respectively; and NEC and NCY are the number of eggs per clutch and number of clutches per year, respectively. Z_E and Z_M are estimated with the Z_{ORG} equation (see above)

Lactational Elimination (k_L)

The rate of PCB elimination via lactation, k_L (d^{-1}), is only applicable to adult female seals and is derived from the following equation:

$$k_L = (Z_{MILK} / Z_M) \bullet (G_D / W_M) \bullet (24 / 365) \qquad [44]$$

Where Z_{MILK} and Z_M (mol/m^3-Pa) are the fugacity capacities of the milk and mother, respectively; G_D (L/d) is the feeding rate of the pup (described above); and W_M (kg) is the wet weight of the mother. Z_{MILK} and Z_M are derived using the Z_{ORG} equation (see above).

Metabolic Elimination (k_M)

Though PCB metabolism has been observed for some congeners in harbour seals [Boon *et al.*, 1987, 1994, 1997] and birds [Drouillard *et al.*, 2001], I found no equations in the literature describing the rate of PCB elimination via metabolism, k_M (d^{-1}), for these organisms. To derive congener-specific k_M values for cormorants, herons, and harbour seals, I calibrated the model to fit empirical PCB concentration data as per Boon *et al.*, 1994, 1997; Gobas and Arnot, 2005. Specifically, I (a) calculated the concentration ratio of PCB-X : PCB-153 (where PCB-X is one of the 209 PCB congeners and PCB-153 is a non-metabolized congener) in the empirical datasets for cormorant eggs, heron eggs, and adult female seals, and (b) adjusted the value of k_M in the model until the predicted PCB-X : PCB-153 ratio matched that of the observed. The k_M values derived for female seals were used for all seals, while k_M values derived for bird eggs were used for adult birds. The results are included in the appendices (Table 6-4). Note that the estimated k_M values are similar to those calculated for the San Francisco Bay [Gobas & Arnot, 2005] and derived from laboratory studies [Drouillard *et al.*, 2001]. For instance, the k_M values for PCB-37 and PCB-99 are relatively high and relatively low, respectively, my model and the literature.

2.4 Seal Pup & Bird Egg Concentrations

Seal pups take up and eliminate PCBs via the same routes as seal adults (i.e., oral ingestion, inhalation, exhalation, egestion, etc.), except that their only source of dietary intake is mother's milk. I used the following equation to estimate the concentration of PCB congeners in seal pups (ng/g):

$$C_{Pj} = (k_{1j} \bullet C_{AGj} + k_{Dj} \bullet (Z_{MILKj} / Z_{Mj}) \bullet C_{Mj}) / (k_{ELIMj}) \quad [45]$$

Where the subscript j denotes the congener of interest, k_1 (d^{-1}) is the respiratory uptake rate constant (described above); C_{AG} (ng/mL) is the PCB concentration in the gas phase; k_D (d^{-1}) is the dietary uptake rate constant (described above); Z_{MILK} (mol/m^3-Pa) is the fugacity capacity of milk (described above); Z_M (mol/m^3-Pa) is the fugacity capacity of the mother seal (described above); C_M (ng/g) is the wet weight PCB concentration in the mother; and k_{ELIM} (d^{-1}) is the sum of the pup's elimination rate constants.

Heron and cormorant eggs get their PCB load solely from their mother as well. I used the following equation to estimate the concentration of PCBs in bird eggs:

$$C_{Ej} = (Z_{EGGj} / Z_{Mj}) \bullet C_{Mj} \qquad [46]$$

Where the subscript j denotes the congener of interest, Z_{EGG} (mol/m^3-Pa) is the fugacity capacity of the egg, Z_M (mol/m^3-Pa) is the fugacity capacity of the mother (described above), and C_M is the PCB concentration in the mother. Z_{EGG} was calculated using the Z_{ORG} equation (described above).

2.5 Water and Air Concentrations

To predict PCB concentrations in biota of the SoG, I required PCB concentrations in sediments, water, and air of the SoG (see equations 3 and 30). Empirical data was available for sediment only, so I estimated the PCB concentrations in water and air from the sediment concentration data as detailed below.

Concentration of Dissolved PCBs in Water (C_{WD})

I used the following equation to estimate the dissolved water concentrations of PCB congeners, C_{WDj} (ng/mL), in the SoG:

$$C_{WDj} = (C_{Sj} / \phi_{OC}) / (\delta_{OCS} \bullet 0.41 \bullet K_{OWj}) / \Pi_{OC} \qquad [47]$$

Where the subscript j denotes the congener of interest, C_S (ng/g) is the concentration of the PCB congener in sediment, ϕ_{OC} (unitless) is the organic carbon content of sediment, δ_{OCS} (kg/L) is the density of organic carbon in sediment, K_{OW} (unitless) is the saltwater adjusted octanol-water partition coefficient, and Π_{OC} (unitless) is the organic carbon magnification factor. The first set of terms in this equation (i.e., $(C_{Sj} / \phi_{OC}) / (\delta_{OCS} \bullet 0.41 \bullet K_{OWj}))$ predicts PCB congener concentrations in water assuming equilibrium between sediment and water. The second term (Π_{OC}) accounts for the disequilibrium between sediment and water typically observed in the field [Gobas & MacLean, 2003; deBruyn & Gobas, 2004]. This field disequilibrium is believed to result from organic carbon mineralization processes that cause the ratio of PCBs in sediment-water to increase substantially above that expected under equilibrium [Gobas & MacLean, 2003; deBruyn & Gobas, 2004]. The organic carbon magnification factor was calculated as follows:

$$\Pi_{OC} = P_{PR} / B_{OC} \qquad [48]$$

Where P_{PR} (g-C/cm^2/y) is the primary production (or formation) rate of organic carbon in the SoG, and the B_{OC} (g-C/cm^2/y) is the organic carbon burial rate in the SoG.

For the SoG, I used a P_{PR} of 0.552 g-C/cm^2/y [Johannessen *et al.*, 2003] and a B_{OC} of 0.011 g-C/cm^2/y [Pauly *et al.*, 1996] to derive a Π_{OC} of 50. This value results in a C_{WD} prediction (using equation 47) that is 50 times lower than that predicted under equilibrium conditions. To verify the accuracy of this prediction, I compared it to the C_{WD} value calculated using an empirically derived sediment-water disequilibrium equation for False Creek [Mackintosh *et al.*, 2006]. The two approaches give similar outputs – for example, a sediment PCB-1 concentration of 1.0 ng/g results in a C_{WD} value of 3.81×10^{-5} using equation 47 and 4.26×10^{-5} using the equation from Mackintosh *et al*.

Concentration of Dissolved PCBs in Air (C_{AG})

To calculate C_{AG} (ng/mL) I assumed simple equilibrium partitioning between water and air, as follows:

$$C_{AGj} = C_{WDj} \bullet K_{AWj} \qquad [49]$$

Where K_{AWj} is the PCB air-water partition coefficient for congener j. K_{AW} was estimated as follows:

$$K_{AW} = K_{OW} / K_{OA} \qquad [50]$$

Where K_{OW} (unitless) is the octanol-water partition coefficient at Tw (the average SoG water temperature), and K_{OA} is the octanol-air partition coefficient at Ta (the average SoG air temperature) – see appendices for Tw and Ta values. Note that the contribution of gas-phase PCBs to total PCB load in mammals and birds in the field is typically insignificant [Kelly & Gobas, 2001; Gobas & Arnot, 2005] and so the assumption of simple equilibrium partitioning between water and air is considered sufficient for this model.

3 METHODS

3.1 BSAF Calculations

3.1.1 Calculation Tools

I used Visual Basic software to run the PCB bioaccumulation component of the model and a combination of Visual Basic and Excel spreadsheets to run the model performance analysis and model application components. A combination of linear algebra and matrix algebra (as described in Campfens & Mackay, 1997; Sharpe & Mackay, 2000; and Stevenson, 2004) was used in the bioaccumulation module. To test for mathematical errors in my Visual Basic code, I ran the model with input data from San Francisco Bay [Gobas & Arnot, 2005] and compared the model's congener concentration predictions to the congener concentration predictions of the San Francisco Bay model [Gobas & Arnot, 2005]. The predictions of my model matched those of the San Francisco Bay model perfectly.

3.1.2 SoG Food Web Structure

The degree of bioaccumulation in a given organism and/or system is strongly dependent on the structure of the system's food web [Hebert & Weseloh, 2006]; thus, accurate BSAF estimates for the SoG require an accurate depiction of the feeding relationships in the SoG. In this section, I detail (i) how organisms were selected for the food web used in the model, (ii) how these organisms interconnect in the food web, (iii) the methods used to verify the accuracy of the food web's structure, and (iv) how PCB transport to and from herring and salmon, which feed outside of the SoG, was addressed.

3.1.2.1 Organism Selection

The food web includes the top predators harbour seals (seals), double-crested cormorants (cormorants), and great blue herons (herons), and all the organisms that fall within their diet pyramids. I focused the model on these three top predators for three reasons. First, all three are subject to potentially high PCB doses as a result of their high trophic position (TP). Second, all three organisms are resident to the SoG and the majority of their caloric intake can be traced back to organisms and sediment of the SoG; it is thus possible to estimate SoG-specific BSAFs. And third, a reasonable set of empirical physiological and PCB concentration data (essential for model parameterization and performance analysis) exists for these organisms.

3.1.2.2 Feeding relationships

The feeding relationships linking the top predators in the model to their prey and ultimately to SoG sediments are depicted generally (Figure 3-1) and in detail (Table 3-1) below. I based the adult seal diet on a matrix assembled by Beamish *et al.*, 2001; the cormorant diet on work by Robertson, 1974 and Sullivan, 1998; and the heron diet on work by Verbeek and Butler, 1989, Butler, 1995, and Harfenist *et al.*, 1995. Note the following diet matrix assumptions:

- juvenile seals eat the same prey as adults;
- seal pups (not shown in the matrix but included in the model) consume mother's milk only;
- diet composition values are annual averages [Dr. R. Beamish, *personal communication*];
- seals eat primarily mature fish [Dr. R. Beamish, *personal communication*]; and
- salmon and herring are migratory and feed primarily outside the SoG [Dr. R. Beamish, *personal communication*]

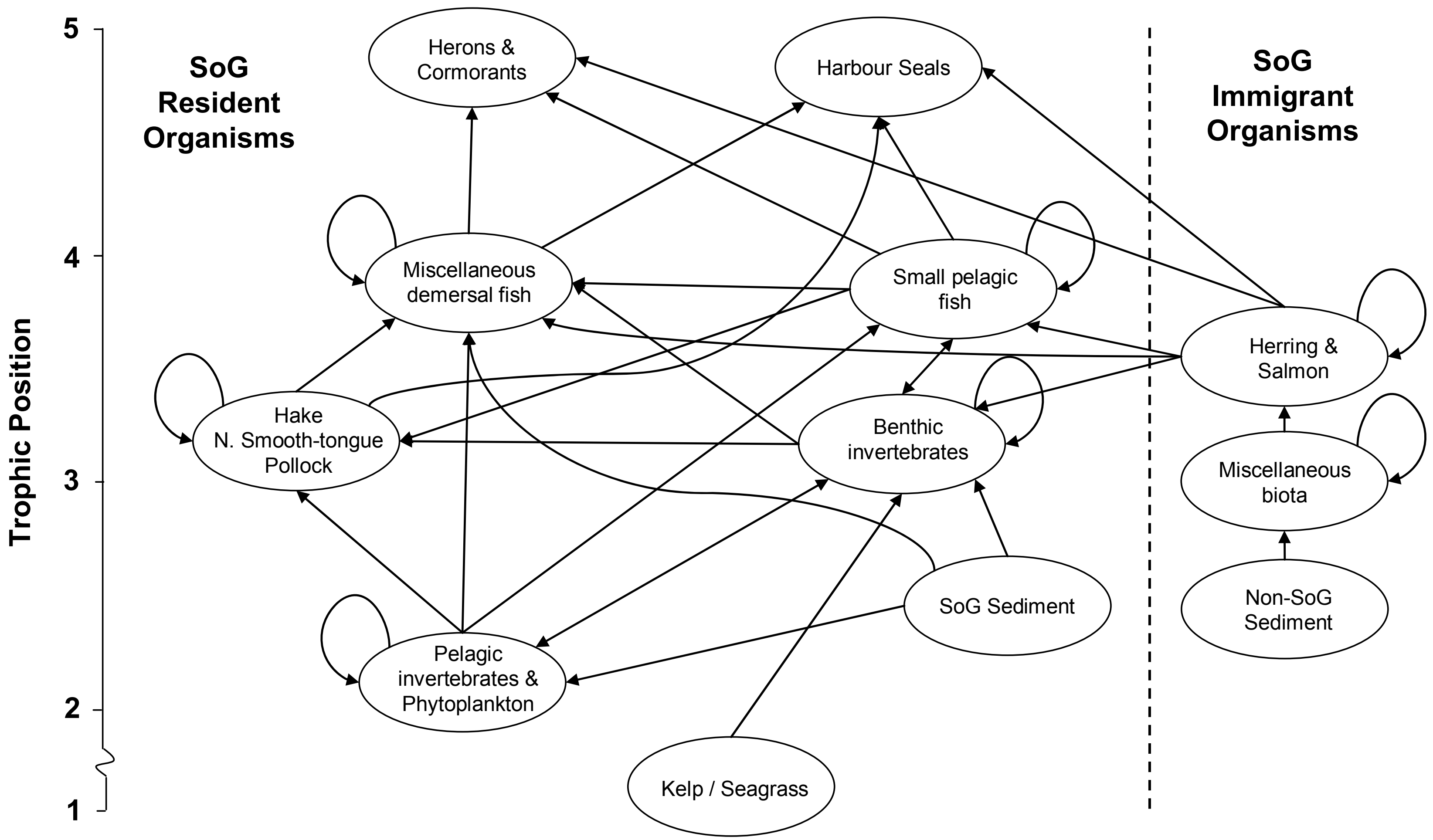

Figure 3-1 **Schematic illustration of trophic linkages for the major feeding groups of concern in the SoG. Arrows point from prey to predators. The trophic position scale (left) is based on the feeding relationships depicted in Table 3-1.**

Table 3-1 A matrix of diet compositions (% wet weight) for select organisms of the SoG. Values represent annual averages

Predator	Prey Detritus	Phytoplankton	Kelp/Sea grass	Herbivorous zooplankton	N. plumchrus	P. minutus	Shellfish	Crab	Grazing invertebrates	Carnivorous zooplankton	Euphausiids	Predatory invertebrates	Herring	Small pelagic fish (seal prey)	Small pelagic fish (bird prey)	River lamprey	Misc. demersal fish (seal prey)	Misc. demersal fish (bird prey)	Chum	Coho	Chinook	Hake	Dogfish	Pollock	Northern smooth-tongue	English sole	Total (%)
Herbivorous zooplankton	30.0	70.0																									100.0
N. plumchrus	30.0	70.0																									100.0
P. minutus	30.0	70.0																									100.0
Shellfish	21.0	57.9	10.0	3.0	5.0	2.0	1.0	0.1																			100.0
Crabs	43.8	0.2	10.0	6.0	2.0	2.0	15.0	1.0	20.0																		100.0
Grazing invertebrates	37.4	17.6	30.0	5.0	5.0	5.0																					100.0
Carnivorous zooplankton	5.0			35.9	40.4	10.2	3.0	0.2	0.3	5.0																	100.0
Euphausiids	14.0	80.9		5.0			0.1																				100.0
Predatory invertebrates	50.0			6.5	5.0	5.0	5.5	1.0	10.0		11.1	3.6	2.2	0.1													100.0
Herring																											0.0
Small pelagic fish (seal prey)		0.5		10.0	15.0	7.0	3.0	1.0	5.0	26.4	15.0	5.0	2.0	10.0					0.1								100.0
Small pelagic fish (bird prey)		0.5		10.0	15.1	7.0	3.0	1.0	5.0	26.4	17.0	5.0			10.0												100.0
River lamprey													64.0	19.9					5.3	5.1	5.1	0.1		0.5			100.0
Misc. demersal fish (seal prey)	10.0	0.5		4.0	5.1	5.0	17.2		9.0	15.4	10.0	4.0	3.0	5.0			10.0		0.1	0.4	0.3	1.0					100.0
Misc. demersal fish (bird prey)	10.0	0.5		5.8	5.1	5.0	17.2		9.0	15.4	13.0	4.0			5.0			10.0									100.0
Chum, Coho, & Chinook																											0.0
Hake		0.5		2.0	2.0	1.0	3.0	0.1		16.3	70.0	0.5		4.0					0.1	0.1	0.1			0.2	0.1		100.0
Dogfish				1.0	1.0	1.0	5.0	1.0	15.0	11.0	8.0	23.5	2.0	4.2		0.5	1.0		5.5	7.0	7.0	5.6	0.5	0.1		0.1	100.0
Pollock		1.0		1.0	3.0	2.0	0.1			9.0	66.8	5.0	5.0	1.0								1.0		0.1	5.0		100.0
Northern smooth-tongue		2.0		31.0	30.0	15.0	0.1		5.6	5.0	10.2			1.0								0.1					100.0
English sole				1.1	1.1		3.0		13.0			10.0		25.0			41.8					5.0					100.0
DC cormorant (adult)													2.7		5.7			91.6									100.0
Great blue heron (adult)															10.9			89.1									100.0
Harbour seal (adult)													23.1	10.0			17.5		1.0	0.8	0.5	46.4	0.1	0.6			100.0
Harbour seal (juvenile)													23.1	10.0			17.5		1.0	0.8	0.5	46.4	0.1	0.6			100.0

3.1.2.3 Diet Matrix Accuracy

I used two methods to test the accuracy of the diet matrix in Table 3-1: (1) comparison with other diet composition reports for the SoG, and (2) comparison of the matrix-implied TP with empirically derived stable nitrogen isotope ($\delta^{15}N$) ratios for matrix organisms. Each approach is described below; the results are presented in Section 4.1.

Comparison with other studies

I compared the harbour seal diet in the matrix with that published by Olesiuk, 1993; the fish diets in the matrix with those published in Froese & Pauly, 2001; and the matrix as a whole with an SoG matrix published in Pauly & Christensen, 1995. I did not perform this analysis for cormorant and heron diets because I could not find any diet studies in the literature for these organisms other than those I used to create the diet matrix (see Section 3.1.2.2 for details).

Comparison of TP and $\delta^{15}N$ Ratios

I graphed matrix-implied TPs against empirically derived $\delta^{15}N$ ratios for a select set of organisms (i.e., those for which literature $\delta^{15}N$ values existed). TP values quantify the relative trophic status implied by the feeding relationships of a diet matrix. For the SoG matrix (Table 3-1), I assigned TP values of 2.5 to detritus and 1.0 to kelp/seagrass and phytoplankton (as per Mackintosh *et al.*, 2004) and estimated the TP of the remaining organisms using the following equation [Vander Zanden & Rasmussen, 1996; Mackintosh *et al.*, 2004]:

$$TP_{predator} = \left(\sum_{i=1}^{n} TP_{prey\ i} * p_{prey\ i}\right) + 1 \qquad [51]$$

where TP (unitless) is the matrix implied trophic position and p (unitless) is the proportion of prey item i in the diet of the predator.

δ^{15}N ratios are often used as an empirical measure of trophic status since their values have been shown to increase with successive trophic steps in food webs [Mackintosh et al., 2004; Minagawa & Wade, 1984; Fry, 1988; Hobson & Welch, 1992]. I obtained δ^{15}N ratio values from the literature for some matrix organisms (see appendices Table 6-3; the calculated TPs for these organisms are also included).

3.1.2.4 Herring and Salmon

Most herring stocks of the SoG are migratory – they begin life in the marine waters of the SoG, spend the majority of their adult life feeding and growing outside the SoG, and return to the SoG to spawn [Lassuy, 1989]. Similarly, salmon feed primarily outside the SoG and are only present within the SoG while passing through to spawn in local rivers. Because they feed outside the SoG, herring and salmon likely obtain some, if not most, of their PCB load from non-SoG sources; thus, estimating their concentrations using SoG sediments alone could result in BSAF prediction errors for them and their predators. To avoid this error, I used empirically measured PCB concentrations, instead of predicted concentrations, when estimating PCB exposure from these fish to their predators. The herring and salmon (i.e., chum, coho, and Chinook) concentration data used in the model are included in the appendices (Table 6-6 and Table 6-7).

3.1.3 Model Parameterization

As indicated in the Bioaccumulation Theory section (i.e., Section 3, above), the model requires a set of SoG specific chemical, environmental, and biological parameter data in order to convert measured sediment, herring, and salmon PCB concentrations into predicted concentrations for the set of modelled organisms. I collected these parameter values from the literature and, where literature values were unavailable, from discussions with experts. The parameter values used in the model, their references, and their standard deviations (not used in the model but included for reference) are included in the appendices (Section 7.4). Also included in the appendices is a model sensitivity analysis

(Section 6.5) which I performed to assess the sensitivity of the model to changes in the model parameter values.

3.1.4 Selection of PCB Congeners

For all organisms except cormorants and herons, the model makes BSAF predictions for the following 57 PCB congeners (forward slashes separate co-eluting congeners): 8, 15, 18/30, 20/28/31, 37, 44/47/65, 49/69, 52, 66, 61/70/74/76, 83/99, 90/101/113, 105, 110/115, 118, 128/166, 129/138/160/163, 146, 147/149, 135/151/154, 153/168, 170, 177, 180/193, 183/185, 187, 194, 198/199, 203, 206, and 209. These congeners include the 34 congeners reported in the sediment dataset (see the "Sediment" column, Table 3-2), and an additional 23 congeners that co-elute with these 34 congeners in the herring and salmon input datasets (see the "Herring" and "Salmon" columns, Table 3-2). I assume that the co-eluting congeners reported in the herring and salmon datasets were present in the sediment samples but were not reported because, for technological reasons, they were not detected, or because the author thought it unnecessary to mention them.

For cormorants and herons, the model makes BSAF predictions for only a subset of the 57 congeners listed above – i.e., for those with reported values in the empirical cormorant and heron datasets (Table 3-2). BSAF predictions are limited to these congeners because k_M estimations for marine birds depend on congener ratios in the empirical dataset (see Section 2.3, above).

Despite the fact that only 57 (or fewer, for birds) of the 209 possible congeners are included in the model, these congeners make up the majority of the ΣPCB mass in the performance analysis datasets for the adult female seal (86%), seal pup (81%), cormorant (90%), and heron (96%); they are thus considered reasonably representative of the behaviour of the entire family of PCB congeners.

Table 3-2 PCB Congeners Reported in the Model Input and Top Predator Verification Datasets.

	MODEL INPUT DATA			**MODEL VERIFICATION DATA**			
	Sediment	**Herring**	**Salmon**	**Adult Seals**	**Seal Pups**	**Cormorant Eggs**	**Heron Eggs**
Year Collected -->	1997	2004	2003	?	2001	1994-2002	1994-2000
	8	8	8	8	-	-	-
	15	15	15	15	15	-	-
	18	18/30	18/30	18/30	18	-	-
	28/31	20/28/31	20/28/31	20/28/31	28/31	28	28
	37	37	37	37	37	-	-
	44	44/47/65	44/47/65	44/47/65	44	-	-
	49	49/69	49/69	49/69	49	-	-
	52	52	52	52	52/73	-	-
	66/70	66	66	66	66/70/76	66	66
	74	61/70/74/76	61/70/74/76	61/70/74/76	61/74	74	74
	99	83/99	83/99	83/99	99	99	99
	101	90/101/113	90/101/113	90/101/113	90/101	90/101	101
	105	105	105	105	105	105	105
	110	110/115	110/115	110/115	110	-	-
	118	118	118	118	118	118	118
	128	128/166	128/166	128/166	128	128	128
	138	129/138/160/163	129/138/160/163	129/138/160/163	129/138/160/163/164	129/138	129/138
	146	146	146	146	146/161	146	146
	149	147/149	147/149	147/149	147/149	149	149
	151	135/151/154	135/151/154	135/151/154	151	151	151
	153	153/168	153/168	153/168	153	153	153
	156	156/157	156/157	156/157	156	156	-
	170	170	170	170	170	170/190	170
	177	177	177	177	177	-	-
	180	180/193	180/193	180/193	180	180	180
	183	183/185	183/185	183/185	183/185	183/185	183/185
	187	187	187	187	187	187	-
	194	194	194	194	194	194	194
	199	198/199	198/199	198/199	198/199	-	-
	203	203	203	203	203	196/203	203
	206	206	206	206	206	206	206
	209	209	209	209	209	-	-
Source -->	Macdonald, R	West, J	Carpenter, DO	Ross, PS	Ross, PS	Elliott, J	Elliott, J

"-" = values were not reported for these congeners

3.1.5 Input and Performance Analysis Data

One of the more challenging aspects of the project was finding the congener-specific concentration data necessary for model input and model performance analysis. Monitoring for PCBs in the SoG (an ongoing exercise), or publication of monitoring data, appears to have been a rare occurrence in the past. Nonetheless, I obtained a limited PCB concentration dataset comprised of a combination of published and unpublished work. The results are summarized (Table 3-3 and Figure 3-2) and discussed below. I report the performance analysis data here instead of the in the performance analysis section that follows so this data can be presented on the same map as the model input data (Figure 3-2).

Table 3-3 Summary of model input and performance analysis data

Medium	No. Samples	Sample Locations	Year Collected
Model Input Data			
Sediment	3	Central SoG (2); Howe Sound (1)	1997
Herring	2	Southeast SoG (Semiahmoo)	2004
Coho	3	SoG supermarkets	2003
Chum	3	SoG supermarkets	2003
Chinook	3	SoG supermarkets	2003
Model Performance Analysis Data			
Seals (adult female)	4	East SoG (Vancouver Airport)	2001?
Seals (pup)	10	Northwest SoG (Hornby Island)	2001
Cormorant eggs	19	Whole SoG	1994 - 2002
Heron eggs	12	Whole SoG	1994 - 2000
Various fish & invertebrates	3*	East SoG (False Creek)	2003

* For each organism, three samples were taken from three different locations

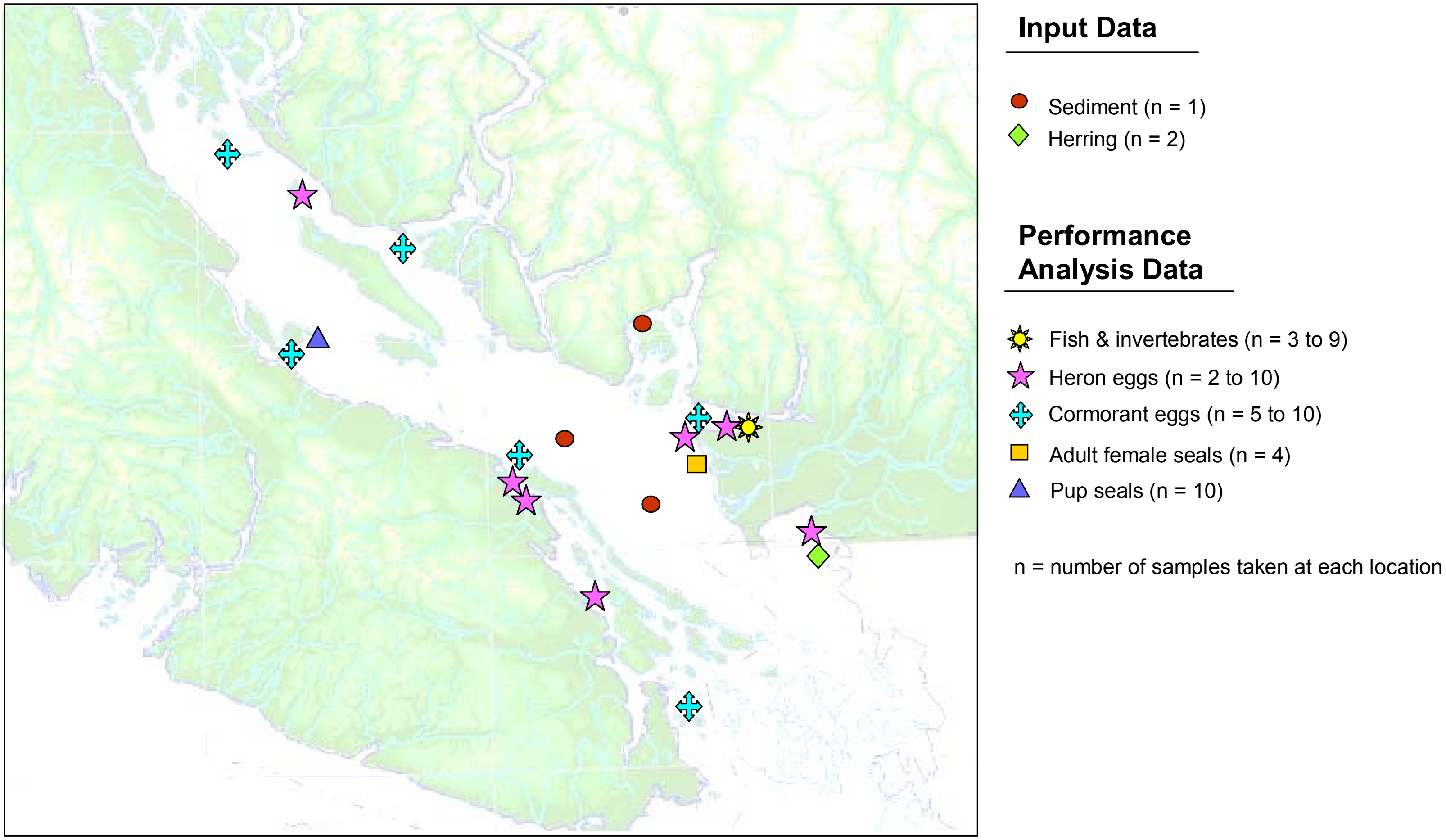

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Figure 3-2 Sampling locations in the SoG for model input and model performance analysis data.

3.1.5.1 Input Data

Sediment

The sediment data (provided by Dr. R. Macdonald) was collected in 1997 from the central SoG (2 samples) and Howe Sound (1 sample). The concentrations for 34 PCB congeners were reported (see appendices Table 6-5). I have assumed that these 34 congeners include 23 co-eluting congeners (see numbers in parentheses in Table 6-5). Standard deviations included in Table 6-5 are for reference only (i.e., they were not utilized in the model). The PCB concentrations at the three SoG sampling locations are similar and about five times lower, on average, than congener concentrations in one sample provided for Burrard Inlet (Dr. R. Macdonald, data not shown). Clearly, this dataset is limited in sample number and spatial diversity and cannot be considered representative of the SoG as a whole. However, for the sake of this project I have assumed that these data represent average PCB concentrations in sediment for the SoG.

Note that I had sediment data from False Creek and Burrard Inlet which could also have been used to derive congener-specific BSAFs. I chose to use the SoG data instead for two main reasons. First, the congener patterns in the three remote location samples from the SoG are probably more representative of congener patterns throughout the SoG than those of the relatively industrialized False Creek and Burrard Inlet water bodies. Second, if I used the False Creek and/or Burrard Inlet data as input for the model, the relative contribution of immigrant fish (i.e., herring & salmon) vs. sediments to PCB loads in organisms predicted by the model would be skewed toward greater contribution from sediments and would not reflect the relative contributions expected for organisms throughout the entire SoG.

Herring & Salmon

The herring dataset (provided by Dr. J. West) was collected in 2004 from Semiahmoo (2 samples); the majority of the 209 congeners were detected. I used 57 of these congeners in the model (see appendices Table 6-6). The salmon dataset (provided by Dr. D.

Carpenter) includes wild salmon purchased in 2003 from Lower Mainland supermarkets (3 samples each for chinook, chum, and coho); the majority of the 209 congeners were detected. I used 57 of these congeners in the model (see appendices Table 6-7). It is not known where these salmonids were caught, and whether or not they represent SoG migrating species. Nonetheless, because salmon contribute only a small proportion (either directly or indirectly) to the diets of SoG top predators (Table 3-1), I considered this data adequate for model input.

3.1.5.2 Performance Analysis Data

Seals

The datasets for adult female seals and seal pups (provided by Dr. P. Ross) were collected in 2001 from Vancouver Airport (4 adult samples) and Hornby Island (10 pup samples); the majority of the 209 congeners were detected. I used 57 of these congeners in adult females and 56 in pups (see appendices Table 6-19) to verify the model's congener-specific predictions (recall that the model makes predictions for only 57 congeners). Adult seals have a foraging range of about 20 km^2 [Cottrell, 1996], suggesting that these empirical datasets may represent the PCB loads expected in adult female seals residing between Vancouver and the central SoG, and seal pups residing in and around the northern SoG.

Cormorant and Heron Eggs

The datasets for cormorant and heron eggs (congener-specific data provided by Dr. J. Elliott; study details provided in Harris *et al.*, 2003 and Harris *et al.*, 2005) were collected from a variety of remote and urban locations throughout the SoG (~ 50 samples for each species). Approximately 40 of the 209 congeners were detected in samples collected since 1994. I used 25 (cormorant eggs) and 24 (heron eggs) of these congeners (i.e., those that matched the congeners used for model input) to assess the model's congener-specific predictions (see appendices Table 6-18). These datasets are, geographically speaking, the best there are for organisms in the SoG. Note that unlike cormorants, herons are known to feed to some extent on terrestrial organisms. This may be a source of disagreement between the model (which assumes a marine-only diet for herons) and these performance analysis data.

Fish & Invertebrates

The dataset for fish and invertebrates was collected from False Creek, a heavily urbanized water body in Vancouver [Mackintosh *et al.*, 2004]. Only concentrations for PCB congeners 18, 99, 118, 180, 194, and 209 were reported [Mackintosh *et al.*, 2004]. I have used this data to assess the model's BSAF predictions for fish & invertebrates because they are the only congener-specific PCB concentration data I could find for the SoG. However, I do not consider these data representative of fish & invertebrates PCB body burdens throughout the SoG for the following reasons. First, the food web structure of False Creek is, due to its small size and extensive human use, potentially quite different from that used to run the model. Second, the organisms reported in Mackintosh *et al.*, 2004 do not reflect the diversity of those used to derive predicted PCB concentrations in the model. For example, while concentrations for only 5 demersal fish were reported in Mackintosh *et al.*, 2004, the miscellaneous demersal fish category in the diet matrix (Table 3-1) represents at least 15 different species. Third, False Creek is one of the most heavily polluted water bodies in BC, and PCB concentrations in its wildlife are likely much higher than in wildlife from the rest of the SoG. This data can therefore be used to test if my model over-predicts PCB concentrations in fish & invertebrates for the SoG (i.e., if predicted concentrations derived from SoG sediments closely match or exceed observed concentrations in False Creek), but will not indicate whether the model closely matches or under-predicts PCB concentrations in fish & invertebrates in the SoG.

3.1.6 Data Gaps and BSAF Prediction Implications

The major gaps in the data described above, and their implications for the model's BSAF predictions, are summarized below in Table 3-4.

Table 3-4 A summary of data gaps and BSAF prediction implications

Data Gap	BSAF Prediction Implications
δ^{15}N values for organisms of the SoG diet matrix (e.g., cormorant and seal δ^{15}N data is from the Gulf of Alaska, while δ^{15}N data for most other organisms is from False Creek (Table 6-4)).	• The lack of representative δ^{15}N data for diet matrix organisms decreases my confidence that the TPs suggested by the diet matrix are correct. This lack of confidence in turn affects my confidence in the model's BSAF predictions. The direction of the effect on BSAF estimates (i.e., BSAF over or underestimation) depends on whether matrix-implied TPs are erroneously high or low. The magnitude of the effect is potentially high.
Metabolic elimination rate constants (k_M) for PCB congeners in seals, cormorants, and herons.	• In the absence of this data, I have assumed that the difference between model-predicted and field-observed PCB-X to PCB-153 ratios for seals, cormorants, and herons is due to PCB congener metabolism. The difference between predicted and observed PCB-X to PCB-153 ratios is likely due to a combination of metabolism and model error. However, because the model is calibrated to match the observed BSAF data, this assumption will only affect the accuracy of predicted k_M values (i.e., cause them to over or underestimate actual k_M values) and not the accuracy of predicted BSAF values.
Juvenile seal diet	• In the absence of juvenile seal diet information, I have assumed that juvenile seals eat the same prey as adult seals. Juvenile seals may eat smaller organisms than those adults eat. Given that smaller organisms typically occupy lower TPs than larger organisms [Cohen *et al.*, 1993; Jennings *et al.*, 2001], this assumption may contribute to concentration and BSAF overestimation for juvenile seals. The magnitude of overestimation is potentially high.

A number of parameter values are based on limited empirical data or were simply estimated (see appendices Section 6.5).	• In general, uncertainty in the model parameter values increases the uncertainty in the model's predictions. The direction of the effect on BSAF estimates depends on the direction of the error in the parameter value. The magnitude of the effect on BSAF estimates depends on a combination of the degree of uncertainty in the parameter values (i.e., those parameters that were "estimated" in Section 6.4 have a high degree of uncertainty associated with them) and the sensitivity of the model to changes in the parameter value (see Section 6.5). Examples of high uncertainty, high sensitivity parameters include the concentration of suspended sediments (Vss), the invertebrate particle scavenging efficiency of invertebrates (σ), and the rate of PCB loss via growth (k_G) in seal pups.
PCB concentrations in SoG sediments from a wide range of regions throughout the SoG	• Without these data, it is not possible to derive a mean and standard deviation for the concentration of PCBs throughout the whole SoG, and therefore it is not possible to estimate the distribution of PCB concentrations in sediments throughout the whole SoG with any reasonable degree of confidence. • It is also not possible to characterize, with confidence, the relationship between PCB concentration distributions in sediments and organisms of the SoG. As a result, the model cannot derive, with confidence, a predicted PCB concentration distribution (or predicted BSAF concentration distribution) for modelled organisms of the SoG.
PCB concentrations in sediments for all 209 congeners (the sediment dataset reports values for only 34 congeners).	• In the absence of data for all 209 congeners, I have assumed that the 34 congeners include 23 co-eluting congeners (i.e., 57 congeners in total), and that these 57 congeners represent the majority of ΣPCBs in sediments. If the sediment concentrations for the 34 congeners represent only those 34 congeners, then the predicted BSAFs for these congeners will be underestimated relative to observed BSAFs. The magnitude of this underestimation may not be significant, however, since

	the 34 listed congeners are the dominant congeners in the co-eluting groups.
PCB concentrations in SoG herring from regions other than Semiahmoo.	• It is not clear to what extent PCB concentrations in herring from Semiahmoo represent PCB concentrations in herring throughout the SoG. One recent report [West et al., 2006] indicates that herring from Semiahmoo have ΣPCB body burdens that are twice as high as herring from the more remote Denman Island in the northern SoG (i.e., 34 vs. 18 ng/g-ww, respectively). This suggests that the herring concentrations used in the model may represent the upper end of the herring's PCB concentration range throughout the SoG. If so, I would expect this data gap to contribute to the overestimation of BSAFs for all herring predators. The degree of this overestimation may be high for organisms that eat significant quantities of herring (e.g., 25% of the seal diet is herring).
PCB concentrations in SoG salmon (data used in the model is from salmon bought from Vancouver supermarkets).	• Store bought salmon may or may not have PCB concentrations equivalent to PCB concentrations in salmon migrating through the SoG's. Using PCB concentrations from store bought salmon as model input may contribute to the over or underestimation of BSAFs for all salmon predators. However, since salmon comprise only a small portion of the diets of SoG top predators of interest (Table 3-1), the degree of BSAF under or overestimation is not expected to be significant.
PCB concentrations sediment, herring, and salmon from logically sequential dates	• Predators in the model consume herring from 2003, salmon from 2004, and hake and other prey items from some earlier date (i.e., 1997 – the sediment sampling year – plus the time it take for PCBs to move from sediments up through the food web). If PCB concentrations from the three input media remained relatively constant from 1997 to 2004, then the temporal difference between sampling dates of each does not matter. If the ratio of PCB concentrations in herring and/or salmon to sediment increased over this time period, then this data gap will contribute to overestimation of the predicted BSAF, and vice versa.

3.2 Model Performance Analysis

I assessed the model's performance by (i) comparing, graphically, the model predicted BSAFs to empirically derived BSAFs on a congener-specific basis, (ii) calculating the model bias (MB) for these observed vs. predicted BSAF graphs, and (iii) comparing these MB values graphically to congener log-K_{OW} values. The methods for each of these are described below.

3.2.1 Comparison of Predicted and Observed BSAFs

I derived predicted congener-specific BSAFs by dividing predicted organism concentrations by observed sediment concentrations (i.e. those used to run the model). I derived observed congener-specific BSAFs by dividing *observed* organism concentrations by observed sediment concentrations (i.e., the same sediment concentrations used to derive predicted BSAFs). I then plotted the predicted and observed BSAFs on the same graph for visual comparison on both a congener-specific and ΣPCB basis. The ΣPCB-BSAF values were calculated as follows:

$$BSAF_{\Sigma PCB} = \left(\sum_{i=1}^{n} C_{Bi}\right) / \left(\sum_{i=1}^{n} C_{Si}\right) \qquad [52]$$

Where C_B (ng/g-ww) is the concentration of congener i in the organism, and C_S (ng/g-dw) is the concentration of congener i in the sediment. Note that the ΣPCB analysis was performed only for top predators because these organisms have the most reliable performance analysis datasets and because these organisms are of most concern from a risk management standpoint.

3.2.2 MB Calculations and Analysis

I estimated the MB using the following equation:

$$\text{MB} = 10^{\frac{\sum_{i=1}^{n}\log\left(\frac{BSAF_{P,i}}{BSAF_{O,i}}\right)}{n}} \qquad [53]$$

Where $BSAF_P$ (unitless) is the predicted BSAF for congener i, $BSAF_O$ (unitless) is the observed BSAF for congener i, and n is the number of congeners. The MB is an indication of the under- or over-prediction by the model. For instance, if the model-predicted BSAF for congener 153 in seal pups is 200, and the observed BSAF for congener 153 in seal pups is 100, then the MB for congener 153 in seal pups is 2.0.

In addition, I plotted the ratio of $BSAF_P$ to $BSAF_O$ vs. log-K_{OW} for each congener in seal mothers, seal pups, cormorant eggs, and heron eggs. The $BSAF_P/BSAF_O$ should be independent of log-K_{OW}; a correlation between $BSAF_P/BSAF_O$ and log-K_{OW} is indicative of systematic bias in the model.

3.2.3 Data Gaps and Model Performance Analysis Implications

The key data gaps of concern for model performance analysis are presented below (Table 3-5).

Table 3-5 A summary of data gaps and model performance analysis implications

Data Gap	Model Performance Analysis Implications
PCB concentrations in modelled SoG organisms other than those listed in Table 3-3 (i.e., adult male seals, hake, euphausiids, etc.)	• I cannot derive observed BSAFs for organisms without a PCB concentration data. As a consequence, I cannot evaluate the accuracy of the model predicted BSAFs for these organisms.
PCB concentrations in adult female seals and sediments from the same SoG region (adult female seal data is from Vancouver Airport, sediment data is from the central SoG / Howe Sound)	• Vancouver Airport is a more industrialized region of the SoG than the central SoG and Howe Sound, and thus may be associated with higher PCB concentrations than these less industrialized regions. As a result, the observed BSAFs for adult female seals may be erroneously high, which may in turn contribute to (i) the perception that model-predicted BSAFs are too low and (ii) the derivation of erroneously low MB estimates. However, given that seals eat primarily hake and herring, both highly mobile fish, it is not inconceivable that PCB concentrations in sediments from the central SoG represent PCB concentrations in sediment to which adult female seals from Vancouver Airport are ultimately exposed, and consequently it is not inconceivable that the observed BSAFs and the MB estimates are reasonably accurate.
PCB concentrations in seal pups and sediments from the same SoG region (seal pup data is from Hornby Island, sediment data is from the central SoG / Howe Sound)	• Hornby Island may be a less industrialized region of the SoG than the central SoG (which receives runoff from the Fraser River) and Howe Sound, and thus may be associated with lower PCB concentrations than these regions. As a result, the observed BSAFs for seal pups may be erroneously low, which may in turn contribute to (i) the perception that model-predicted BSAFs are too high and (ii) the derivation of erroneously high MB estimates.

PCB concentrations in fish & invertebrates and sediments from the same SoG region (fish & invertebrate data is from False Creek, sediment data is from the central SoG / Howe Sound)	• False Creek is a more industrialized region of the SoG than the central SoG and Howe Sound and is definitely associated with higher PCB concentrations than these less industrialized regions. As a result, the observed BSAFs for fish & invertebrates will probably be erroneously high, which will in turn contribute to (i) the perception that model-predicted BSAFs are too low and (ii) the derivation of erroneously low MB estimates. I expect the overestimation of observed BSAFs to be more pronounced for invertebrates than fish because of their smaller foraging ranges (i.e., more time spent in False Creek).
PCB concentrations in sediment from bird egg sampling locations (i.e., sediment data is from the central SoG and Howe Sound, bird egg data is from various coastal locations throughout the SoG).	• If PCB concentrations in sediments from the central SoG and Howe Sound are similar to the average PCB concentrations in sediments from the locations where bird eggs were sampled, then the observed BSAFs and MB estimates will be reasonably accurate. If PCB concentrations in sediments from the central SoG and Howe Sound are higher than the average in sediments from the locations where bird eggs were sampled, then the observed BSAFs will underestimate actual BSAFs, and vice versa.
PCB concentrations in sediment and performance analysis organisms from logically sequential dates (see Table 3-3 for temporal differences)	• If PCB concentrations in the SoG did not change from 1994 to 2004, then this data gap does not influence the observed BSAFs. If PCB concentrations in the SoG are increased from 1994 to 2004, this data gap may contribute to the overestimation of observed BSAFs for organisms sampled after 1997, and underestimation of observed BSAFs for organisms sampled before 1997. If PCB concentrations in the SoG are decreasing, then the opposite is true.

3.3 Model Application

3.3.1 Overview

Once the model performance analysis was satisfactorily completed, I used the model-predicted and empirical BSAFs to facilitate an ecological risk assessment (ERA) for seals and cormorants of the SoG, evaluation of the current SQG for ΣPCBs, recommendation of a new SQG for ΣPCBs, and proposal of SoG-specific SQTs for ΣPCBs. The methods for each of these applications are described below.

3.3.2 Ecological Risk Assessment for Top Predators

3.3.2.1 Overview

ERA is a process for evaluating the likelihood that adverse ecological effects are occurring or may occur as a result of exposure to one or more stressors [US EPA, 1992]. I conducted an ERA to evaluate the potential risks posed by PCB exposure to adult female seal, seal pup, and cormorant egg populations in the SoG. The ERA for each receptor group is based on a single line of evidence: comparison of predicted and observed ΣPCB body burdens with ΣPCB concentrations suspected to cause adverse effects. The incorporation of additional lines of evidence (e.g., field observations, laboratory tests, etc.) is beyond the scope of this project. I derived the ΣPCB body burdens and ΣPCB effects concentrations for the exposure and effects comparison as described below. Note that the ERA was limited to seal and cormorant receptors because these were the only top predators for which I could obtain effects data.

3.3.2.2 ERA for Seals

<u>ΣPCB Effects Estimation</u>

I obtained ΣPCB effects data for seals from the literature. Kannan *et al.*, 2000 reviewed a study reported in Boon *et al.*, 1987 and Brouwer *et al.*, 1989 where one group of captive adult harbour seals consumed fish with relatively high PCB body burdens, while another group consumed fish with relatively low PCB body burdens. Blood from seals in the high-dose group contained significantly less retinol and thyroid hormone (indicators of immune system function) than blood from seals in the low-dose group. In addition, the reproductive success of the high-dose group was significantly lower than the low-dose group. Based on this study and others, Kannan *et al.*, 2000 recommended a NOAEL of 5.2 μg-PCB/g-lipid, a LOAEL of 25 μg-PCB/g-lipid, and a threshold effects concentration of 11 μg-PCB/g-lipid (i.e., the geometric mean of the NOAEL and LOAEL) for harbour seals. Kannan *et al.*, 2000 provides a discussion of the uncertainties associated with these TRVs. Note that Brouwer *et al.*, 2000 detected only some of the 209 PCB congeners in their study (see those identified in Table 3-6).

ΣPCB Exposure Estimation

I derived observed and model-predicted probability distributions for ΣPCB body burdens in adult female seals and seal pups using the following equation:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e\left(- \frac{(x-\mu)^2}{2\sigma^2} \right) \qquad [54]$$

Where f(x) (unitless) is the frequency of a given ΣPCB value x (ng/g), μ is the mean ΣPCB concentration in the organism (ng/g), and σ is the standard deviation of the ΣPCB concentration in the organism (ng/g).

For the observed probability distributions for adult female seals and seal pups, I used mean and standard deviation values derived from empirical data provided by Dr. P. Ross. Specifically, I totalled the congener concentrations for each of the ten seal pup samples from Hornby Island to derive a ΣPCB concentration for each, and used these ΣPCB concentrations to estimate a mean and standard deviation for the location. Note that I only included those congeners in the ΣPCB calculation for adult female seals and seal pups that matched, as much as possible, the congeners used to derive the TRV (see Table 3-6 for details).

For the model-predicted probability distributions for adult female seals and seal pups, I used as the mean the ΣPCB concentrations predicted by the model (i.e., those estimated from PCB concentrations in central-SoG sediments, Semiahmoo herring, and supermarket salmon). I used as a standard deviation the observed standard deviation for ΣPCB concentrations in cormorant eggs (data provided by Dr. J. Elliott). I used the observed cormorant egg standard deviation to represent the variability in seals because, unlike the observed seal standard deviations, the observed cormorant variability represents a relatively wide spatial range in the SoG (Figure 3-2). Furthermore, cormorants occupy a similar TP as seals, like seals they eat only marine fishes, and the observed SD for ΣPCB concentrations in cormorants is not unrealistic (for instance, the SDs of the log-ΣPCB values for adult female seals from Vancouver Airport and the cormorant eggs from throughout the SoG are 0.18 and 0.26 ng/g-lipid, respectively). Note that I only included those congeners in the ΣPCB calculation for adult female seals and seal pups that matched, as closely as possible, the congeners used to derive the TRV (see Table 3-6 for details).

Table 3-6 PCB congeners used to calculate the seal TRVs and the ΣPCB concentration distributions for model-predicted seals, observed adult female seals, and observed seal pups used in the ERA

Seal TRVs	ΣPCB Concentration Distribution		
	Model-Predicted	Observed Adult Seal	Observed Seal Pup
18	18	18/30	18
28	20/28/31	20/28	38
26	-	26/29	26
37/42	37	37	37/59/42
41/64/71/72	40/41/71	40/41/71	-
44	44/47/65	44/47/65	44
49	49/69	49/69	49
52/73	52	52	52/73
75/47	-	59/62/75	47/75/48
60/71	-	60	-
61/74	61/70/74/76	61/70/74/76	71/41/64
93/66/80/95	66	66	66/95
83/78	-	78	78/83/109
99	83/99	83/99	99
84	-	84	90/101
119/150	87/97/108/119/125	87/97/108/119/125	119/150
101	90/101/113	90/101/113	90/101
92	-	92	92/84
70/98	93/95/98/100/102	93/95/98/100/102	-
105	105	105	105
115/87/90/116	110/115	110/115	115/87
118	118	118	118/106
128	128/166	128/166	128
138/160/163/164	129/138/160/163	129/138/160/163	160/163/164/138
151	135/151/154	135/151/154	151
136	-	136	-
137	-	137	137
139/149	-	139/140	149/139/140
141/179	-	141	141
153	153/168	153/168	153
156/171	156/157	156/157	171/156
170/190	170	170	170/190
172/192	-	172	172/192
177	177	177	177
180	180/193	180/193	180
183	-	183/185	183
187	187	187	187/182
194	194	194	194
195/208	-	195	195/208
200/157	-	197/200	200
201	-	201	201
209	209	209	209
Source --> Brouwer *et al.* , 1989	-	Dr. P. Ross	Dr. P. Ross

3.3.2.3 ERA for Cormorants

ΣPCB Effects Estimation

I obtained ΣPCB effects data for cormorant eggs from the literature. In their ERA for cormorant eggs in the San Francisco Bay, Gobas & Arnot, 2005 used a LOAEL of 5.0

μg/g-ww and cited Hoffman *et al.*, 1996 as the source of this TRV. Gobas & Arnot noted that cormorant exposure to ΣPCB concentrations in this range is associated with embryonic mortality, beak deformities, and club foot in the field [Gobas & Arnot, 2005]. I was unable to obtain a copy of the Hoffman *et al.*, 1996 publication to confirm this LOAEL. I was also unable to locate a published effects threshold or NOAEL for cormorant egg exposure to ΣPCBs. I instead estimated a NOAEL by multiplying the LOAEL by 0.1; apparently this approach was used by Hoffman *et al.*, 1996 as well [Dr. F. Gobas, *personal communication*]. I was also unable to determine which PCB congeners were used to derive the ΣPCB concentration for the cormorant egg LOAEL.

ΣPCB Exposure Estimation

I derived observed and model-predicted probability distributions for ΣPCB body burdens in cormorant eggs using equation 54. For the observed distribution, I used a mean and standard deviation derived from empirical data provided by Dr. J. Elliott. For the predicted distribution, I used the mean value predicted by the model and the standard deviation value derived from empirical data provided by Dr. J. Elliott. All congeners were included in the ΣPCB estimation for the predicted and observed distributions.

3.3.3 Sediment Quality Guideline Evaluation and Recommendation

3.3.3.1 SQG Evaluation

I used two approaches to evaluate the level of protection offered by the current SQG for ΣPCBs. First, I "forward calculated" the ΣPCB concentration in adult female seals, seal pups, and cormorant eggs from the current SQG for ΣPCBs using the following equation:

$$C_{B\text{-}SQG} = SQG \bullet BSAF \qquad [55]$$

Where $C_{B\text{-}SQG}$ (ng/g-ww) is the point estimate (i.e., not a distribution) ΣPCB concentration associated with the current SQG (ng/g-dw) and BSAF (g/g) is the predicted BSAF for the organism. I then compared, graphically, the $C_{B\text{-}SQG}$ for each organism to their respective TRVs and to their respective observed and predicted ΣPCB concentration distributions (derived as described in Section 3.3.2).

Second, I again "forward calculated" the ΣPCB concentration in adult female seals and cormorant eggs (but not seal pups) using Equation 55. This time, however, I multiplied the SQG by both the observed and predicted BSAF for each organism, and, using the resulting $C_{B\text{-}SQG}$ as a geometric mean for the organisms, the observed cormorant egg SD as the SD for the organisms, and Equation 54, I estimated a ΣPCB concentration distribution for each. I then compared these ΣPCB distributions to the TRVs for these organisms. In effect, this approach estimates the ΣPCB concentration distributions and levels of protection expected in adult female seals and cormorant eggs if the geometric mean ΣPCB concentration in sediments of the SoG were at the SQG.

3.3.3.2 SQG Recommendation

The SQG for ΣPCBs is intended to ensure that all organisms in BC are exposed to "safe levels" of PCBs [MOE, 2006]. The results of the SQG evaluation (Section 4.4.2.2, below) indicate that this protection goal is not being met for top predators of the SoG. To derive a SQG for ΣPCBs that results in safe levels of ΣPCBs in adult female seals, seal pups, and cormorant eggs, I "backward calculated" a ΣPCB concentration in sediment from a ΣPCB concentration in these organisms using the following equation:

$$SQG_R = NOAEL / BSAF_P \qquad [56]$$

Where SQG_R (ng/g-dw) is the recommended SQG associated with protection to the NOAEL, NOAEL (ng/g-ww) is the NOAEL for the organism, and $BSAF_P$ (g/g) is the model-predicted BSAF for the organism.

3.3.4 Sediment Quality Target Proposals

To derive proposed SQTs for ΣPCBs that meet various protection goals (e.g., 5% of seal pups above the NOAEL, 5% of cormorant eggs above the LOAEL, etc.), I "backward calculated" ΣPCB concentrations in sediment from various target concentration in organisms using the following equation:

$$SQT = C_{BT} / BSAF_P \qquad [57]$$

Where SQT (ng/g-dw) is the SQT, C_{BT} (ng/g-ww) is the concentration target for the organism, and $BSAF_P$ (g/g) if the model-predicted BSAF for the organism.

3.3.5 Data Gaps and Model Application Implications

The key data gaps of concern for model application phase of the project are presented below (Table 3-7).

Table 3-7 A summary of data gaps and model application implications

Data Gap	Model Application Implications
PCB concentrations in SoG sediments from a wide range of regions throughout the SoG	• I cannot use the model to predict a distribution of PCB body burden for seals or cormorants. To compensate for this data gap, I used the observed SD for cormorants to derive a model-predicted distribution for both seals and cormorant eggs. I do not expect this to increase uncertainty in the ERA for cormorants, but I do expect it to increase the uncertainty in the ERA for seals (i.e., the distribution may be erroneously wide or narrow).
TRVs for organisms other than adult seals and cormorant eggs	• I cannot assess the effects of model predicted or empirically observed PCB body burdens in organisms other than seals and cormorants. I also cannot confirm the adequacy of current SQGs, recommended SQGs, or proposed SQTs for these organisms. This is probably not a concern for lower trophic organisms, but may be a concern for herons and some upper trophic fish. • This gap could lead to the underestimation of PCB exposure risks to seals (which may in turn contribute to erroneously high SQGs and SQTs for seals) if developing seal pups and foetuses are more sensitive to PCBs (a known endocrine disruptor [Van den Berg *et al.*, 1998; Newsted *et al.*, 1995; Ross *et al.*, 2000]) than seal adults.
TRVs specific to seals and cormorants of the SoG (i.e., seal TRVs were derived using Atlantic seals)	• This gap leads to increased uncertainty in the ERA results for seals and cormorants since the relative sensitivities of SoG and non-SoG seals and cormorants to PCB exposure are unknown.
Other studies, besides those cited	• Seal and cormorant TRVs used in the ERA are point estimates, rather than distributions, and thus

above, that estimate seal and cormorant TRVs	the ERA cannot account for the variability in sensitivity to PCBs between individuals.
TRVs for seals and cormorants that include the same PCB congers as those used to estimate exposure (i.e., see Table 3-6)	• This gap contributes to uncertainty in the ERA results. However, this data gap may not be significant since the model predicted exposures, observed exposures, and TRVs for seals and cormorants probably include most of the PCB congeners that make up the ΣPCB values for each.
A NOAEL for cormorant eggs (I applied a ten-fold uncertainty factor to the LOAEL in lieu of this)	• The ten-fold uncertainty factor probably underestimates the actual NOAEL, which will in turn result in an overly conservative SQG, and overly conservative SQTs that use the estimated NOAEL as a protection endpoint, for the protection of cormorant eggs.

4 RESULTS & DISCUSSION

4.1 Accuracy of the Diet Matrix

Comparison with other studies

The model's diet matrix (Table 3-1) as a whole did not conflict with the matrix by Pauly & Christensen, 1995 (appendix Table 6-2) and in general had higher resolution. Fish diets in the model did not differ from those in Froese & Pauly, 2001. And there was good agreement between the seal diet in the model and that reported in Olesiuk, 1993. For instance, the proportion of hake, herring, salmonids, walleye pollock, and miscellaneous demersals consumed by seals in the model fall within the range estimated by Olesiuk (appendices Table 6-1). The only discrepancies between the seal diet in the model and that in Olesiuk, 1993 are that small pelagic fish comprise a marginally larger proportion of the seal's diet in the model, and dogfish are included as prey species in the model (0.1 % of the seal's diet) but were not reported as such in the Olesiuk paper. These minor differences may simply be due to Olesiuk's inclusion of dogfish and some unidentified pelagic fish in his unidentified/other category.

Trophic Position vs. δ^{15}N Ratios

Calculated TPs and literature derived δ^{15}N ratios and their references are presented in the appendices (Table 6-3), while a plot of the relationship between TP and δ^{15}N is presented below (Figure 4-1). It should be noted that δ^{15}N values for cormorants and adult seals were taken from Gulf of Alaska organisms and are thus less than ideal for testing the accuracy of the diet matrix. Also, δ^{15}N values were not available for all species represented by organism groups in the model (i.e., miscellaneous demersal fish, small pelagic fish, predatory invertebrates, shellfish, and crabs); thus the range of δ^{15}N values for these groups in Figure 4-1 may underestimate their true δ^{15}N variability.

Despite the $\delta^{15}N$ data limitations, Figure 4-1 demonstrates a strong proportional relationship between TP and $\delta^{15}N$ for most of the organisms/organism groups considered in the model ($r^2 = 0.70$). Furthermore, key SoG organisms and organism groups, including Euphausia pacifica (representing half the summer biomass of zooplankton in the SoG [Heath, 1977]), Neocalanus plumchrus (annually the most abundant component of zooplankton in the SoG [Harrison *et al.*, 1983]), predatory invertebrates, and demersal and pelagic fish, all lie in close proximity to the regression line. Note that the relatively high $\delta^{15}N$ values for seals and cormorants suggest that these organisms occupy higher TPs in the Gulf of Alaska than in the SoG.

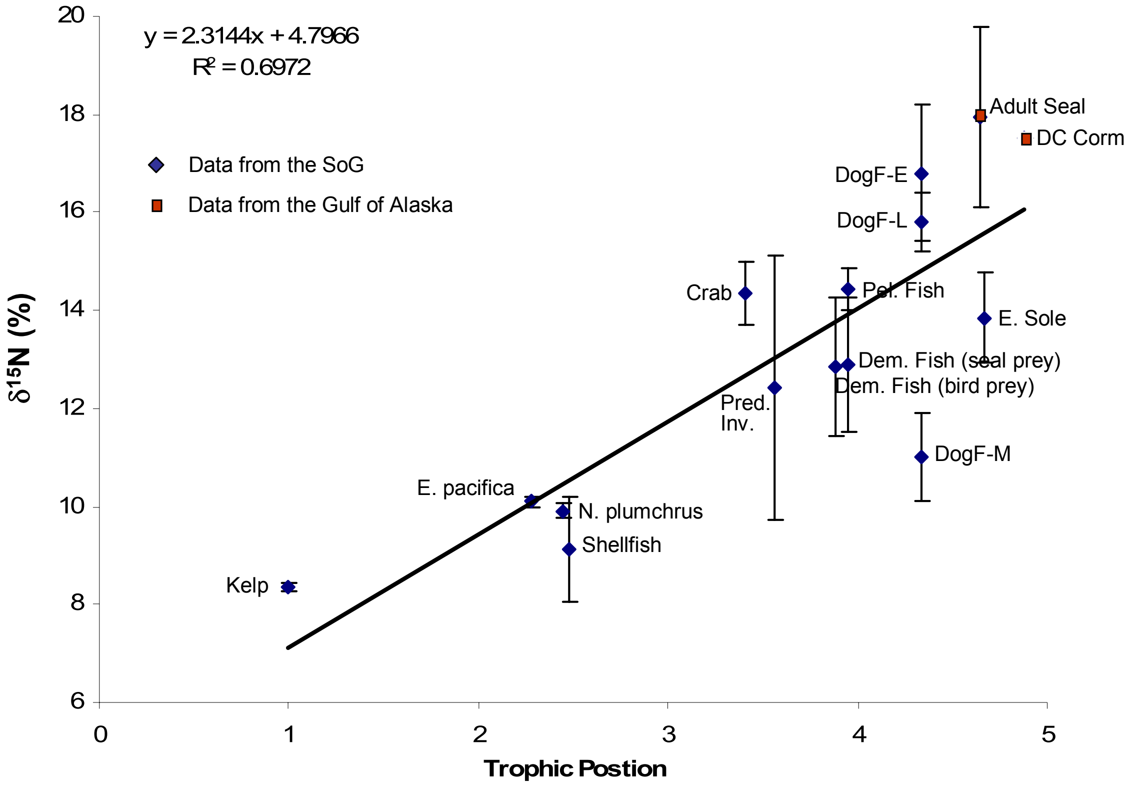

Figure 4-1 **Correlation between tropic position and $\delta^{15}N$ isotope ratios for select organisms. $\delta^{15}N$ values and references are presented in Table 6-3 (see Appendices).**

4.2 BSAF Predictions for ΣPCBs

Model-predicted BSAFs for ΣPCBs in modelled SoG organisms are presented in Figure 4-2. Log-BSAF values range from a low of -2.70 (or a BSAF of 0.002) g/g for phytoplankton to a high of 2.71 (or a BSAF of 513) g/g for seal pups. This represents an increase in the BSAF of roughly 250,000 times (on a wet weight basis) from phytoplankton to seal pups, and an increase in concentration of roughly 500 times from sediment (dry weight) to seal pups (wet weight).

Note that BSAF values for organisms with similar diets fall within distinct ranges. Specifically, herbivorous organisms, including Euphausia pacifica and grazing invertebrates, occupy the log-BSAF range from -0.29 to 0.42 g/g (or BSAFs ranging between 0.5 and 2.6 g/g). Invertebrate consumers, including pelagic fish (bird prey) and demersal fish (seal prey), occupy the log-BSAF range from 0.69 to 1.13 g/g (or BSAFs ranging between 4.9 and 13 g/g). Piscivorous organisms, including dogfish and seal pups, occupy the log-BSAF range from 1.55 to 2.71 g/g (or BSAFs ranging between 35 and 513). This result is consistent with previous food web studies [Gobas & Arnot, 2005; Gobas et al., 1998; Morrison et al., 1997; Stevenson, 2003; Mackintosh et al., 2004] and suggests that the model's mathematical structure is generally sound.

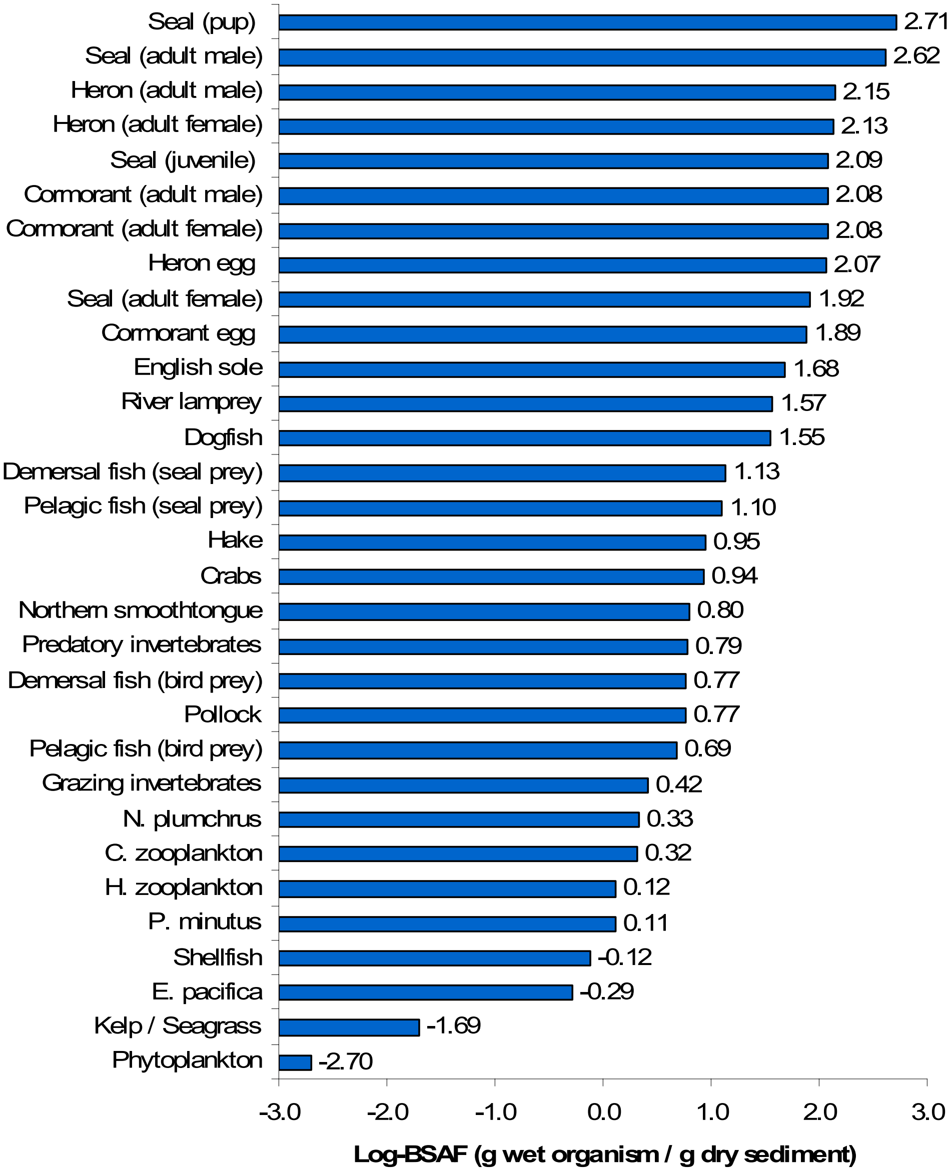

Figure 4-2 **Predicted BSAFs for ΣPCB in all modelled organisms of the SoG**

4.3 Model Performance Analysis

Evaluation of the model's performance allows one to gain a better understanding of the model's strengths and weaknesses. This understanding is important because it allows model users to maximize the model's potential as a decision-making tool and avoid making poor decisions (or no decisions at all). To assess the model's performance, I (i) compared, graphically, model-predicted BSAFs to observed BSAFs on a congener-specific and ΣPCB basis, (ii) estimated the MB on a congener-specific and ΣPCB basis, and (iii) compared the MB of individual congeners to their log-K_{OW} values. The results of these analyses are presented below.

4.3.1 Model Performance Analysis for PCB Congeners

Model-predicted and observed BSAFs are compared together, on a congener-specific basis, in Figure 4-3 through to Figure 4-12 (below). The corresponding MB results are shown in Table 4-1. Note that only organisms with a reasonable empirical dataset were included in this analysis, and only the dominant of co-eluting congeners are listed on the x-axis of the graphs.

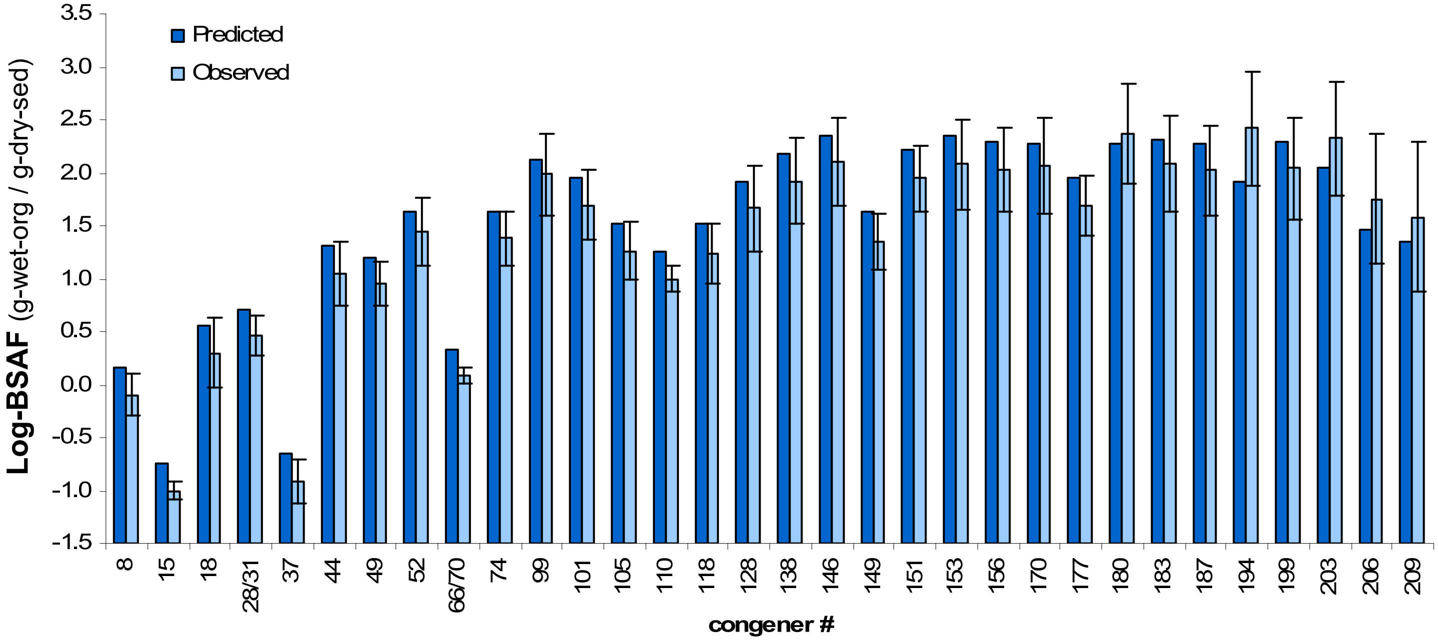

Figure 4-3 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in adult female seals from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 4).

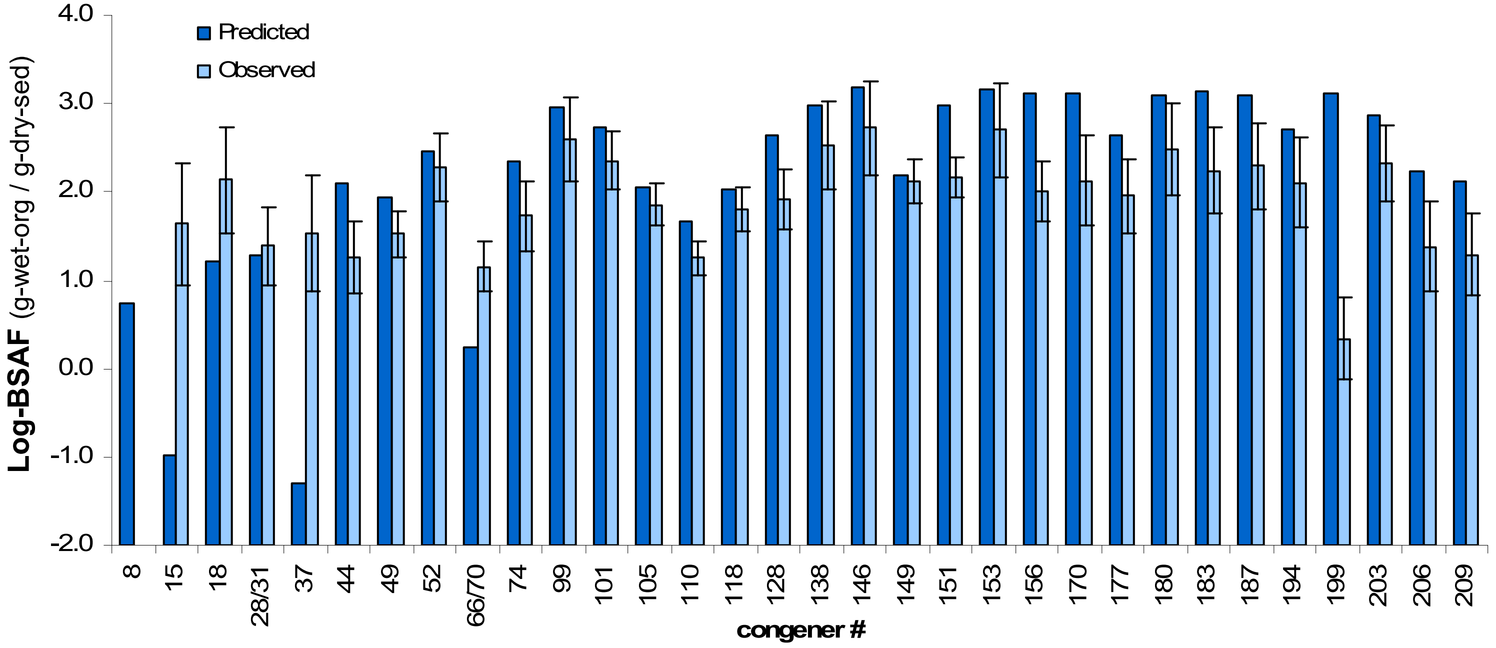

Figure 4-4 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in seal pups from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 10).

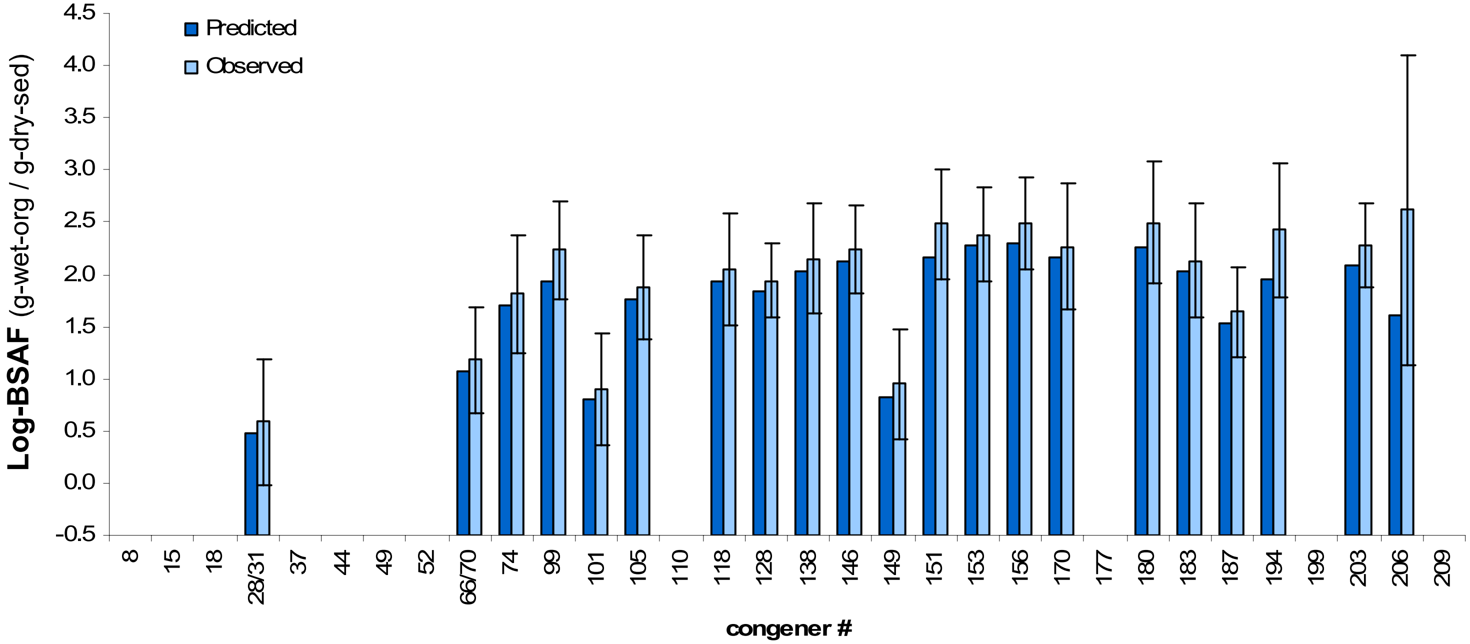

Figure 4-5 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in cormorant eggs from the SoG. Error bars represent two standard deviations of the observed geometric mean (n= 19).

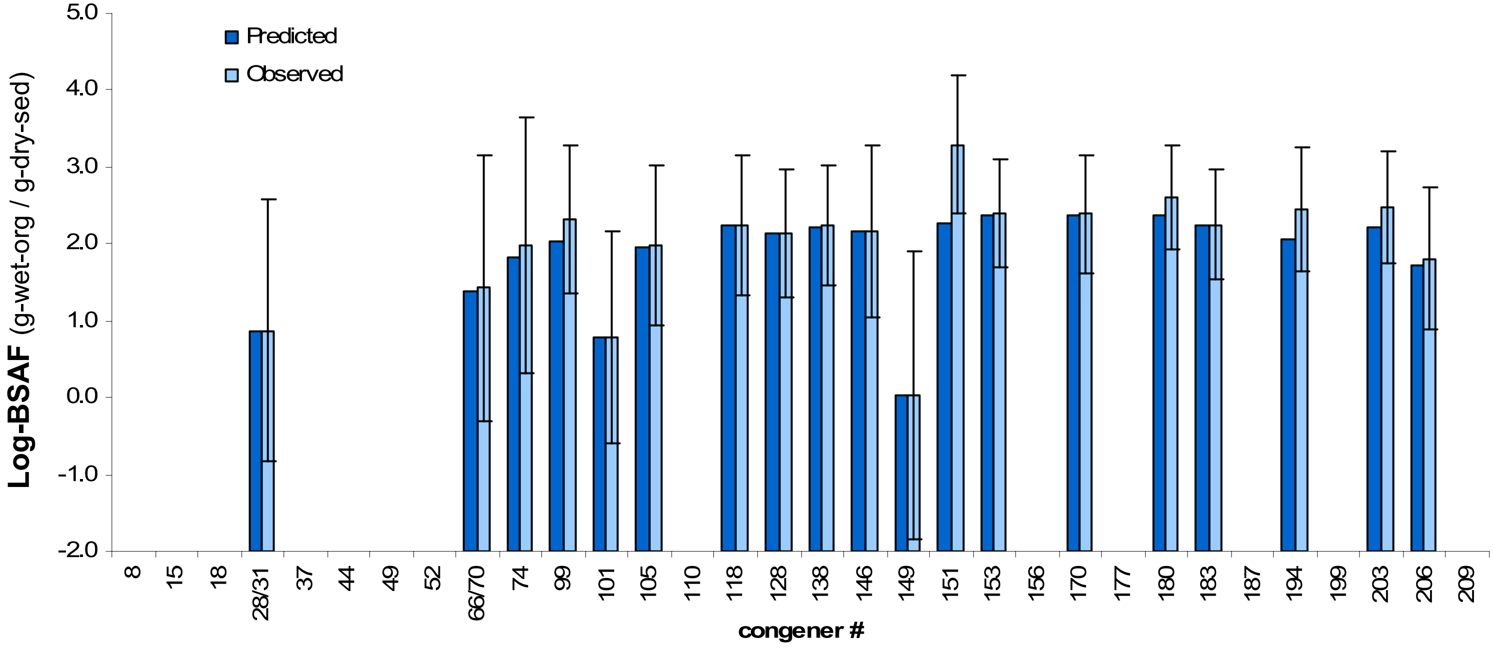

Figure 4-6 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in heron eggs from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 12).

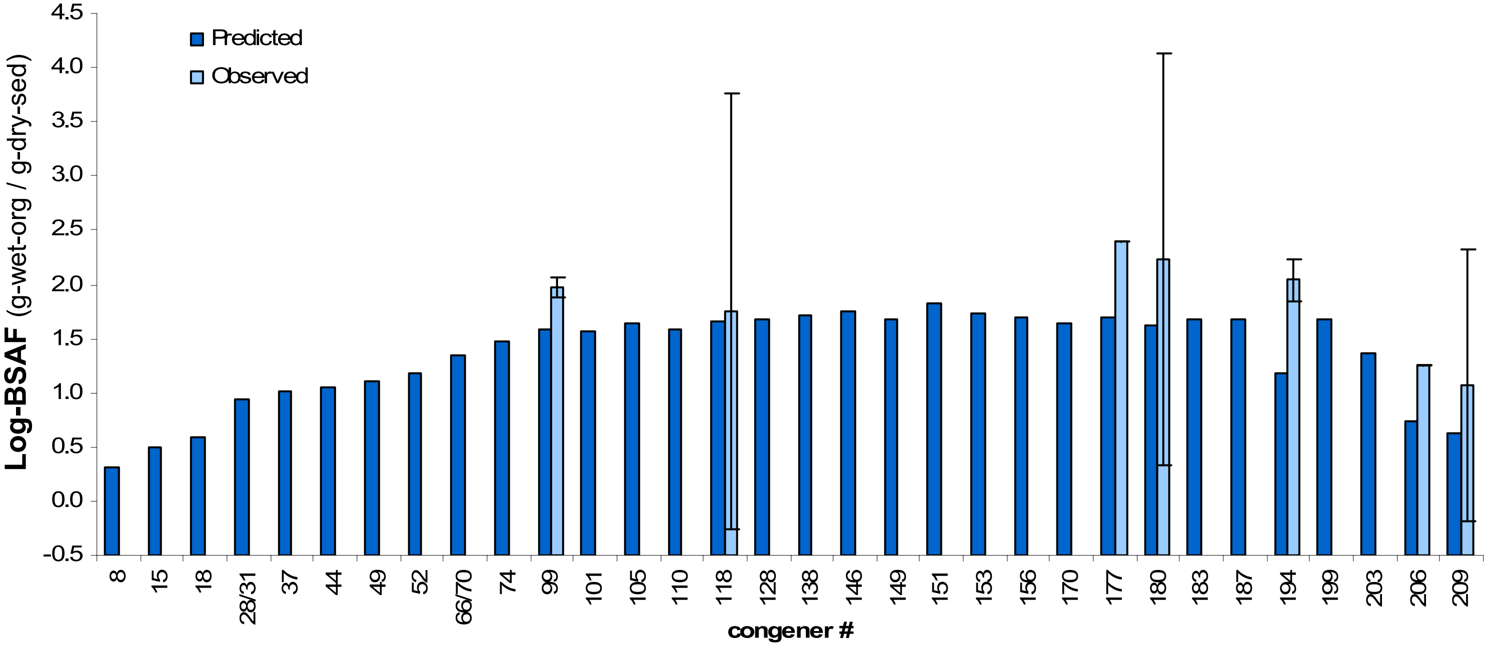

Figure 4-7 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in dogfish from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 9).

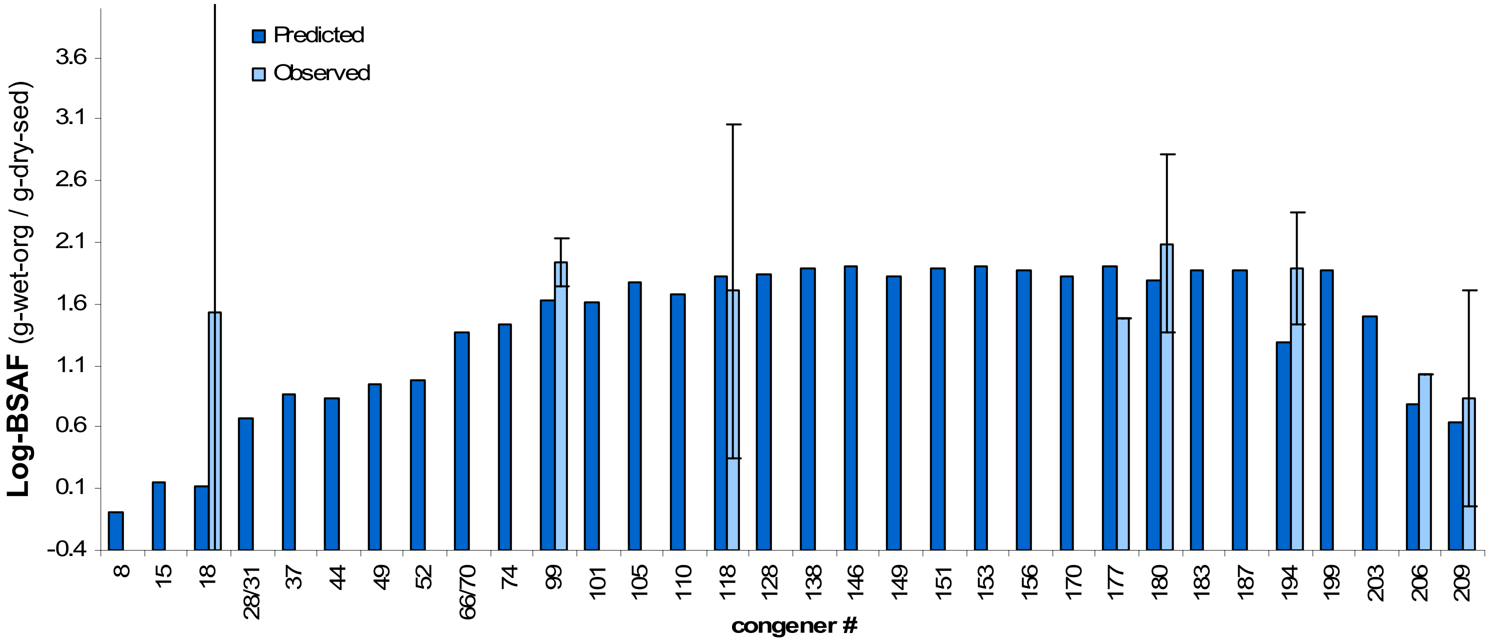

Figure 4-8 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in English sole from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 9).

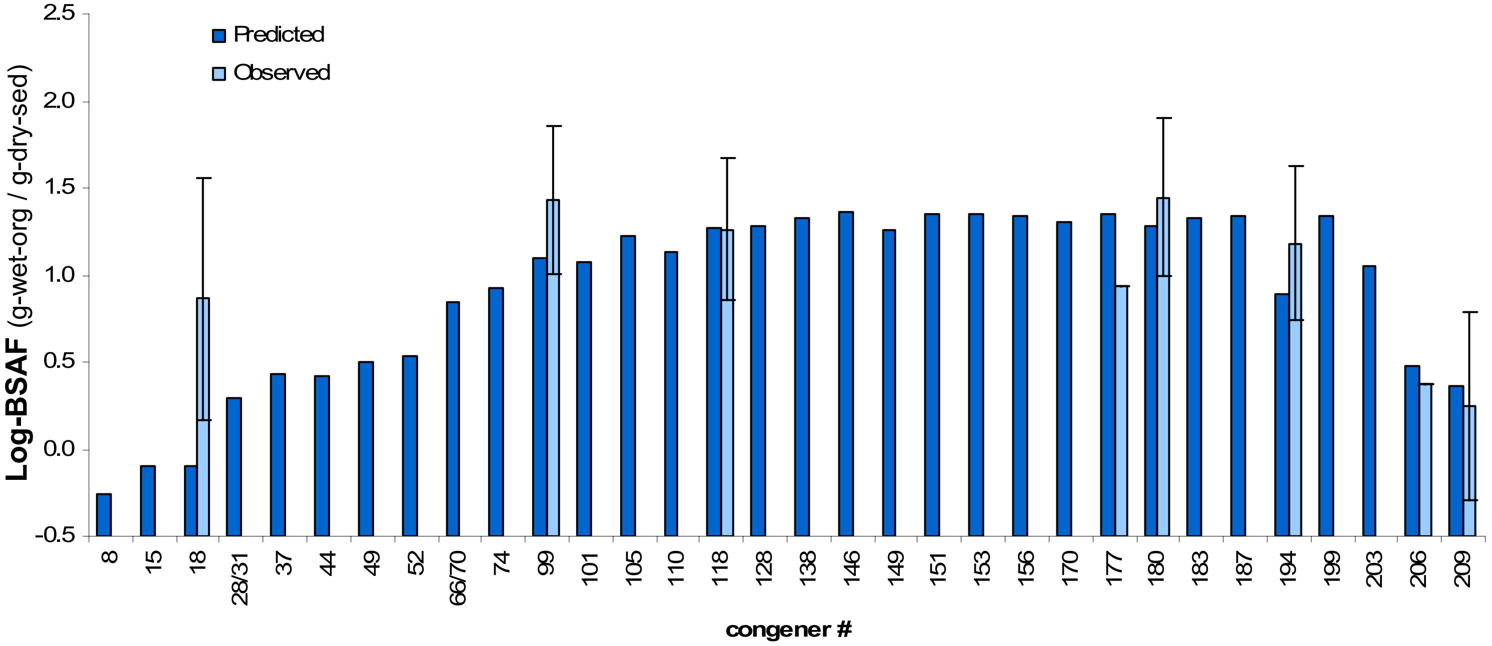

Figure 4-9 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in miscellaneous demersal fish (seal prey) from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 5).

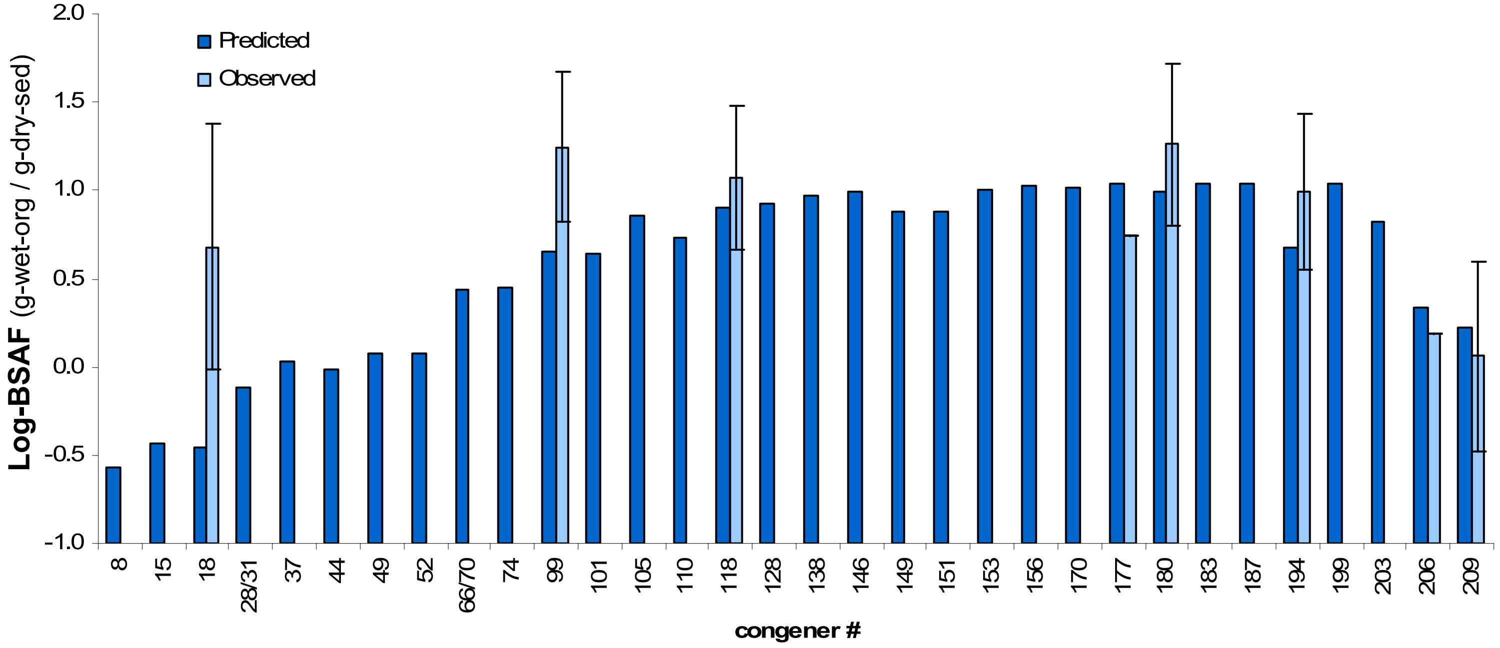

Figure 4-10 **Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in miscellaneous demersal fish (bird prey) from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 5).**

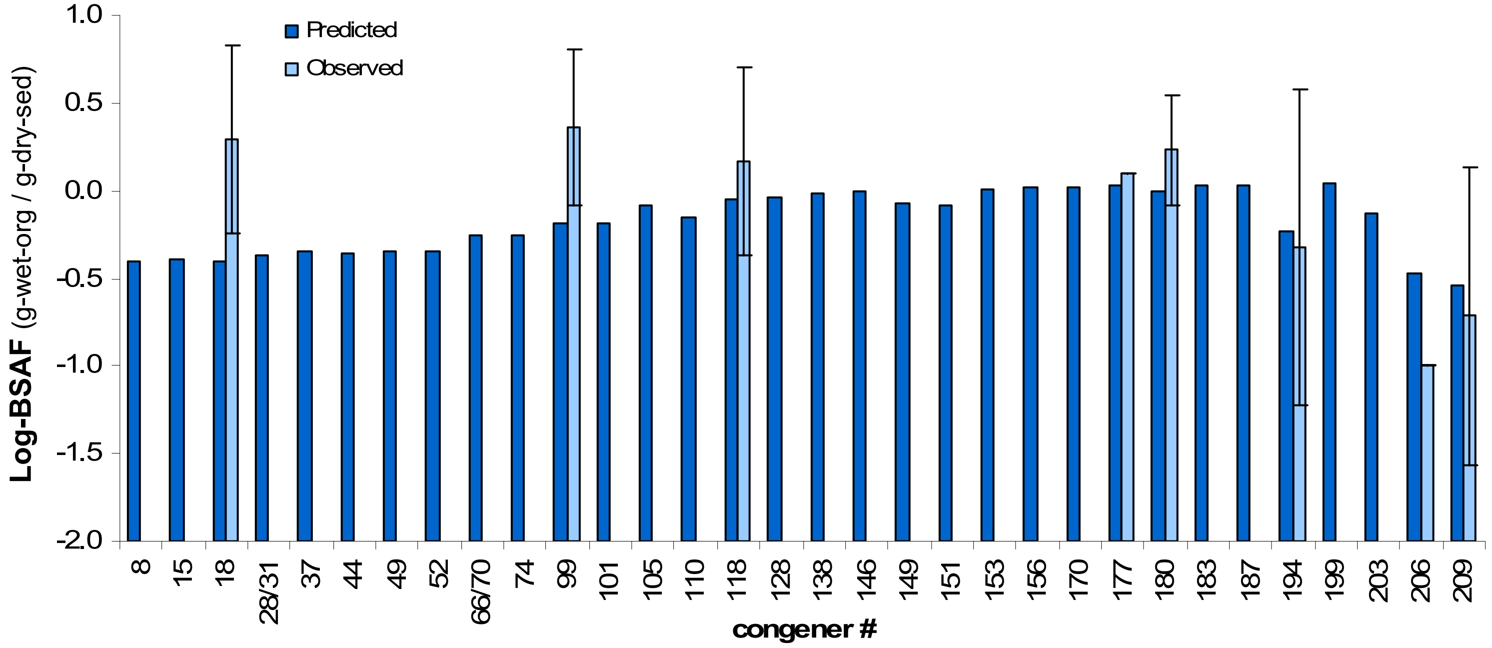

Figure 4-11 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in shellfish from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 4).

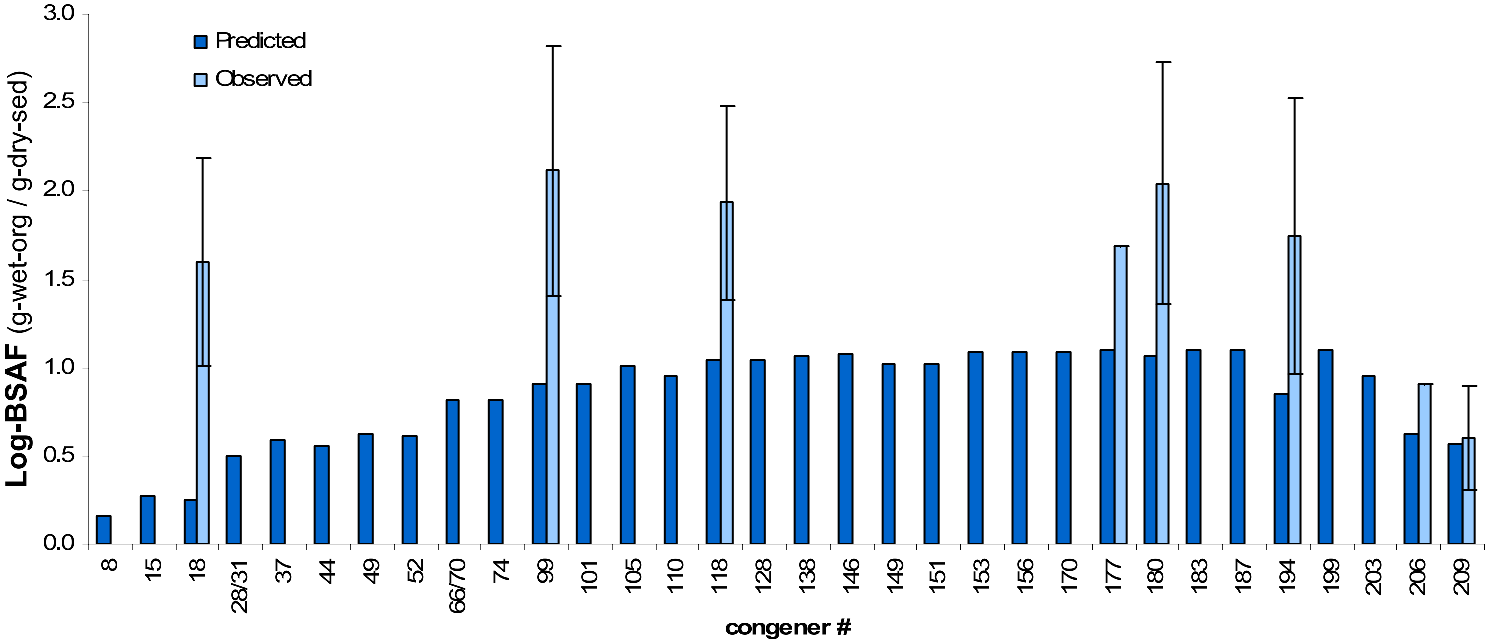

Figure 4-12 Predicted and observed BSAFs (g-wet-organism / g-dry-sediment) of various PCB congeners in crabs from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 9).

Table 4-1 Individual and combined MB results (i.e., mean, lower 95%, and upper 95%) for select organisms of the SoG (i.e., those with a performance analysis dataset) on a congener-specific basis

Organism	Model Bias			
	n	Mean	Lower 95% CI	Upper 95% CI
Shellfish	8	0.76	0.13	4.43
Crabs	8	0.17	0.02	1.27
Predatory invertebrates	7	1.23	0.04	35.13
Demersal fish (seal prey)	8	0.73	0.11	4.68
Demersal fish (bird prey)	8	0.58	0.07	4.81
Dogfish	7	0.31	0.10	0.94
English sole	8	0.49	0.04	5.45
Seal (adult female)	32	1.47	0.59	3.70
Seal (pup)	31	2.10	0.02	211.73
Cormorant egg	21	0.63	0.24	1.60
Heron egg	19	0.73	0.24	2.21
All organisms	-	0.90	0.06	14.35

n = number of congeners on which the MB values are based. Co-eluting groups count as one congener.

Adult Female Seals

Comparison of observed and predicted BSAFs for adult female seals (Figure 4-3) and the mean MB result for adult female seals (Table 4-1) reveal three key points about the model's predictions. First, predicted BSAFs for adult female seals are in reasonable agreement with the observed BSAFs – the majority of congener predicted BSAFs fall within two standard deviations of observed geometric mean BSAFs. Only the BSAFs of congener groups 8, 15, 28/31, 37, 49, 66/70, 110, and 149 (i.e., 8 of the 32 congener groups) fall outside the observed range, all marginally above. Second, Figure 4-3 and the corresponding mean MB of 1.47 (Table 4-1) indicate that the model systematically over-predicts, to a small extent, the BSAFs for adult female seals. Third, Figure 4-3 indicates that the BSAFs of some of the most heavily chlorinated congeners (i.e., 194, 203, 206, and 209) are under-predicted. This BSAF under-prediction could be the result of site specific differences in the PCB congener pattern of sediments used as model input (i.e., those from central SoG) and sediments to which observed female seals (i.e., those used in the model performance analysis) are exposed (i.e., sediments near Vancouver Airport). Ross *et al.*, 2004 found that more heavily chlorinated PCB congeners comprised a greater proportion of ΣPCB concentrations in harbour seals from industrialized areas of the Northeast Pacific Ocean than in harbour seals from remote areas of the Northeast Pacific Ocean. The BSAF under-prediction for the most heavily chlorinated congeners could also be due to model error. For instance, higher chlorinated PCBs may be selectively retained by reproducing and nursing females to a greater extent than estimated by the model.

Seal Pups

Figure 4-4, which compares observed and predicted BSAFs for seal pups, indicates that agreement between model BSAF predictions and empirical data for seal pups is limited. Only the BSAFs of congener groups 28/31, 52, 99, 105, 118, 138, 149, and 153 (i.e., 8 of the 32 modelled congener groups) fall within two standard deviations of the observed geometric means – the majority of congener predictions (i.e., 75%) fall outside the observed range. Figure 4-4, and the corresponding mean MB of 2.10 for seal pups (Table 4-1), also indicate that the model systematically over-predicts the BSAFs for seal pups, and does so to a greater degree than it does for adult female seals.

The systematic over-prediction of seal pup BSAFs could be due, in part, to a difference in PCB concentrations in sediments from the central SoG (i.e., those used as input for the model) and the northern SoG (i.e., those to which the empirical seal pups used to test the model are probably exposed). For instance, if PCB concentrations in central SoG sediments are higher than those in the northern SoG (I do not have the data to confirm one way or the other), then model over-prediction for seal pups is not surprising. The systematic over-prediction of seal pup BSAFs could also be due to model inaccuracies (i.e., an inaccurate diet matrix, inaccurate k_G and k_M values for seal pups, etc.).

Figure 4-4 also demonstrates, in contrast to the results for adult female seals (Figure 4-3), a general trend of congener under-prediction to over-prediction from light to heavily chlorinated congeners in seal pups. This trend could be the result of site specific differences in the PCB congener pattern of sediments used as model input (i.e., those from central SoG) and sediments to which observed seal pups (i.e., those used in the model performance analysis) are exposed (i.e., sediments near Hornby Island). Ross *et al.*, 2004 found that more heavily chlorinated PCB congeners comprised a greater proportion of ΣPCB concentrations in harbour seals from industrialized areas of the Northeast Pacific Ocean than in harbour seals from remote areas of the Northeast Pacific Ocean. The trend of BSAF under- to over-predictions of light to heavy chlorinated congeners in seal pups could also be due to model error. For instance, higher chlorinated PCBs may be selectively retained by reproducing and nursing females to a greater extent than estimated by the model.

Bird Eggs

Figure 4-5 and Figure 4-6 illustrate that predicted BSAFs for cormorant eggs and heron eggs fall within two standard deviations of the observed geometric mean for all congener groups except PCB-151 in herons. Table 4-1 shows a small systematic under-prediction of the BSAF for cormorant eggs (mean MB = 0.63) and heron eggs (mean MB = 0.73).

Fish

Figure 4-7 and Figure 4-8 indicate that, for English sole and dogfish, predicted BSAFs for congeners 118, 180, and 209 fall within the two standard deviations of the observed geometric means, while predicted BSAFs for congeners 99 and 194 fall outside the observed range. BSAF predictions for PCB 18 also fall within two standard deviations of the observed range for English sole, however the observed variability for this congener was extremely large. Figure 4-9, which shows the BSAF comparison results for demersal fish (seal prey), illustrates that predicted BSAFs for congeners 99, 118, 180, 194, and 209 fall within two standard deviations of the observed BSAF ranges, while the BSAF prediction for congener 18 falls outside this range. Figure 4-10, which shows the BSAF comparison results for demersal fish (bird prey), illustrates that predicted BSAFs for congeners 118, 180, 194, and 209 fall within two standard deviations of the observed BSAF ranges, while BSAF predictions for congeners 18 and 99 fall outside this range. Table 4-1 shows that the model systematically under-predicts the BSAFs for all fish – mean MBs for dogfish, English sole, demersal fish (seal prey), and demersal fish (bird prey) are 0.31, 0.49, 0.73, and 0.58, respectively. The systematic under-prediction for all modelled fish is likely due to the fact that the fish were collected from False Creek, where PCB concentrations are higher than in the central SoG.

Invertebrates

Figure 4-11 illustrates that, for shellfish, predicted BSAFs for congeners 118, 180, 194, and 209 fall within two standard deviations of observed BSAFs, while predicted BSAFs for congeners 18 and 99 fall outside of the observed BSAF ranges. Figure 4-12, illustrates that, for crabs, only the predicted BSAF for congener 209 falls within two standard deviations of the observed BSAF; the predicted BSAFs for congeners 18, 99, 118, 180, and 194 fall outside of the observed BSAF ranges. Table 4-1 shows that the model systematically under-predicts the BSAFs for shellfish (mean MB = 0.76) and crabs (mean MB = 0.17). As with fish, this systematic under-prediction may be due to the fact that these invertebrates were collected from False Creek, where PCB concentrations are higher than in the central SoG. Table 4-1 also illustrates that the model over-predicts the BSAFs for predatory invertebrates. This result is suspect, however, because the empirical data used to compare against predictions is derived from only one organism (seastar) for which there were PCB quantification difficulties [Mackintosh *et al.*, 2004].

Figure 4-13 compares – for adult female seals, seal pups, cormorant eggs, and heron eggs – the log-ratio of predicted and observed BSAF values to log-K_{OW} values for individual congeners. Table 4-2 summarizes the regression correlation data for Figure 4-13. This analysis was performed to determine whether a relationship between log-K_{OW} and the log-ratio of predicted and observed BSAF values exists. Existence of such a relationship would suggest the existence of systematic error in the model for a given organism.

Table 4-2 indicates that the slope of the regression lines are slightly negative for adult female seals, cormorant eggs, and heron eggs (a = -0.16, -0.21, and -0.05, respectively). The slope of the line for seal pups, on the other hand, is positive (a = 0.82). For adult female seals, seal pups, and cormorant eggs, R^2 values for the regression equations are 0.40, 0.37, and 0.35, respectively. This suggests that only 35-40% of the variation in the log-ratio of predicted and observed BSAF for these organisms is explained by the log-K_{OW}. The p-values for these equations are well below 0.05 (Table 4-2), suggesting that the results are statistically significant.

Together, the R^2 and p-values for the regression equations for adult female seals, seal pups, and cormorant eggs indicate a weak to moderate relationship between the log-ratio of predicted and observed BSAF values and log-K_{OW} for each congener assessed. This result provides weak to moderate support for the existence of systematic error in the model for these three top predators. For heron eggs, the R^2 and p-values of 0.01 and 0.5, respectively, suggest that no relationship exists between the log-ratio of predicted and observed BSAF values and log-K_{OW} for the congeners assessed, and thus no evidence exists for the existence of systematic error in the model for this top predator.

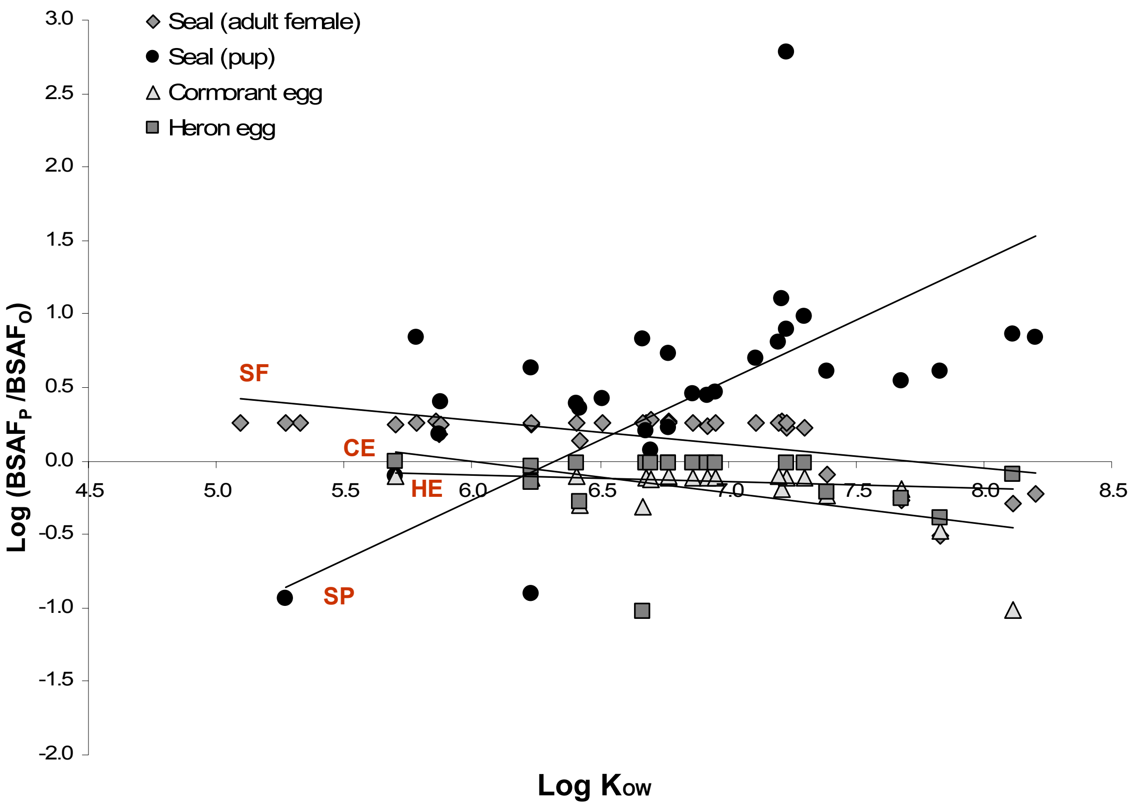

Figure 4-13 Comparison of the ratio of predicted (P) and observed (O) BSAF values to log-K_{OW} values, on a congener-specific basis, for modelled top predators of the SoG. SF = adult female seals, SP = seal pups, CE = cormorant eggs, and HE = heron eggs.

Table 4-2 Correlation data for Figure 4-13

Organism	Equation of the Line	R^2	p	n
Adult Female Seals	y = -0.16x + 1.24	0.40	1.23E-04	32
Seal Pups	y = 0.82x - 5.17	0.37	3.48E-04	31
Cormorant Eggs	y = -0.21x + 1.27	0.35	5.30E-03	21
Heron Eggs	y = -0.04x + 0.19	0.01	5.13E-01	19

4.3.2 Model Performance Analysis for ΣPCBs

Figure 4-14, which compares predicted and observed BSAFs on a ΣPCB basis, indicates that predicted BSAFs for adult female seals, cormorant eggs, and heron eggs all fall within two standard deviations of the observed geometric mean, while predicted BSAFs for seal pups fall slightly above the observed range. Table 4-3, which shows the ΣPCB MB results for seals and birds, illustrates that the model over-predicts the BSAF on a ΣPCB basis for adult female seals and seal pups (MB = 1.60 and 3.18, respectively) and slightly under-predicts the BSAF on a ΣPCB basis for cormorant and heron eggs (MB = 0.73 and 0.81, respectively). These results generally agree with the results of the performance analysis done on a congener specific basis, above.

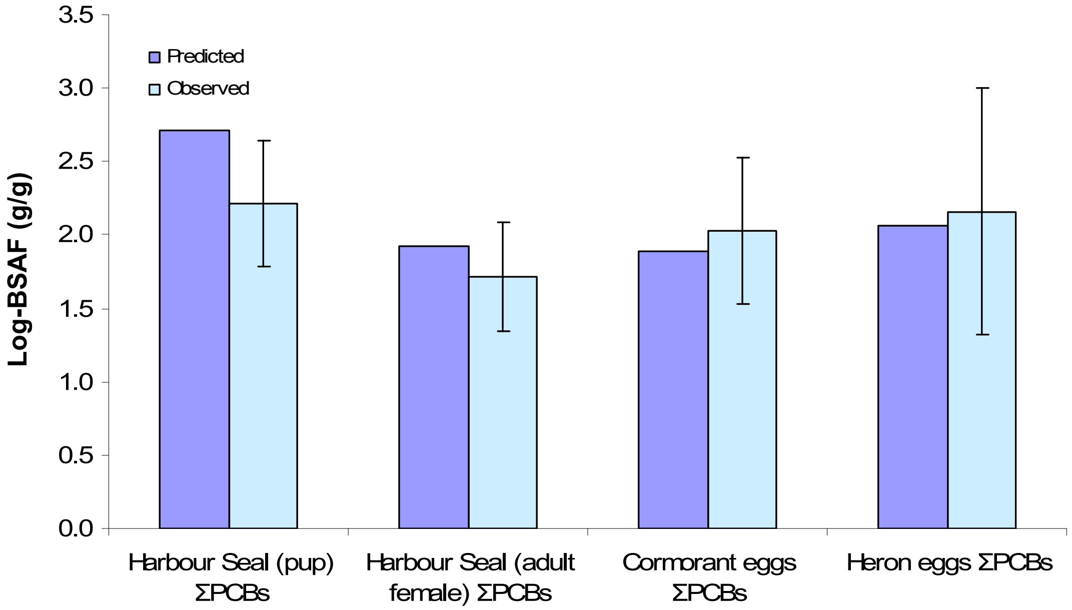

Figure 4-14 Predicted and observed BSAFs (g/g) of ΣPCBs for seal pups, adult female seals, cormorant eggs, and heron eggs from the SoG. Error bars represent two standard deviations of the observed geometric mean (n = 10 for seal pups, 4 for adult female seals, 19 for cormorant eggs, and 12 for heron eggs)

Table 4-3 MB results for adult female seals, cormorant eggs, and heron eggs on a ΣPCBs basis

Organism	ΣPCBs Model Bias
Pup Seals	3.18
Adult Female Seals	1.60
Cormorant Eggs	0.73
Heron Eggs	0.81

4.3.3 Performance Analysis Uncertainty

The MB values above, which are intended to serve as estimates of model error, suggest that the model makes reasonable BSAF predictions for adult female seals, cormorant eggs, and heron eggs of the SoG, and somewhat reasonable BSAF predictions for seal pups. However, note that, due to gaps in the performance analysis dataset (e.g., spatial limitations and temporal inconsistencies in the top predator and sediment datasets, see Table 3-5), I am somewhat uncertain about the accuracy of the observed BSAFs used in the model performance analysis. As a result, I am somewhat uncertain about the accuracy of the MB values derived using these observed BSAFs (e.g., the actual degree of model bias for seal pups may be under or overstated by the MB of 3.18). Because of this uncertainty, I chose not to calibrate the model to fit the observed data (i.e., adjust the predicted BSAFs to correct for the MB) when using the model in the following model application phase of the project. I instead display the model application results expected using both observed and model-predicted BSAFs, and address the associated uncertainties with a qualitative analysis.

4.4 Model Application

In the following three sections, I apply the model to conduct an ERA for select top predators of the SoG, evaluate the current SQG for ΣPCBs, recommend a new SQG for ΣPCBs, and propose SQTs for ΣPCBs that meet various protection goals for top predators of the SoG.

4.4.1 Ecological Risk Assessment

4.4.1.1 ERA for Adult Female Seals

Figure 4-15 shows the observed and model predicted distributions of ΣPCB concentrations (ng/g-lipid) in adult female seals of the SoG in relation to the effects threshold. The observed distribution ranges from a log-ΣPCB concentration of approximately 2.7 to 3.8 ng/g-lipid, while the model predicted distribution ranges from a log-ΣPCB concentration of approximately 2.7 to 4.3 ng/g-lipid. Figure 4-15 illustrates that approximately one percent of the model-predicted adult female seal population, and no members of the observed adult female seal population, are anticipated to have PCB body burdens that exceed the log-ΣPCB effects threshold of 4.06 ng/g-lipid.

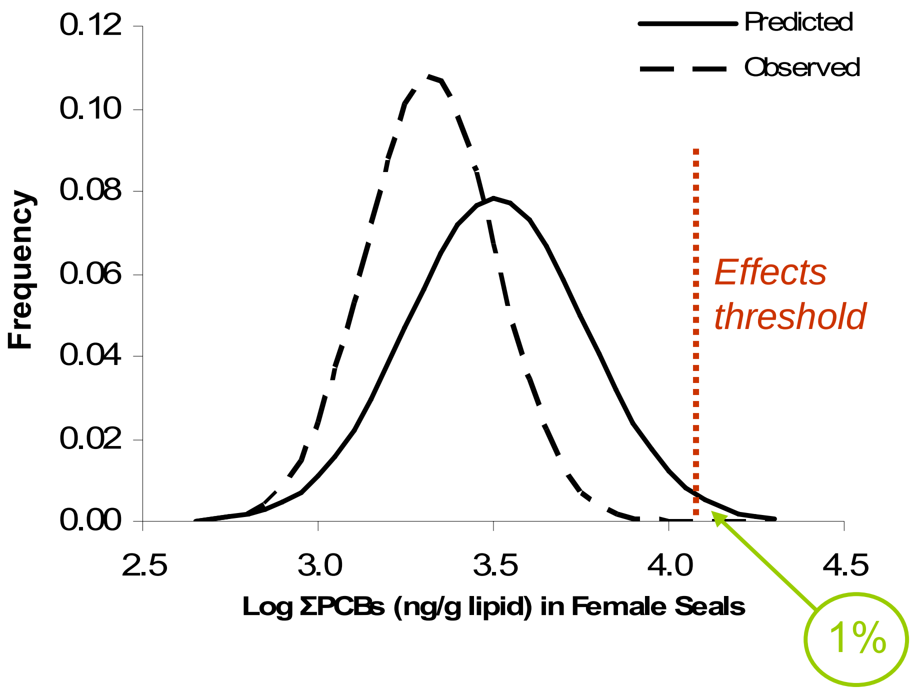

Figure 4-15 The predicted and observed distribution (n = 4) of ΣPCB concentrations (ng/g lipid) in adult female seals in relation to the effects threshold. The solid and dashed curves depict the predicted and observed ΣPCB distributions, respectively. The horizontal dotted line marks the effects threshold. The circled value indicates the proportion of adult female seals in the SoG predicted to have ΣPCB concentrations above the threshold.

Given that nearly the entire ΣPCB concentration distribution for observed and predicted adult female seals lies below the effects threshold (Figure 4-15), it appears that the risk of adverse effects associated with PCB exposure to adult female seals in the SoG is low. However, note the following uncertainties associated with this risk characterization. First, it is not clear to what extent the observed ΣPCB distribution for adult female seals, which is based on four seals from Vancouver Airport, represents the actual ΣPCB distribution for adult female seals throughout the entire SoG. Second, given the lack of model input and performance analysis data (Table 3-4 and Table 3-5), the MB of 1.60 for adult female seals, and the use of the cormorant egg SD to derive the variability for the predicted distribution, it is not clear to what extent the predicted distribution represents the actual ΣPCB distribution for adult female seals throughout the entire SoG. Finally, given the TRV data gaps (Table 3-7) and the uncertainties associated with the effects threshold [Kannan *et al.*, 2000], it is not clear to what extent the effects threshold in Figure 4-15 represents the actual ΣPCB effects threshold for adult female seals throughout the SoG. Therefore, though the risk of adverse effects associated with PCB exposure to adult female seals in the SoG appears to be low, the possibility of adverse effects to a significant proportion of the adult female seal population cannot be ruled out.

4.4.1.2 ERA for Seal Pups

Figure 4-16 shows the observed and model predicted distributions of ΣPCB concentrations (ng/g-lipid) in seal pups of the SoG in relation to the effects threshold. The observed distribution ranges from a log-ΣPCB concentration of approximately 2.75 to 4.0 ng/g-lipid, while the model predicted distribution ranges from a log-ΣPCB concentration of approximately 3.1 to 4.6 ng/g-lipid. Figure 4-16 illustrates that approximately thirty-one percent of the model-predicted seal pup population, and no members of the observed seal pup population, are anticipated to have PCB body burdens that exceed the log-ΣPCB effects threshold of 4.06 ng/g-lipid.

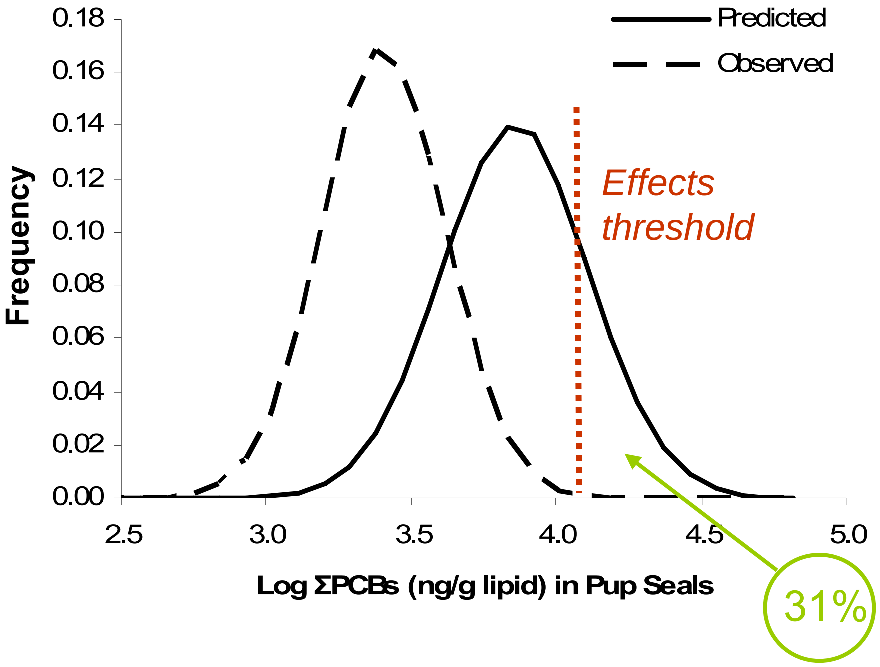

Figure 4-16 The predicted and observed distribution (n = 10) of ΣPCB concentrations (ng/g lipid) in seal pups in relation to the effects threshold. The solid and dashed curves depict the predicted and observed ΣPCB distributions, respectively. The horizontal dotted line marks the effects threshold. The circled value indicates the proportion of seal pups in the SoG predicted to have ΣPCB concentrations above the threshold.

The ERA result for seal pups (Figure 4-16) suggests that the risk of adverse effects associated with PCB exposure to seal pups in the SoG is low to moderate. However, note the following uncertainties associated with this risk characterization. First, it is not clear to what extent the observed ΣPCB distribution for seal pups, which is based on ten seals from Hornby Island, represents the actual ΣPCB distribution for seal pups throughout the entire SoG. Second, given the lack of model input and performance analysis data (Table 3-4 and Table 3-5), the MB of 3.18 for seal pups, and the use of the cormorant egg SD to derive the variability for the predicted distribution, it is not clear to what extent the predicted distribution represents the actual ΣPCB distribution for seal pups throughout the entire SoG. Finally, given the fact that effects threshold used was derived for adult seals and is associated significant uncertainty itself [Kannan *et al.*, 2000], it is not clear to what extent the effects threshold in Figure 4-16 represents the actual ΣPCB effects threshold for seal pups throughout the SoG. Therefore, though the risk of adverse effects associated with PCB exposure to seals pups in the SoG appears to be low to moderate, the possibility of adverse effects to a larger proportion of the seal pup population than suggested by Figure 4-16 cannot be ruled out.

4.4.1.3 ERA for Cormorant Eggs

Figure 4-17 shows the observed and model predicted distributions of ΣPCB concentrations (ng/g-lipid) in cormorant eggs in relation to the LOAEL. The observed distribution ranges from a log-ΣPCB concentration of approximately 3.2 to 4.6 ng/g-lipid, while the model predicted distribution ranges from a log-ΣPCB concentration of approximately 3.1 to 4.6 ng/g-lipid. The figure illustrates that no members of the observed or model-predicted cormorant egg populations are anticipated to have PCB body burdens that exceed the LOAEL (the PCB concentration distribution, in fact, lie well below the LOAEL).

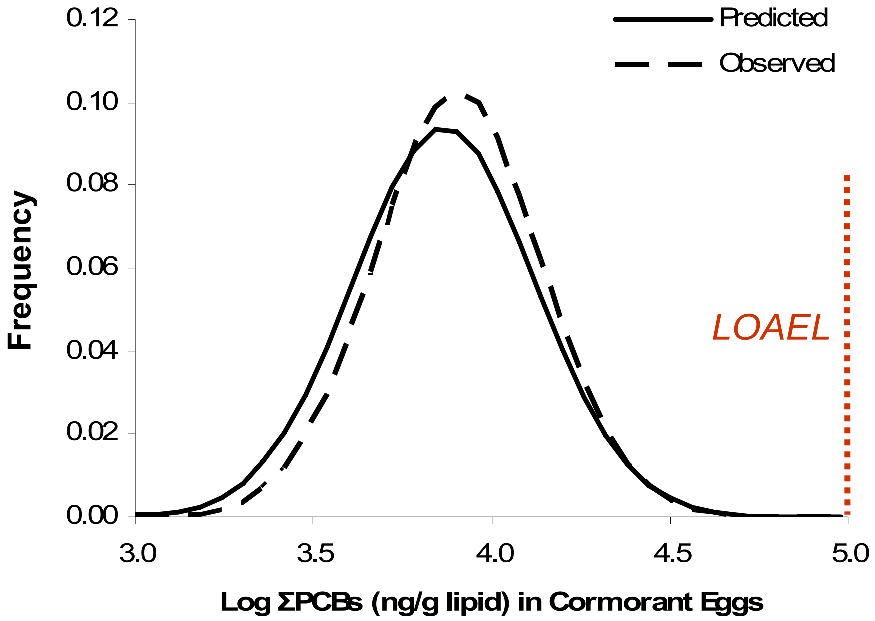

Figure 4-17 The predicted and observed distribution of ΣPCB concentrations (ng/g lipid) in cormorant eggs in relation to the LOAEL. The solid and dashed curves depict the predicted and observed ΣPCB distributions, respectively. The horizontal dotted line marks the LOAEL.

The ERA result for cormorant eggs (Figure 4-17) suggests that the risk of adverse effects associated with PCB exposure to cormorant eggs in the SoG is low. My confidence in this risk characterization is somewhat high mainly because my confidence in the observed distribution (which is based on a strong dataset) and predicted distribution (which closely matches the observed distribution) is high. However, because the TRV used in the assessment is a LOAEL rather than an effects threshold, is a point estimate, and is based on studies with non-SoG organisms [Hoffman *et al.*, 1996], the possibility of adverse effects associated with PCB exposure to at least some members of the cormorant egg population in the SoG cannot be ruled out.

4.4.2 Sediment Quality Guideline Evaluation and Recommendation

4.4.2.1 SQG Definition

SQGs "apply province-wide and are safe levels of substances for the protection of a given water use, including drinking water, aquatic life, recreation and agricultural uses" [MOE, 2006]. It is unclear what the MOE considers to be a "safe level" of exposure; however, Dr. Glyn Fox of the MOE indicated that water quality guidelines are typically set to protect aquatic organisms to the NOAEL [Dr. Glyn Fox, MOE, *personal communication*].

4.4.2.2 SQG Evaluation

The SQG for ΣPCBs is set to a maximum value of 2.0 μg/g organic carbon (OC) [MOE, 2006]. This guideline is based on a combination of (i) PCB exposure and effects data from laboratory studies conducted primarily on freshwater fish and invertebrates, (ii) the application of simple equilibrium partitioning equations, and (iii) the application of uncertainty factors [Nagpal, 1992]. Given that little, if any, SoG-specific exposure and effects data was used to derive the SQG, and given the large BSAFs predicted for the system (Figure 4-2), it is unclear whether the current SQG for ΣPCBs does indeed result in safe levels of PCBs in aquatic organisms of the SoG.

Figure 4-18 shows a comparison of the ΣPCB concentration associated with the SQG (i.e., the $C_{B\text{-}SQG}$, which was derived by multiplying the SQG by the model-predicted BSAF) to the predicted ΣPCB concentration distribution, observed ΣPCB concentration distribution, and TRVs for cormorant eggs, adult female seals, and seal pups of the SoG. This figure illustrates that the SQG for ΣPCBs is expected to result in a ΣPCB concentration (the blue arrows with the $C_{B\text{-}SQG}$ identifier) that is 6.3 times above the NOAEL for adult female seals, 12.6 times above the NOAEL for seal pups, and at the LOAEL and above the NOAEL for cormorant eggs. The $C_{B\text{-}SQG}$ is also well above the effects threshold for adult female seals and seal pups. Note that multiplication of the SQG by the observed BSAF for each organism also results in exceedances of the NOAEL and effects threshold for adult female seals and seal pups, and a match of the LOAEL for cormorant eggs (results not shown). These results suggest that the SQG for ΣPCBs does not result in safe levels of PCBs in seals or cormorant eggs of the SoG, and thus the current SQG may not be adequate to meet the MOE's protection goals.

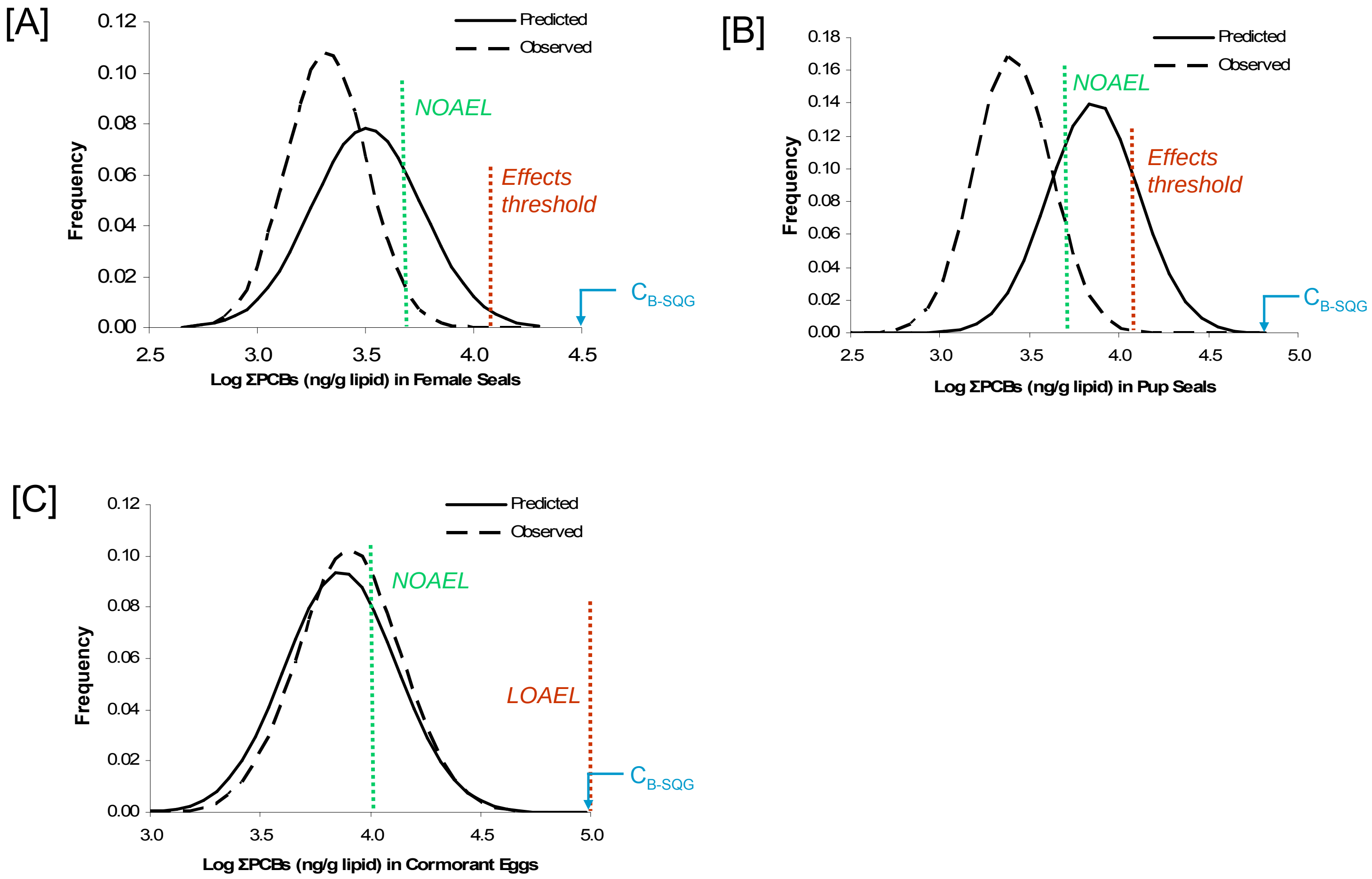

Figure 4-18 The ΣPCB concentration predicted from the current SQG (as indicated by the blue arrow on each graph) for adult female seals [A], seal pups [B], and cormorant eggs [C], relative to their TRVs and predicted (solid lines) and observed (dashed lines) ΣPCB distributions.

Figure 4-19 shows the distribution of ΣPCB concentrations (ng/g-lipid) in adult female seals (A) and cormorant eggs (B) that would be expected if the geometric mean ΣPCB concentration in sediments of the SoG were at the SQG. The dashed and solid distribution in each graph were derived by multiplying the SQG for ΣPCBs by the observed and model-predicted BSAF, respectively. For adult female seals, the majority of both ΣPCB concentration distributions exceed threshold effects level, while for cormorant eggs, about half of both ΣPCB concentration distributions exceed the LOAEL. These results further suggest that the SQG for ΣPCBs does not result in safe levels of PCBs in adult female seals or cormorant eggs of the SoG, and thus the current SQG may not be adequate to meet the MOE's protection goals.

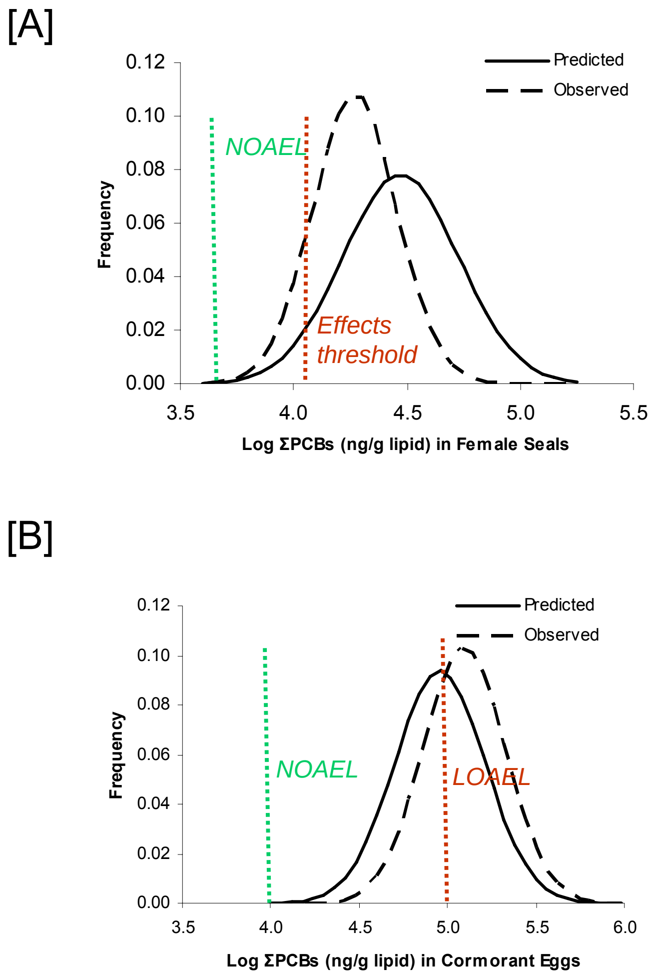

Figure 4-19 The ΣPCB concentration distribution predicted by multiplying the current SQG by the observed (dashed line) and predicted (solid line) BSAFs for adult female seals [A] and cormorant eggs [B] relative to their TRVs.

4.4.2.3 SQG Evaluation Uncertainty

There exists some uncertainty about the accuracy of the observed and predicted BSAFs used to estimate the ΣPCB concentrations in Figure 4-18 and Figure 4-19 (see Section 4.3.3). As a result, there exists some uncertainty about the extent to which the ΣPCB concentrations in top predators of the SoG associated with the SQG would, in the field, actually exceed the TRVs for these organisms. However, given the degree of the TRV exceedances estimated with both the observed and model-predicted BSAFs (Figure 4-18 and Figure 4-19), the uncertainties about the accuracy of the TRVs (Section 3.3.2 and

Table 3-7), and the fact that only a limited number of top predators from the SoG were evaluated in this project, I remain reasonably confident that the current SQG for ΣPCBs does not result in safe levels of PCBs in top predators of the SoG.

4.4.2.4 SQG Recommendation

In an effort to derive a SQG for ΣPCBs that meets the provincial objective of safe levels for all aquatic organisms, I "back calculated", using model-predicted BSAFs, the maximum ΣPCB concentration in SoG sediment associated with a safe level (i.e., 0.1% of organisms above the NOAEL) for adult female seals, seal pups, and cormorant eggs. The results, shown in Table 4-4, indicate that safe maximum ΣPCB concentrations in sediment range from 0.1 µg/g-OC for protection of 99.9% of seal pups to the NOAEL to 0.4 µg/g-OC for the protection of 99.9% of adult female seals to the NOAEL. Since the ΣPCB concentration in sediment derived for the protection of seal pups is protective of all other evaluated organisms, I recommend that the current SQG be reduced from 2.0 to 0.1 µg/g-OC.

Table 4-4 Comparison of current and recommended SQGs for ΣPCBs (µg/g-OC).

Current BC-SQG (µg/g ΣPCBs-OC) **2.0**

Receptor	**Protection Goal**	**Recommended SQG** (µg/g OC)
Adult Female Seals	0.1% > NOAEL	**0.4**
Pup Seals	0.1% > NOAEL	**0.1**
Cormorant Eggs	0.1% > NOAEL	**0.2**

Given the possibility that model-predicted BSAFs for seal pups are somewhat overestimated, I am reasonably confident that the recommended SQG is adequate to meet the MOE's protection objective. I am also aware, however, that the recommended SQG may be lower than necessary to protect these receptors. From a wildlife protection point of view, a SQG for ΣPCBs that is unnecessarily low may be defensible. PCBs are only one of the contributing stressors to ecological receptors in the SoG (others include POPs and other chemicals, habitat destruction, reduced prey availability, etc.), and the SoG food web potentially extends to higher trophic levels (e.g., to the endangered and declining population of orcas) which could be subject to higher PCB doses than seals and cormorants are. Furthermore, a conservatively low SQG for the protection of seal pups may be warranted, in this case, given the uncertainty associated with the PCB body burdens in, and related health effects to, seal pups and seal foetuses.

4.4.3 Sediment Quality Target Proposals

4.4.3.1 SQT Definition

A SQT (also known as a sediment quality objective) is a level of a given substance in sediment that one aims to achieve. This level can be a single value (e.g., a maximum value like the SQG) or a distribution of values. SQTs are typically site-specific (i.e., they do not necessarily apply province wide) and can be set to achieve whatever protection endpoint is desired (e.g., no more than 10% of the seal pup population in the SoG shall be exposed to ΣPCBs in concentrations that exceed their effects threshold). I am not aware of any provincial or federal SQT for ΣPCBs in the SoG.

4.4.3.2 SQT Proposals

In an effort to guide provincial and federal environment managers to SQTs that meet protection goals for top predators of the SoG, I “back calculated”, using model-predicted BSAFs, maximum allowable ΣPCB concentrations in sediment associated with a variety of protection outcomes for seals and cormorant eggs. Note that it would be more useful to express the proposed SQTs as distributions rather than maximum values. However, my uncertainty about the relationship between the distribution of PCB concentrations in sediments and top predators of the SoG is too high to derive SQT distributions with any reasonable degree of confidence. The results of my SQT derivation, shown in Table 4-5, indicate that proposed SQTs range from a ΣPCB concentration of 0.4 µg/g-OC (5% of seal pups above the NOAEL) to 6.0 µg/g-OC (5% of cormorant eggs above the LOAEL).

Table 4-5 Proposed sediment quality targets for ΣPCBs (µg/g-OC) for the protection of seals and marine birds in the SoG.

Receptor	**Protection Goal**	**Recommended SQT** (µg/g OC)
Adult Female Seals	5% > NOAEL	**1.0**
	5% > Effects Threshold	**1.9**
	5% > LOAEL	**4.8**
Pup Seals	5% > NOAEL	**0.4**
	5% > Effects Threshold	**1.0**
	5% > LOAEL	**1.9**
Cormorant Eggs	0.1% > LOAEL	**2.4**
	5% > LOAEL	**6.4**

Given that model-predicted BSAFs for seal pups and adult female seals may be somewhat overestimated (i.e., they have MB values of 3.18 and 1.60, respectively), I am reasonably confident that the proposed SQTs for these organisms are adequate to meet the desired protection goal. Given that the model-predicted BSAF for cormorant eggs is associated with an MB of 0.73, the SQT for this organism may be slightly high.

5 CONCLUSIONS & RECOMMENDATIONS

5.1 Project Summary

In an effort to enhance the understanding of POP-bioaccumulation dynamics in the SoG and improve the decision-making capacity of environmental managers, I (i) developed, parameterized, and tested a mechanistic bioaccumulation model for PCBs in the SoG; (ii) used this model to help conduct an ERA for the SoG's top predators, assess the adequacy of the current SQG for ΣPCBs, propose a new SQG, and propose a range of SQTs; and (iii) identified gaps in the data required to support the development, testing, and application of the bioaccumulation model. The results of these project phases are summarized below.

- Model performance analysis indicates that model-predicted BSAFs for ΣPCBs in cormorant eggs, heron eggs, and adult female seals are in reasonable agreement with observed BSAFs (MB values are 0.73, 0.81, and 1.60, respectively), while model-predicted BSAFs for seal pups are potentially overestimated (MB = 3.18). The performance analysis dataset for these organisms was limited spatially, temporally, chemically, and statistically (Table 3-5), however, and thus the model was not calibrated to fit the observed data before the model application phase of the project.

- The ERA estimated that virtually no members of the cormorant egg or adult female seal population in the SoG have ΣPCB body burdens in excess of their LOAEL (Figure 4-17) and effects threshold (Figure 4-15), respectively. The ERA also estimated that virtually no members of the observed seal pup population (i.e., that from Hornby Island) and 31% of the model-predicted seal pup population have ΣPCB body burdens in excess of their effects threshold (Figure 4-16). Based on these results, the ERA concluded that risks associated with current levels of PCB exposure to cormorant eggs and adult female seals are probably low, while risks to seal pups are probably low to moderate. It was acknowledged, however, that given the gaps in the empirical dataset (e.g., empirical seal concentrations for the entire SoG, appropriate TRVs, etc. – see Table 3-4, Table 3-5, and Table 3-7), the possibility of adverse effects to a larger proportion of these top predator populations than indicated by the ERA cannot be definitively ruled out.

- Evaluation of the SQG for ΣPCBs suggests that if ΣPCB concentrations in SoG sediments were equivalent to the SQG, ΣPCB body burdens in a large portionof the population of adult female seals, seal pups, and cormorant eggs would exceed their NOAELs for ΣPCBs and, possibly, their threshold effects levels as well. As a consequence, the MOE's goal of protecting all aquatic organisms in BC to the NOAEL would not be achieved with the current SQG for ΣPCBs.

- The proposed SQG that is expected to protect all organisms investigated to the NOAEL is approximately 0.1 μg/g-OC, a value that is 20 times lower than the current SQG of 2.0 μg/g-OC.

- The proposed SQTs for the protection of top predators in the SoG to various ecological endpoints range from a ΣPCB concentration of 0.4 μg/g-OC (5% of seal pups above the NOAEL) to a ΣPCB concentration of 6.0 μg/g-OC (5% of cormorant eggs above the LOAEL).

- The main gaps in the project's data include the following: $\delta^{15}N$ values for organisms of the SoG diet matrix, k_M values for birds and seals, PCB concentrations in sediments and biota of the SoG, TRVs for most organisms of the food web, and a various model parameter values.

5.2 Key Findings and Implications

The first key finding is that the current SQG for ΣPCBs does not appear to protect top predators in the SoG to the NOAEL or, potentially, to the threshold effects level (Section 4.4.2.2). This finding suggests that the current approach used by the MOE to derive SQGs for PCBs does not adequately account for the degree of PCB biomagnification in the resident food web of the SoG (i.e., potentially a 500-fold increase in ΣPCB concentrations from sediment (dw) to seal pups (ww) (Section 4.2)). It is unclear whether this is of concern for the management of wildlife exposure to PCBs in the SoG. Current PCB levels in the SoG, which are not expected to increase, appear to pose low risks to the SoG's resident top predators (Section 4.4.1); however, they may not pose low risks to BC orcas which occupy a higher trophic position than seals, have high PCB body burdens, and are experiencing population declines [Ross *et al.*, 2000]. Regardless, the lack of accounting for PCB biomagnification in the SoG is a concern for the management of the thousands of currently unregulated POPs. Derivation of inappropriate SQGs for POPs could lead to POP body burdens in BC's top predators that exceed effects thresholds for individual POPs, which is inconsistent with the environmental protection goals of the province. For POPs with similar modes of toxicity (i.e., PCBs, PBDEs, PCDDs, furans, etc), the degree of threshold effects exceedance, and the associated risks to the health of wildlife and humans in BC, could be substantial.

The second key finding is that there are significant gaps in the set of empirical data required for model development, model performance analysis, and model application (Table 3-4, Table 3-5, and Table 3-7). These data gaps affect the confidence in the model-predicted BSAFs – e.g., confidence in the accuracy of the model-predicted BSAF for hake is low because the observed PCB concentration data for hake, required for model performance analysis, were not available. The data gaps also limit the extent to which I could apply the model-predicted BSAFs to address management issues – e.g., I could not assess the risks of PCB exposure to herons or assess the adequacy of the current SQG for their protection because I lacked heron TRVs. In addition, the data gaps affected my confidence in the model application results – e.g., I could not state with confidence whether any seal pups in the SoG are expected to have ΣPCB body burdens that exceed their ΣPCB effects threshold because I lacked appropriate empirical PCB concentration data for pups from throughout the SoG and because I lacked pup-specific TRVs.

The impact of data gaps on the level of confidence in the model is important because the level of confidence in the model ultimately affects the ability of risk managers to make model-informed decisions. For example, the lack of data on the distribution of PCB concentrations in herring, salmon, and hake limits the ability of the model to estimate, with confidence, the relative contribution of immigrant and resident organisms to PCB body burdens in seals. This, in turn, could hamper a manager's ability to control seal exposure to PCBs by leading to the misallocation of funds between programs aimed at reducing PCB body burdens in immigrant organisms (e.g., via the pursuit of international pollution abatement agreements) and programs aimed at reducing PCB body burdens in resident organisms (e.g., by the remediation of local sediments). While the influence of data gaps on model confidence and ultimately management decisions may not be of concern for the management of seal exposure to PCBs (note that risks to resident organisms appear to below (Section 4.4.1)), it may certainly be of concern for the management of seal and other top predator exposure to the broad class of emerging POPs, particularly those with synergistic modes of toxicity.

5.3 Recommendations

<u>The MOE should revise its methodology for deriving SQGs for POPs</u>

The results of this project suggest that the methodology used by the MOE to derive SQGs for ΣPCBs does not adequately account for the degree of PCB biomagnification in the SoG food web. As a result, the SQG goal of ensuring safe levels of PCBs for the protection of aquatic life [MOE, 2006] is likely not being met by the current SQG for PCBs. To avoid the derivation of inappropriate SQGs for other POPs, I recommend that the MOE revise its SQG derivation methodology for POPs. Specifically, I recommend that the MOE continue to support the development of, and use, POP bioaccumulation models such as the one developed here for PCBs. Note that this model can potentially be adapted to derive SQGs for other POPs (e.g., PBDEs).

<u>GBAP should reduce gaps in the PCB bioaccumulation datasets</u>

The GBAP aims to improve the capacity of environmental managers to make decisions by advancing scientific understanding [Environment Canada, 2005]. The scientific understanding of PCB bioaccumulation dynamics in the SoG is, as this project determined, limited due to the lack of data required for model parameterization, testing, and application. As a result, the capacity of environmental managers to make cost-effective decisions aimed at reducing potential PCB exposure risks to wildlife is currently limited. To reduce uncertainty in the model and improve its utility for making management decisions, I recommend that the GBAP direct more efforts towards narrowing the gaps in the empirical datasets. Included below are the key data gaps, listed in order of highest to lowest research priority, that should be addressed.

1. *PCB Concentrations in Sediment*. The current dataset of PCB concentrations in sediment is deficient spatially (data is from the central SoG and Howe Sound only), temporally (data are from 1997), chemically (concentrations for only 34 congeners were reported), and statistically ($n = 3$). These deficiencies affect all phases of the project and are ultimately the greatest source of doubt about model accuracy. Resources should be directed at improving the sediment PCB concentration database through increased sampling, improved chemical analysis, and/or increased publication of existing data.

2. *PCB Concentrations in Organisms*. The current dataset of PCB concentrations in herring and salmon is deficient spatially (i.e., from limited and unknown regions of the SoG, respectively) and statistically ($n = 2$ and 3, respectively). The current datasets of PCB concentrations in organisms used for model performance analysis are deficient temporally (bird data is from the 1990s), spatially (seal and fish data

are from geographically small areas of the SoG), chemically (congener data is limited for all organisms except seals), and statistically (sample sizes are small for adult female seals, fish, and invertebrates). In addition, performance analysis data is missing for a number of organisms (i.e., plants, invertebrates, most fish, adult male seals, juvenile seals, seal foetuses, etc.) and for related seal pups and mothers. All these data gaps reduce confidence in the results of the development, performance analysis, and application phases of the project. As a second priority, resources should be directed at improving the empirical performance analysis dataset. Particular attention should be paid to improving the datasets of hake, herring, and seals since these are especially important for characterizing PCB bioaccumulation to seals. As above, this can be accomplished through increased sampling or increased publication of existing data.

3. *δ15N Data*. The current diet matrix (Table 3-1), based on observational studies and scat collection, appears to reasonably represent feeding relationships throughout the SoG. However, the lack of spatially diverse δ15N data for most organisms of the matrix makes verification of the matrix's accuracy difficult. Given the strong link between TP and POP concentration [Mackintosh et al., 2004; Fisk et al., 2001; Burreau et al., 2004], resources should be directed to improving the picture of feeding relationships in the SoG through collection and analysis of more δ15N data (note that δ15N analysis is relatively inexpensive). Improvements in understanding SoG feeding relationships may be particularly important as the SoG ecosystem changes with increased anthropogenic interference (i.e., fishing, tourism, trade, etc.) and climate change.

4. *Toxicity Data*. The toxicity dataset is limited to a point value NOAEL and LOAEL for adult seals and cormorant eggs. Moreover, there is considerable uncertainty associated with these point value TRVs, particularly when extrapolated from non-SoG organisms in captivity to SoG organisms in the wild. These data gaps limit the accuracy of and confidence in the results of the model application phase of the project. For instance, because toxicity data for seal pups

and foetuses is missing, the potential health risks to these organisms associated with PCB exposure are not clear. Improving the toxicity database is ranked fourth in research priority because it affects only the model application phase of the project and because conservative assumptions can be used to fill these data gaps for the moment.

5. *Model Parameter Data*. A number of parameter values are based on limited empirical data (e.g., OC content of sediment, body temperatures of birds and seals, growth rate constant for phytoplankton, etc.) or were simply estimated (seal k_M values, water fraction in crabs, etc.) – see appendices Section 7.4. Errors in parameter values primarily affect the model development (i.e., BSAF predictions) phase of the project. As a group, these data are ranked fifth in research priority because the benefit/cost ratio associated with improving them is lower than that associated with improving the datasets above.

Note that, regardless of whether wildlife exposure to PCBs is still of management concern, it remains important to address the PCB-relevant data gaps above (i.e., #1, 2, and 5) because all future POP modelling will depend on, and be affected by, the quality of the bioaccumulation model for PCBs.

GBAP should improve the data collection and management framework

As discussed above, there are considerable gaps in the PCB bioaccumulation datasets. As a result, significant funds will likely be required to obtain the amount of PCB and other POP bioaccumulation data necessary for well-informed decision making by risk managers. In order to get the most out of limited data collection funds, I recommend that GBAP promote data collection efficiencies by encouraging, and earmarking funds for, data collectors to obtain additional data during their research that is not of direct interest to them but is of interest to the broader scientific and management objectives of GBAP. For instance, a researcher collecting heron eggs for PBB analysis could be given additional funds to collect proximate sediment, soil, and heron prey samples, and analyze these for lipid content, δ15N values, various POPs of concern, etc. This use of funds will be cheaper in the long run than making numerous different excursions for each of these types of data. It also addresses some of the temporal and spatial limitations of current bioaccumulation datasets.

Further to making the above efficiency improvements, the GBAP should establish a data inventory where data collection priorities can be made explicit, and where data collection results can be organized and posted. This will help data collectors to identify data requirements, modellers to improve the accuracy of their models, and the GBAP to avoid funding work that has already been done.

6 APPENDICES

6.1 Diet Matrix Verification Data

Table 6-1 The estimated annual average diet of harbour seals in the SoG [from Olesiuk, 1993]

Species	Diet composition (% mass)	Lower - upper limit (% mass)	Matrix prey category
Pacific hake	42.6	26.3 – 57.2	na
Pacific herring	32.4	19.8 – 54.7	na
Salmonids	4.0	1.3 – 8.6	na
Plainfin midshipman	3.4	0.8 – 7.8	misc. demersal
Lingcod	3.0	1.3 – 5.4	misc. demersal
Surfperches	2.3	0.5 – 5.4	misc. demersal
Cephalopods (i.e., squid)	2.1	0.0 – 5.9	small pelagic
Flatfish species	1.2	0.5 – 2.9	misc. demersal
Sculpins	1.2	0.1 – 3.1	misc. demersal
Rockfish	1.1	0.4 – 2.4	misc. demersal
Pacific tomcod	1.0	0.6 – 1.4	misc. demersal
Walleye pollock	1.0	0.6 – 1.3	na
Pacific sand lance	0.8	0.4 – 2.1	small pelagic
Pacific cod	0.5	0.3 – 0.7	misc. demersal
Smelts (mainly eulachon)	0.4	0.3 – 1.8	small pelagic
Unidentified / other fishes	2.7	1.0 – 3.0	na
Other invertebrates	0.2	0.0 – 0.6	na
Total	100.0		

na = not applicable

Table 6-2 SoG diet matrix reported in Pauly & Christensen, 1995

	Prey														
Predator	Mammals (res.)	Large Pelagics	Small Pelagics	Hake	Misc. Demersals	Jellies	Lg. Macrobenthos	Sm. Macrobenthos	Carn. Zooplankton	Herb. Zooplankton	Primary Producers	Birds	Transient Orcas	Salmon	Detritus	Total (%)
Mammals (res.)		1.0	30.0	30.0	10.1		0.9	4.0	1.0					23.0		100.0
Large Pelagics			20.0	10.0	5.0	1.0			45.0	19.0						100.0
Small Pelagics								10.0	10.0	80.0						100.0
Hake		10.0	20.0	7.0	7.0				35.0	21.0						100.0
Misc. Demersals			10.0	5.0			20.0	20.0	40.0	5.0						100.0
Jellies						3.0			26.0	71.0						100.0
Lg. Macrobenthos							5.0	30.0							65.0	100.0
Sm. Macrobenthos								5.0							95.0	100.0
Carn. Zooplankton										50.0	25.0				25.0	100.0
Herb. Zooplankton											90.0				10.0	100.0
Primary Producers																0.0
Birds			22.0		15.0		20.0	19.0		6.0	1.0				17.0	100.0
Transient Orcas	85.0										5.0	5.0	5.0			100.0
Salmon																0.0
Detritus																0.0

Table 6-3 Calculated TPs and literature derived δ^{15}N ratios for organisms of the SoG feeding matrix

		δ^{15}N%				
Organism	**Calculated TP**	**Mean**	**SD**	**Date Sampled**	**Sample location**	**Source**
Phytoplankton	1.00					
Kelp/Sea grass	1.00	8.4	0.1	Jun-Sep 99	False Creek	*1*
H. zooplankton	2.45					
N. plumchrus	2.45	9.9	0.2	1993	SoG	*2*
P. minutus	2.45					
Shellfish	2.48	9.1	1.1	1993; 1999	SoG; False Creek	*1,2*
Crab	3.40	14.4	0.6	1993; 1999	SoG; False Creek	*1,2*
Grazing invertebrates	2.78					
C. zooplankton	3.51					
Euphausiids	2.28	10.1	0.1	1993	SoG	*2*
Predatory invertebrates	3.56	12.4	2.7	1993; 1999	SoG; False Creek	*1,2*
Small pelagic fish (seal prey)	3.95	14.4	0.4	1990; 1993	West Vancouver Island; SoG	*2,3*
Small pelagic fish (bird prey)	3.92					
Lampetra ayresi	4.60					
Misc. demersal fish (seal prey)	3.95	12.9	1.4	1999	False Creek	*1*
Misc. demersal fish (bird prey)	3.89	12.9	1.4	1999	False Creek	*1*
Hake	3.57					
Dogfish muscle	4.34	11.0	0.9	1999	False Creek	*1*
Dogfish liver	"	15.8	0.6	1999	False Creek	*1*
Dogfish embryo	"	16.8	1.4	1999	False Creek	*1*
Pollock	3.60					
Leuroglossus	3.49					
English sole	4.87	13.9	0.9	1993; 1999	SoG; False Creek	*1,2*
DC cormorant (adult)	4.89	17.5		1990	Gulf of Alaska	*3*
Great blue heron (adult)	4.89					
Seals (adult)	4.65	17.9	1.8	1995; 1996	Gulf of Alaska	*4*
Seals (juvenile)	4.65					

1 = Mackintosh *et al.* , 2004
2 = Parsons & Lee Chen, 1995
3 = Hobson *et al.* , 1994
4 = Hirons *et al.* , 2001

6.2 Seal and Bird k_M Values

Table 6-4 Estimated seal and bird k_M values

		Cormorant k_M	Heron k_M	Seal k_M
	Units -->	d^{-1}	d^{-1}	d^{-1}
PCB	**8**	-	-	2.25E-02
Congener	**15**	-	-	2.95E-01
I	**18/30**	-	-	1.47E-02
I	**20/28/31**	3.50E-02	8.00E-03	2.29E-02
V	**37**	-	-	7.80E-01
	44/47/65	-	-	3.65E-03
	49/69	-	-	7.35E-03
	52	-	-	0.00E+00
	66	3.12E-02	1.00E-02	2.00E-01
	61/70/74/76	1.00E-03	0.00E+00	8.05E-03
	83/99	0.00E+00	0.00E+00	0.00E+00
	90/101/113	1.15E-01	9.43E-02	2.66E-03
	105	1.20E-02	4.90E-03	2.66E-02
	110/115	-	-	4.43E-02
	118	6.80E-03	8.50E-04	3.03E-02
	128/166	1.15E-02	2.68E-03	7.80E-03
	129/138/160/163	5.20E-03	1.89E-03	2.25E-03
	146	3.39E-03	3.70E-03	0.00E+00
	147/149	1.84E-01	9.70E-01	2.23E-02
	135/151/154	0.00E+00	0.00E+00	3.46E-03
	153/168	0.00E+00	0.00E+00	0.00E+00
	156/157	0.00E+00	-	6.38E-04
	170	3.00E-03	3.50E-04	0.00E+00
	177	-	-	9.59E-03
	180/193	0.00E+00	0.00E+00	0.00E+00
	183/185	8.00E-03	2.79E-03	0.00E+00
	187	4.40E-02	-	6.61E-04
	194	0.00E+00	0.00E+00	0.00E+00
	198/199	-	-	1.65E-04
	203	0.00E+00	0.00E+00	0.00E+00
	206	0.00E+00	0.00E+00	0.00E+00
	209	-	-	0.00E+00

Note: "-" indicates data was unavailable to estimate this k_M

6.3 Empirical Model Input Data

Table 6-5 Empirical sediment data used as model input (n = 3). Congener numbers in bold were included in the dataset provided by R. Macdonald; congener numbers in brackets are the co-eluting congeners assumed to be represented by the numbers in bold.

		SEDIMENT (n = 3)		
		Geometric mean	**Log Geomean**	**Geometric SD**
	Units -->	ng/g dw	ng/g dw	ng/g dw
PCB	**8**	0.04	-1.45	0.20
Congener	**15**	0.13	-0.90	0.21
I	**18** (30)	0.04	-1.40	0.07
I	**28/31** (20)	0.36	-0.45	0.05
V	**37**	0.12	-0.93	0.09
	44 (47/65)	0.22	-0.67	0.10
	49 (69)	0.19	-0.73	0.12
	52	0.20	-0.70	0.16
	66/70	0.52	-0.28	0.05
	74 (61/70/76)	0.13	-0.90	0.04
	99 (83)	0.17	-0.76	0.11
	101 (90/113)	0.28	-0.56	0.11
	105	0.17	-0.77	0.11
	110 (115)	0.32	-0.50	0.11
	118	0.44	-0.36	0.14
	128 (166)	0.11	-0.96	0.11
	138 (129/160/163)	0.54	-0.27	0.12
	146*	0.07	-1.13	na
	149 (147)	0.36	-0.44	0.15
	151 (135/154)	0.04	-1.39	0.28
	153 (168)	0.49	-0.31	0.11
	156 (157)	0.02	-1.61	0.05
	170	0.09	-1.02	0.25
	177	0.09	-1.02	0.16
	180 (193)	0.14	-0.87	0.09
	183 (185)	0.08	-1.09	na
	187	0.25	-0.60	0.08
	194	0.03	-1.54	na
	199 (198)	0.08	-1.11	na
	203	0.03	-1.53	na
	206	0.05	-1.31	na
	209	0.02	-1.66	na

na = not applicable

Reference: data supplied by Dr. Robie Macdonald

Year collected: 1997

* PCB 146 value estimated using Burrard Inlet data (MOE) supplied by the BC Ministry of Environment

Table 6-6 Empirical herring data used as model input (n = 2)

		HERRING (n = 2)		
		Geometric mean	**Log Geomean**	**Geometric SD**
	Units -->	ng/g ww	ng/g dw	ng/g ww
PCB	**8**	9.68E-03	-2.01	6.34E-04
Congener	**15**	2.19E-03	-2.66	4.34E-02
I	**18/30**	4.22E-02	-1.37	2.84E-02
I	**20/28/31**	3.96E-01	-0.40	2.40E-02
V	**37**	9.53E-04	-3.02	1.26E-02
	44/47/65	4.87E-01	-0.31	8.18E-02
	49/69	2.29E-01	-0.64	2.68E-03
	52	7.10E-01	-0.15	5.49E-02
	66	3.92E-01	-0.41	1.96E-02
	61/70/74/76	8.38E-01	-0.08	1.28E-02
	83/99	1.34E+00	0.13	1.39E-01
	90/101/113	1.77E+00	0.25	1.34E-01
	105	5.41E-01	-0.27	8.60E-02
	110/115	1.43E+00	0.16	1.55E-01
	118	1.43E+00	0.15	9.64E-02
	128/166	3.35E-01	-0.48	9.42E-02
	129/138/160/163	2.82E+00	0.45	1.10E-01
	146	5.80E-01	-0.24	1.18E-01
	147/149	1.88E+00	0.27	1.43E-01
	135/151/154	7.69E-01	-0.11	1.61E-01
	153/168	3.30E+00	0.52	1.18E-01
	156/157	1.56E-01	-0.81	7.87E-02
	170	2.80E-01	-0.55	6.14E-02
	177	3.16E-01	-0.50	8.92E-02
	180/193	8.43E-01	-0.07	5.89E-02
	183/185	3.32E-01	-0.48	8.57E-02
	187	9.88E-01	-0.01	9.36E-02
	194	1.12E-01	-0.95	9.45E-02
	198/199	2.12E-01	-0.67	1.62E-01
	203	1.07E-01	-0.97	1.60E-01
	206	5.09E-02	-1.29	9.67E-02
	209	2.48E-02	-1.61	7.55E-02

Reference: data supplied by Dr. Jim West

Year collected: 2004

Table 6-7 Empirical salmon data used as model input (n = 3 for all salmon species)

PCB Congener	CHUM (n = 3)			COHO (n = 3)			CHINOOK (n = 3)		
	Geometric mean	Log Geomean	Geometric SD	Geometric mean	Log Geomean	Geometric SD	Geometric mean	Log Geomean	Geometric SD
Units -->	ng/g ww	ng/g dw	ng/g ww	ng/g ww	ng/g dw	ng/g ww	ng/g ww	ng/g dw	ng/g ww
8	2.18E-03	-2.66	5.39E-02	8.87E-03	-2.05	9.07E-02	8.01E-03	-2.10	1.86E-01
15	7.71E-04	-3.11	1.11E-01	1.50E-03	-2.82	9.78E-02	-	-	-
18/30	1.58E-02	-1.80	5.85E-02	3.74E-02	-1.43	1.17E-01	3.26E-02	-1.49	1.42E-01
20/28/31	7.65E-02	-1.12	7.65E-02	7.65E-02	-1.12	7.65E-02	7.65E-02	-1.12	7.65E-02
37	1.50E-03	-2.83	8.60E-02	1.90E-03	-2.72	1.36E-01	2.70E-03	-2.57	1.02E-02
44/47/65	5.12E-02	-1.29	5.12E-02	5.12E-02	-1.29	5.12E-02	5.12E-02	-1.29	5.12E-02
49/69	3.11E-02	-1.51	3.11E-02	3.11E-02	-1.51	3.11E-02	3.11E-02	-1.51	3.11E-02
52	8.53E-02	-1.07	3.82E-02	2.34E-01	-0.63	6.61E-02	4.17E-01	-0.38	1.32E-01
66	3.77E-02	-1.42	3.77E-02	3.77E-02	-1.42	3.77E-02	3.77E-02	-1.42	3.77E-02
61/70/74/76	3.77E-02	-1.42	3.77E-02	3.77E-02	-1.42	3.77E-02	3.77E-02	-1.42	3.77E-02
83/99	7.68E-02	-1.11	1.68E-02	2.18E-01	-0.66	7.74E-02	6.92E-01	-0.16	1.24E-01
90/101/113	1.20E-01	-0.92	1.30E-02	3.27E-01	-0.49	6.92E-02	9.73E-01	-0.01	1.31E-01
105	2.28E-02	-1.64	2.11E-02	6.51E-02	-1.19	1.04E-01	2.21E-01	-0.66	9.58E-02
110/115	5.88E-02	-1.23	5.88E-02	5.88E-02	-1.23	5.88E-02	5.88E-02	-1.23	5.88E-02
118	6.52E-02	-1.19	2.16E-02	1.94E-01	-0.71	8.01E-02	6.08E-01	-0.22	1.08E-01
128/166	1.38E-02	-1.86	1.38E-02	1.38E-02	-1.86	1.38E-02	1.38E-02	-1.86	1.38E-02
129/138/160/163	1.26E-01	-0.90	1.03E-02	3.14E-01	-0.50	8.64E-02	1.28E+00	0.11	1.08E-01
146	2.86E-02	-1.54	3.34E-02	7.48E-02	-1.13	8.74E-02	3.00E-01	-0.52	1.27E-01
147/149	1.05E-01	-0.98	3.66E-02	2.65E-01	-0.58	7.80E-02	8.48E-01	-0.07	1.10E-01
135/151/154	6.37E-02	-1.20	6.37E-02	6.37E-02	-1.20	6.37E-02	6.37E-02	-1.20	6.37E-02
153/168	1.57E-01	-0.80	3.15E-02	4.11E-01	-0.39	9.12E-02	1.57E+00	0.20	1.12E-01
156/157	4.09E-03	-2.39	4.09E-03	4.09E-03	-2.39	4.09E-03	4.09E-03	-2.39	4.09E-03
170	1.12E-02	-1.95	3.49E-02	1.46E-02	-1.84	1.09E-01	1.31E-01	-0.88	8.47E-02
177	1.32E-02	-1.88	2.58E-02	2.23E-02	-1.65	8.73E-02	1.45E-01	-0.84	1.09E-01
180/193	3.36E-02	-1.47	2.35E-02	5.47E-02	-1.26	9.70E-02	4.08E-01	-0.39	1.03E-01
183/185	1.47E-02	-1.83	3.52E-02	2.63E-02	-1.58	9.38E-02	1.64E-01	-0.78	1.10E-01
187	4.42E-02	-1.35	2.42E-02	8.00E-02	-1.10	1.11E-01	4.68E-01	-0.33	1.21E-01
194	3.41E-03	-2.47	3.58E-02	5.13E-03	-2.29	1.37E-01	5.66E-02	-1.25	2.79E-02
198/199	7.18E-03	-2.14	2.67E-02	9.94E-03	-2.00	1.35E-01	9.61E-02	-1.02	9.84E-02
203	3.38E-03	-2.47	4.71E-02	4.45E-03	-2.35	1.45E-01	5.15E-02	-1.29	8.88E-02
206	1.44E-03	-2.84	6.01E-02	2.34E-03	-2.63	1.54E-01	2.40E-02	-1.62	5.76E-02
209	9.18E-04	-3.04	8.08E-02	2.28E-03	-2.64	1.34E-01	1.30E-02	-1.89	7.68E-02

"-" = not available

Reference: data supplied by Dr. David O. Carpenter

Year collected: 2003

6.4 Model Parameter Values

Table 6-8 Values for PCB congener properties used in the model

PCB Congener	Molecular weight	LeBas molar volume	Log Kow fw @ 9.5°C	Log Kow fw @ 37.5°C	Log Koa @ 10.3°C	Log Koa @ 37.5°C
Units -->	g/mol	cm^3/mol	Unitless	Unitless	Unitless	Unitless
8	223.10	226.40	5.19	5.10	7.68	6.59
15	223.10	226.40	5.42	5.33	8.56	7.39
18 (30)	257.54	247.40	5.37	5.27	7.93	6.82
28/31 (20)	257.54	247.40	5.80	5.70	8.61	7.44
37	257.54	247.40	5.96	5.86	9.47	8.22
44 (47/65)	291.99	268.40	5.88	5.78	9.18	7.96
49 (69)	291.99	268.40	5.98	5.88	8.80	7.61
52	291.99	268.40	5.97	5.87	8.81	7.62
66/70	291.99	268.40	6.33	6.23	9.87	8.58
74 (61/70/76)	291.99	268.40	6.33	6.23	9.68	8.41
99 (83)	326.43	289.40	6.53	6.42	9.87	8.58
101 (90/113)	326.43	289.40	6.52	6.41	9.85	8.56
105	326.43	289.40	6.79	6.68	10.72	9.36
110 (115)	326.43	289.40	6.62	6.51	9.76	8.48
118	326.43	289.40	6.88	6.77	10.43	9.09
128 (166)	360.88	310.40	6.87	6.77	10.50	9.16
138 (129/160/163)	360.88	310.40	6.96	6.86	10.61	9.26
146	360.88	310.40	7.02	6.92	10.57	9.22
149 (147)	360.88	310.40	6.80	6.70	10.26	8.94
151 (135/154)	360.88	310.40	6.77	6.67	10.32	8.99
153 (168)	360.88	310.40	7.05	6.95	10.55	9.20
156 (157)	360.88	310.40	7.31	7.21	11.14	9.74
170	395.32	331.40	7.40	7.30	11.30	9.89
177	395.32	331.40	7.21	7.11	11.13	9.73
180 (193)	395.32	331.40	7.49	7.39	11.58	10.14
183 (185)	395.32	331.40	7.33	7.23	11.30	9.88
187	395.32	331.40	7.30	7.20	11.11	9.71
194	429.77	352.40	7.92	7.83	11.92	10.45
199 (198)	429.77	352.40	7.32	7.23	11.67	10.22
203	429.77	352.40	7.77	7.68	11.89	10.43
206	464.21	373.40	8.20	8.11	12.50	10.98
209	498.66	394.40	8.27	8.20	13.80	12.16

References
- Log Kow values derived from Li *et al.* , 2003
- Log Koa values derived from Chen *et al.* , 2003

Table 6-9 Environmental parameter definitions, values, and references

ENVIRONMENTAL PARAMETERS

Parameter	Symbol	Units	Mean	SD	n	Reference
Concentration of particulate OC* in water	*Xpoc*	kg/L	5.66E-07	4.71E-08	6	Estimated from Johannessen *et al.* , 2003
Concentration of dissolved OC in water	*Xdoc*	kg/L	1.32E-06	1.10E-07	6	Johannessen *et al.* , 2003
Concentration of suspended solids	Vss	kg/L	1.55E-05	1.57E-06	-	Estimated from Gobas and Arnot, 2005
Water temperature	Tw	°C	9.50E+00	1.50E+00	-	Estimated from Davenne and Masson, 2001
Air temperature	Ta	°C	1.03E+01	5.70E+00	12	Estimated from Environment Canada, 2005
Salinity	PSU	g/kg	3.00E+01	2.00E+00	-	Estimated from Fisheries and Oceans Canada, 2003
Density of OC in sediment	δ_{OCS}	kg/L	9.00E-01	-	-	Gobas and Arnot, 2005
OC content of sediment	OCS	-	2.69E-02	1.38E-02	6	Johannessen *et al.* , 2003
Dissolved oxygen concentration (90% saturation)	Cox	mg O_2/L	7.50E+00	1.00E+00	-	Estimated from Pawlowicz *et al.* , 2003
Setschenow proportionality constant	S_PC	L/cm^3	1.80E-03	-	-	Xie *et al.* , 1997
Ideal gas law constant (Rgaslaw)	RGL	K	8.31E+00	-	-	Universal constant
Absolute temperature	Tabs	K	2.73E+02	-	-	Universal constant
Molar concentration of seawater @ 35 ppt	MCS	mol/L	5.00E-01	-	-	Xie *et al.* , 1997
OC burial rate	OCBR	gC/cm^2/yr	1.10E-02	8.80E-03	6	Johannessen *et al.* , 2003
Primary production rate of OC	PPR	gC/cm^2/yr	5.52E-01	-	-	Pauly *et al.* , 1996

* OC = organic carbon

"-" = not available

Table 6-10 General biological parameter definitions, values, and references

GENERAL ORGANISM PARAMETERS

Parameter	Applicable Organisms	Symbol	Units	Mean	SD	n	Reference
NLOM – octanol proportionality constant	All	β	-	3.50E-02	-	-	Gobas *et al* ., 1999
Growth rate factor	Fish	GRF_F	-	7.00E-04	7.00E-05	-	Thomann *et al* ., 1992
Growth rate factor	Invertebrates	GRF_I	-	3.50E-04	3.50E-05	-	Thomann *et al.* , 1992
Particle scavenging efficiency	Filter feeding invertebrates	σ	-	1.00E+00	-	-	Default value
Metabolic transformation rate	Plants, invertebrates, & fish	k_{Mp}	d^{-1}	0.00E+00	-	-	Arnot and Gobas, 2004
Mean homeothermic temperature	Birds & seals	T_B	°C	3.75E+01	1.00E+00	-	Gobas and Arnot, 2005
Density of lipids	Birds & seals	δ_L	kg/L	9.00E-01	-	-	Gobas and Arnot, 2005
Ew constant A	Plants, invertebrates, & fish	E_WA	-	1.85E+00	1.30E-01	-	Arnot and Gobas, 2004
Dietary absorption efficiency of lipid	Zooplankton	ε_L	-	7.20E-01	-	-	Arnot and Gobas, 2004
Dietary absorption efficiency of NLOM	Zooplankton	ε_N	-	7.20E-01	-	-	Arnot and Gobas, 2004
Dietary absorption efficiency of lipid	Invertebrates (exc. zooplankton)	ε_L	-	7.50E-01	-	-	Arnot and Gobas, 2004
Dietary absorption efficiency of NLOM	Invertebrates (exc. zooplankton)	ε_N	-	7.50E-01	-	-	Arnot and Gobas, 2004
Dietary absorption efficiency of lipid	Fish	ε_L	-	9.00E-01	-	-	Arnot and Gobas, 2004; Kelly *et al.* , 2004
Dietary absorption efficiency of NLOM	Fish	ε_N	-	5.00E-01	-	-	Arnot and Gobas, 2004
Dietary absorption efficiency of water	Invertebrates & fish	ε_W	-	5.50E-01	-	-	Arnot and Gobas, 2004
Dietary absorption efficiency of lipid	Birds	ε_L	-	9.50E-01	-	-	Derived from Drouillard and Norstrom, 2000
Dietary absorption efficiency of lipid	Seals	ε_L	-	9.30E-01	-	-	Kelly *et al* , 2004; Trumble *et al.* , 2003; Muelbert *et al* ., 2003
Dietary absorption efficiency of NLOM	Birds & seals	ε_N	-	7.50E-01	-	-	Gobas and Arnot, 2005
Dietary absorption efficiency of water	Birds & seals	ε_W	-	8.50E-01	-	-	Gobas and Arnot, 2005
ED constant A	Invertebrates & fish	E_DA	-	8.50E-08	1.40E-08	-	Gobas and Arnot, 2005
ED constant B	Invertebrates & fish	E_DB	-	2.00E+00	6.00E-01	-	Gobas and Arnot, 2005
ED constant A	Birds	E_DA	-	3.00E-09	4.90E-10	-	Gobas and Arnot, 2005
ED constant B	Birds	E_DB	-	1.04E+00	2.00E-03	-	Gobas and Arnot, 2005
ED constant A	Seals	E_DA	-	1.00E-09	1.70E-10	-	Gobas and Arnot, 2005
ED constant B	Seals	E_DB	-	1.03E+00	1.25E-03	-	Gobas and Arnot, 2005
Lung uptake efficiency	Birds & seals	E_A	-	7.00E-01	-	-	Gobas and Arnot, 2005

"-" = not available

Table 6-11 Plant parameter definitions, values, and references

PHYTOPLANKTON

Parameter	Symbol	Units	Mean	SD	n	Reference
Lipid fraction in organism	v_{LB}	-	9.00E-04	2.00E-04	9	Mackintosh *et al.* , 2004
Non-lipid OC fraction in organism	v_{NB}	-	6.00E-04	2.00E-04	9	Mackintosh *et al.* , 2004
Water fraction in organism	v_{WB}	-	9.99E-01	-	-	Deduced
Growth rate constant	k_G	d^{-1}	1.25E-01	4.50E-02	-	Gobas & Arnot, 2005
Aqueous phase resistance constant	A_P	d^{-1}	6.00E-05	2.00E-05	-	Arnot & Gobas, 2004
Organic phase resistance constant	B_P	d^{-1}	5.50E+00	3.70E+00	-	Arnot & Gobas, 2004

KELP / SEAGRASS

Parameter	Symbol	Units	Mean	SD	n	Reference
Lipid fraction in organism	v_{LB}	-	8.00E-04	2.00E-04	9	Mackintosh *et al.* , 2004
Non-lipid OC fraction in organism	v_{NB}	-	6.20E-02	5.30E-02	9	Mackintosh *et al.* , 2004
Water fraction in organism	v_{WB}	-	9.37E-01	-	-	Deduced
Growth rate constant	k_G	d^{-1}	1.25E-01	4.50E-02	-	Gobas & Arnot, 2005
Aqueous phase resistance constant	A_P	d^{-1}	6.00E-05	2.00E-05	-	Arnot & Gobas, 2004
Organic phase resistance constant	B_P	d^{-1}	5.50E+00	3.70E+00	-	Arnot & Gobas, 2004

"-" = not available

Table 6-12 Invertebrate parameter definitions, values, and references

HERBIVOROUS ZOOPLANKTON

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	7.10E-08	-	-	Gobas and Arnot, 2005
Lipid fraction in biota	v_{LB}	-	3.96E-02	2.23E-01 *	12	Derived from Lee, 1974
NLOM fraction in biota	v_{NB}	-	1.46E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.14E-01	9.00E-03	-	Mauchline, 1998
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated

* Geometric mean and SD

NEOCALANUS PLUMCHRUS

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	4.54E-06	7.55E-02 *	10	Derived from Evanson *et al.* , 2000
Lipid fraction in biota	v_{LB}	-	1.22E-01	2.33E-02 *	10	Derived from Evanson *et al.* , 2000
NLOM fraction in biota	v_{NB}	-	6.36E-02	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.14E-01	9.00E-03	-	Mauchline, 1998
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated

* Geometric mean and SD

PSEUDOCALANUS MINUTUS

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	8.84E-08	2.13E-01 *	2	Derived from Huntley, 2004
Lipid fraction in biota	v_{LB}	-	3.96E-02	2.23E-01 *	12	Derived from Lee, 1974
NLOM fraction in biota	v_{NB}	-	1.46E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.14E-01	9.00E-03	-	Mauchline, 1998
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated

* Geometric mean and SD

SHELLFISH

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	8.06E-03	3.31E-01 *	10	Derived from Stout and Beezhold, 1981
Lipid fraction in biota	v_{LB}	-	1.20E-02	1.53E-01 *	11	Derived from Stout and Beezhold, 1981 and Mackintosh et al. 2004
NLOM fraction in biota	v_{NB}	-	1.88E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.00E-01	-	-	Estimated
Fraction of respiration involving pore water	m_P	-	2.00E-01	-	-	Estimated

* Geometric mean and SD

CRABS

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	5.37E-01	1.20E-01 *	7	Derived from Ikonomou *et al* ., 2004; Swain & Walton, 1994
Lipid fraction in biota	v_{LB}	-	3.00E-02	-	-	Stevenson, 2003
NLOM fraction in biota	v_{NB}	-	1.70E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.00E-01	-	-	Estimated
Fraction of respiration involving pore water	m_P	-	2.00E-01	-	-	Estimated

* Geometric mean and SD

GRAZING INVERTEBRATES

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	5.00E-02	- *	-	Estimated
Lipid fraction in biota	v_{LB}	-	1.50E-02	- *	-	Estimated
NLOM fraction in biota	v_{NB}	-	1.85E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.00E-01	-	-	Estimated
Fraction of respiration involving pore water	m_P	-	2.00E-01	-	-	Estimated

* Geometric mean and SD

CARNIVOROUS ZOOPLANKTON (AMPHIPODS)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	3.23E-07	6.50E-02 *	8	Derived from EPA, 1999
Lipid fraction in biota	v_{LB}	-	3.68E-02	1.92E-01 *	7	Derived from Lee, 1974; Sargent & Lee, 1975
NLOM fraction in biota	v_{NB}	-	1.33E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.30E-01	1.41E-02	2	Derived from Lee, 1974; Sargent & Lee, 1975
Fraction of respiration involving pore water	m_P	-	5.00E-02	-	-	Estimated

* Geometric mean and SD

EUPHAUSIA PACIFICA (KRILL)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	4.03E-05	1.83E-01 *	3	Derived from Huntley & Zhou, 2004; NMFS, 2005
Lipid fraction in biota	v_{LB}	-	1.59E-02	1.00E-02 *	3	Derived from Mauchline & Fischer, 1969
NLOM fraction in biota	v_{NB}	-	1.56E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.28E-01	3.80E-02	3	Derived from Mauchline & Fischer, 1969
Fraction of respiration involving pore water	m_P	-	5.00E-02	-	-	Estimated

* Geometric mean and SD

PREDATORY INVERTEBRATES

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	1.00E+00	- *	-	Estimated
Lipid fraction in biota	v_{LB}	-	2.00E-02	- *	-	Estimated
NLOM fraction in biota	v_{NB}	-	1.80E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	8.00E-01	-	-	Estimated
Fraction of respiration involving pore water	m_P	-	2.00E-01	-	-	Estimated

* Geometric mean and SD

Table 6-13 Fish parameter definitions, values, and references

SMALL PELAGIC FISH (SEAL PREY)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	4.49E-02	6.42E-01 *	4	Derived from Iverson *et al* ., 2002
Lipid fraction in biota	v_{LB}	-	3.86E-02	5.44E-01 *	4	Derived from Iverson *et al* ., 2002
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.61E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

* Geometric mean and SD

SMALL PELAGIC FISH (BIRD PREY)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	4.92E-03	3.63E-01 *	2	Derived from Butler, 1995; Iverson *et al* ., 2002
Lipid fraction in biota	v_{LB}	-	1.53E-02	4.85E-01 *	4	Derived from Harfenist *et al* ., 1995; Iverson *et al* ., 2002
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.85E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

* Geometric mean and SD

RIVER LAMPREY

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	1.43E-02	5.00E-03	-	Derived from Beamish, 1980
Lipid fraction in biota	v_{LB}	-	1.25E-01	3.00E-02	-	Derived from Larsen, 1980
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	6.75E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

MISCELLANEOUS DEMERSAL FISH (SEAL PREY)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	1.81E-01	4.13E-01 *	5	Estimated from Iverson *et al* ., 2002; Gobas & Arnot, 2005
Lipid fraction in biota	v_{LB}	-	2.51E-02	1.28E-01 *	5	Estimated from Iverson *et al* ., 2002; Gobas & Arnot, 2005
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.75E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	5.00E-02	-	-	Estimated from Froese & Pauly, 2002

* Geometric mean and SD

MISCELLANEOUS DEMERSAL FISH (BIRD PREY)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	4.72E-03	5.34E-01 *	3	Derived from Butler, 1995
Lipid fraction in biota	v_{LB}	-	1.63E-02	1.40E-01 *	2	Derived from Harfenist *et al* ., 1995
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.84E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	5.00E-02	-	-	Estimated from Froese & Pauly, 2002

* Geometric mean and SD

PACIFIC HAKE

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	3.74E-01	-	-	Derived from Saunders & McFarlane, 1999
Lipid fraction in biota	v_{LB}	-	5.20E-02	-	-	Stout and Beezhold, 1981
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.48E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

SPINY DOGFISH

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	2.00E+00	2.00E-01	9	Mackintosh *et al.* , 2004
Lipid fraction in biota	v_{LB}	-	1.00E-01	5.00E-02	9	Mackintosh *et al.* , 2004
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.00E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

POLLOCK

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	7.97E-02	1.19E-02	7	Derived from Iverson et al., 2002
Lipid fraction in biota	v_{LB}	-	2.16E-02	1.75E-01 *	36	Derived from Iverson et al., 2002
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.78E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

* Geometric mean and SD

NORTHERN SMOOTH-TONGUE

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	7.50E-04	-	-	Estimated from Froese & Pauly, 2002
Lipid fraction in biota	v_{LB}	-	4.99E-02	-	-	Estimated
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.50E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	0.00E+00	-	-	Estimated from Froese & Pauly, 2002

ENGLISH SOLE

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	7.40E-02	-	-	Mackintosh et al., 2004
Lipid fraction in biota	v_{LB}	-	4.00E-02	-	-	Stout and Beezhold, 1981
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.60E-01	-	-	Deduced
Fraction of respiration involving pore water	m_P	-	5.00E-02	-	-	Estimated from Froese & Pauly, 2002

Table 6-14 Double-crested Cormorant parameter definitions, values, and references

DOUBLE-CRESTED CORMORANT (ADULT MALE)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	2.50E+00	3.50E-01	-	Gobas & Arnot, 2005
Lipid fraction in biota	v_{LB}	-	7.50E-02	1.50E-02	-	Gobas & Arnot, 2005
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Gobas & Arnot, 2005
Water fraction in biota	v_{WB}	-	7.25E-01	-	-	Deduced
Rate of PCB loss via growth	k_G	d^{-1}	0.00E+00	-	-	Estimated
Activity Factor	AF	-	3.00E+00	-	-	Gobas & Arnot, 2005
G_D constant A	G_DA	-	3.00E-01	-	-	Gobas & Arnot, 2005

DOUBLE-CRESTED CORMORANT (ADULT FEMALE)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	2.40E+00	3.50E-01	-	Gobas & Arnot, 2005
Lipid fraction in biota	v_{LB}	-	7.50E-02	1.50E-02	-	Gobas & Arnot, 2005
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Gobas & Arnot, 2005
Water fraction in biota	v_{WB}	-	7.25E-01	-	-	Deduced
Rate of PCB loss via growth	k_G	d^{-1}	0.00E+00	-	-	Estimated
Activity Factor	AF	-	3.00E+00	-	-	Gobas & Arnot, 2005
G_D constant A	G_DA	-	3.00E-01	-	-	Gobas & Arnot, 2005

DOUBLE-CRESTED CORMORANT (EGG)

Parameter	Symbol	Units	Mean	SD	n	Reference
No. clutches per year	NCY	clut/yr	1.00E+00	-	-	Gobas & Arnot, 2005
No. eggs per clutch	NEC	eggs	4.00E+00	-	-	Gobas & Arnot, 2005
Wet weight of egg	W_E	kg	4.49E-02	-	-	Gobas & Arnot, 2005
Lipid content of egg	v_{LE}	-	4.62E-02	7.00E-02 *	7	Derived from Elliott *et al.* , 2005
NLOM content of egg	v_{NE}	-	1.15E-01	-	-	Deduced
Water content of egg	v_{WE}	-	8.39E-01	1.08E-03 *	3	Derived from Elliott *et al.* , 2005

Table 6-15 Great Blue Heron parameter definitions, values, and references

GREAT BLUE HERON (ADULT MALE)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	2.58E+00	2.99E-01	17	Dunning, 1993
Lipid fraction in biota	v_{LB}	-	7.50E-02	-	-	Estimated
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.25E-01	-	-	Deduced
Rate of PCB loss via growth	k_G	d^{-1}	0.00E+00	-	-	Estimated
Activity Factor	AF	-	3.00E+00	-	-	Estimated
G_D constant A	G_DA	-	3.00E-01	-	-	Gobas & Arnot, 2005

GREAT BLUE HERON (ADULT FEMALE)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	2.20E+00	3.37E-01	15	Dunning, 1993
Lipid fraction in biota	v_{LB}	-	7.50E-02	-	-	Estimated
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Estimated
Water fraction in biota	v_{WB}	-	7.25E-01	-	-	Deduced
Rate of PCB loss via growth	k_G	d^{-1}	0.00E+00	-	-	Estimated
Activity Factor	AF	-	3.00E+00	-	-	Estimated
G_D constant A	G_DA	-	3.00E-01	-	-	Gobas & Arnot, 2005

GREAT BLUE HERON (EGG)

Parameter	Symbol	Units	Mean	SD	n	Reference
No. clutches per year	NCY	clut/yr	1.00E+00	-	-	Butler, 1995
No. eggs per clutch	NEC	eggs	4.00E+00	-	-	Butler, 1995
Wet weight of egg	W_E	kg	7.10E-02	-	-	Heron Working Group, 2001
Lipid content of egg	v_{LE}	-	6.28E-02	3.01E-02 *	12	Derived from Elliott *et al.* , 2005
NLOM content of egg	v_{NE}	-	1.20E-01	-	-	Deduced
Water content of egg	v_{WE}	-	8.17E-01	3.56E-03 *	11	Derived from Elliott *et al.* , 2005

* Geometric mean and SD

Table 6-16 Harbour seal parameter definitions, values, and references

HARBOUR SEAL (ADULT MALE)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	8.70E+01	6.60E+00	-	Bigg, 1969
Lipid fraction in biota	v_{LB}	-	4.30E-01	-	-	Gobas & Arnot, 2005
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Gobas & Arnot, 2005
Water fraction in biota	v_{WB}	-	3.70E-01	-	-	Deduced
Rate of PCB loss via growth	k_G	d^{-1}	7.50E-05	-	-	Gobas & Arnot, 2005
Activity Factor	AF	-	2.50E+00	-	-	Gobas & Arnot, 2005
G_D constant A	G_DA	-	7.00E-02	-	-	Gobas & Arnot, 2005

HARBOUR SEAL (ADULT FEMALE)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	6.48E+01	4.40E+00	-	Bigg, 1969
Lipid fraction in biota	v_{LB}	-	1.50E-01	-	-	P. Ross, *personal communication*
NLOM fraction in biota	v_{NB}	-	2.00E-01	-	-	Gobas & Arnot, 2005
Water fraction in biota	v_{WB}	-	3.70E-01	-	-	Deduced
Rate of PCB loss via growth	k_G	d^{-1}	1.00E-05	-	-	Gobas & Arnot, 2005
Activity Factor	AF	-	2.50E+00	-	-	Gobas & Arnot, 2005
G_D constant A	G_DA	-	1.10E-01	-	-	Gobas & Arnot, 2005
Proportion of population reproducing	P_R	-	9.00E-01	-	-	P. Ross, *personal communication*
Weight of fetus	W_F	kg	1.12E+01	1.64E+00	28	Derived from Cottrell *et al.* , 2002
Lipid content of fetus	v_{LF}	-	1.10E-01	-	-	Gobas & Arnot, 2005
NLOM content of fetus	v_{NF}	-	2.00E-01	-	-	Gobas & Arnot, 2005
Water content of fetus	v_{WF}	-	6.90E-01	-	-	Deduced
Lipid content of milk	v_{LM}	-	4.93E-01	4.58E-02	5	Estimated from *Lang et al.* , 2005
NLOM content of milk	v_{NM}	-	1.17E-01	-	-	Deduced
Water content of milk	v_{WM}	-	3.90E-01	4.29E-02	5	Estimated from Lang *et al.* , 2005

HARBOUR SEAL (1-YEAR OLD)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	3.33E+01	2.86E+00	5	Muelbert *et al.* , 2003
Lipid fraction in biota	v_{LB}	-	1.16E-01	-	-	Muelbert *et al.* , 2003
NLOM fraction in biota	v_{NB}	-	2.46E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	6.38E-01	-	-	Muelbert *et al.* , 2003
Rate of PCB loss via growth	k_G	d^{-1}	1.00E-03	-	-	Gobas & Arnot, 2005
Activity Factor	AF	-	2.50E+00	-	-	Gobas & Arnot, 2005
G_D constant A	G_DA	-	8.00E-02	-	-	Gobas & Arnot, 2005

HARBOUR SEAL (PUP)

Parameter	Symbol	Units	Mean	SD	n	Reference
Wet weight of organism	W_B	kg	2.39E+01	5.66E+00	10	Data provided by PS Ross.
Lipid fraction in biota	v_{LB}	-	4.13E-01	-	-	Derived from Muelbert *et al.* , 2003
NLOM fraction in biota	v_{NB}	-	1.51E-01	-	-	Deduced
Water fraction in biota	v_{WB}	-	4.36E-01	-	-	Derived from Muelbert *et al.* , 2003
Rate of PCB loss via growth	k_G	d^{-1}	2.50E-02	-	-	Gobas & Arnot, 2005
Activity Factor	AF	-	1.50E+00	-	-	Gobas & Arnot, 2005
G_D constant A	G_DA	-	6.00E-02	-	-	Gobas & Arnot, 2005

6.5 Model Sensitivity Analysis

Model sensitivity analysis measures the sensitivity of model predictions to small changes in individual model parameter values. To test the sensitivity of the SoG bioaccumulation model to changes in the values of its parameters, I increased individual parameter values, one at a time, by 1%, ran the model, and compared the resulting BSAF for a given organism to that obtained using baseline parameters with the following equation:

$$S = (BSAF_O' - BSAF_O) / BSAF_O \qquad [58]$$

Where S (unitless) is the model sensitivity; $BSAF_O$' (ng/ng) is the BSAF for an organism calculated after one parameter value is increased by 1%; and $BSAF_O$ (ng/ng) is the BSAF for an organism calculated using baseline parameter values.

The results of the sensitivity analyses are presented in Figure 6-1 to Figure 6-4. Refer to the legend in Table 6-17 for figure definitions. Note that all parameters were included in the sensitivity analysis, but, for the sake of brevity, only those with sensitivity values greater than 0.002 or less than -0.002 are included in the figures below.

Table 6-17 Organism legend for sensitivity analysis figures

Symbol	Organism
I2	Neocalanus plumchrus
I7	Carnivorous zooplankton
F2	Small pelagic fish (seal prey)
F3	Small pelagic fish (bird prey)
F5	Miscellaneous demersal fish (seal prey)
F6	Miscellaneous demersal fish (bird prey)
F10	Pacific hake
B2	Cormorant (adult female)
B4	Heron (adult female)
S1	Seal (adult male)
S2	Seal (adult female)
S4	Seal (pup)

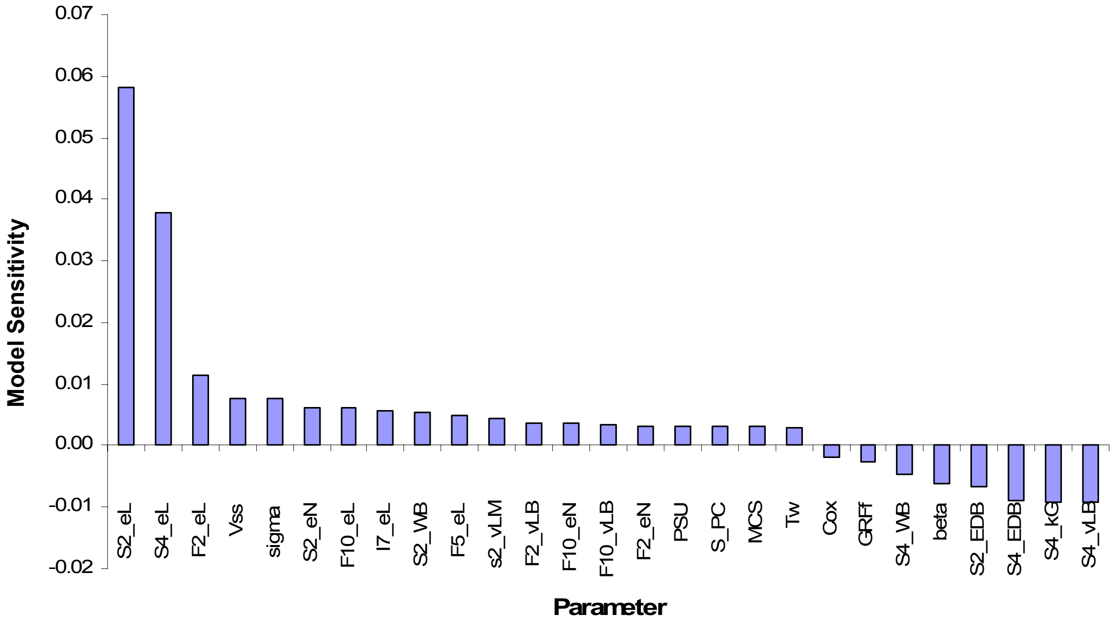

Figure 6-1 Results of sensitivity analysis for seal pups

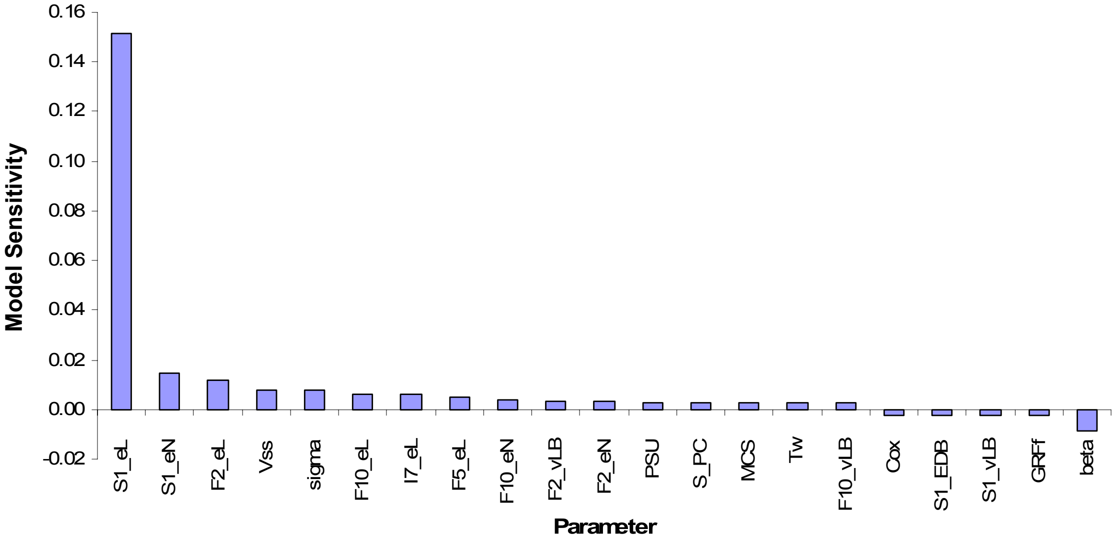

Figure 6-2 Results of sensitivity analysis for adult male seals

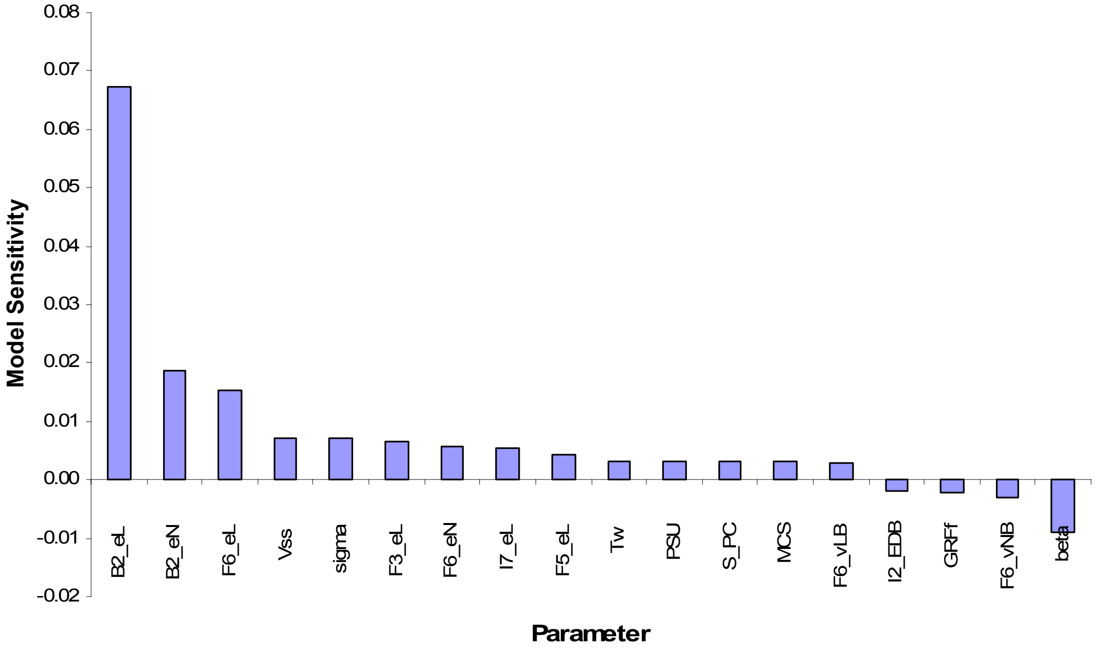

Figure 6-3 Results of sensitivity analysis for cormorant eggs

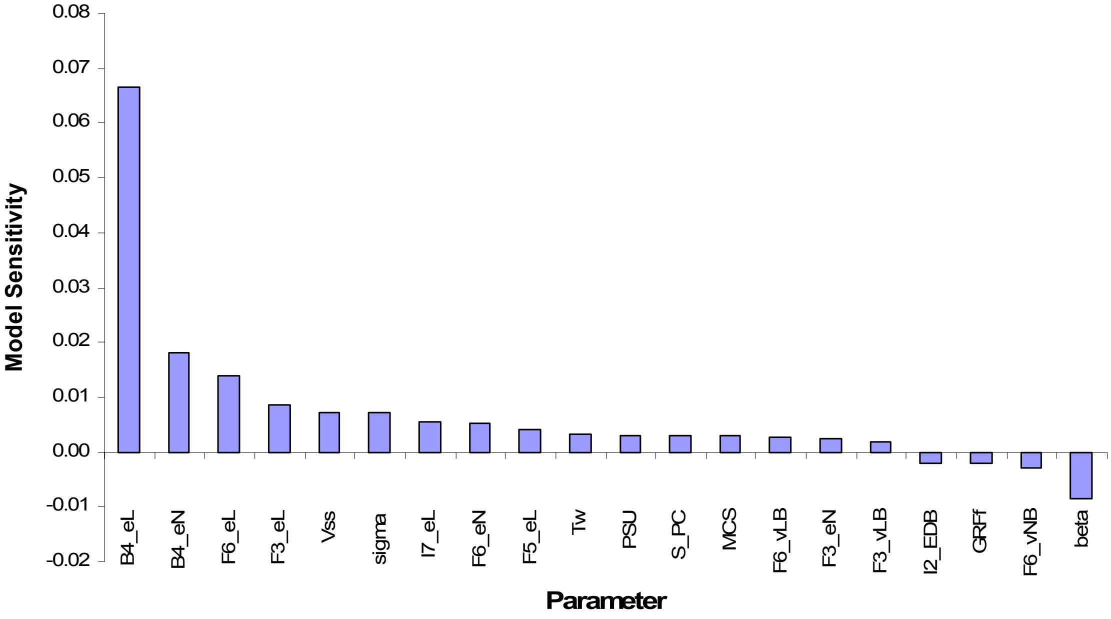

Figure 6-4 Results of sensitivity analysis for heron eggs

The results above indicate that the lipid digestive efficiency is by far the most influential of all the parameter values. For example, the three most influential parameters for seal pup concentration predictions are lipid digestive efficiencies of its mother, itself, and the small pelagic fish in its mother's diet. Other parameter values to which the model is most sensitive include the seal pup lipid content, seal pup k_G rate, and seal pup E_D constant B for seal pup concentration predictions; the seal NLOM digestive efficiency, concentration of suspended solids, and NLOM-octanol proportionality constant for adult male seal BSAF predictions; and the mother bird NLOM digestive efficiency, concentration of suspended solids, and invertebrate particle scavenging efficiency for bird egg BSAF predictions. Note that the findings of this sensitivity analysis agree with those conducted on a similar model developed for San Francisco Bay [Gobas & Arnot, 2005].

6.6 Model Performance Analysis Data

Table 6-18 Empirical bird data used to verify model predictions

		CORMORANT EGG (n = 19)			HERON EGG (n = 12)		
		Geometric mean	Log Geomean	Geometric SD	Geometric mean	Log Geomean	Geometric SD
	Units -->	ng/g lipid	ng/g lipid	ng/g lipid	ng/g lipid	ng/g lipid	ng/g lipid
PCB	**8**	-	-	-	-	-	-
Congener	**15**	-	-	-	-	-	-
I	**18/30**	-	-	-	-	-	-
I	**28**	2.96E+01	1.47	3.12E-01	4.25E+01	1.63	8.69E-01
V	**37**	-	-	-	-	-	-
	44	-	-	-	-	-	-
	49	-	-	-	-	-	-
	52	-	-	-	-	-	-
	66	1.71E+02	2.23	2.63E-01	2.21E+02	2.34	8.88E-01
	74	1.77E+02	2.25	2.91E-01	1.94E+02	2.29	8.45E-01
	99	6.42E+02	2.81	2.43E-01	5.74E+02	2.76	4.90E-01
	90/101	4.75E+01	1.68	2.77E-01	2.69E+01	1.43	7.09E-01
	105	2.77E+02	2.44	2.54E-01	2.57E+02	2.41	5.31E-01
	110	-	-	-	-	-	-
	118	1.05E+03	3.02	2.76E-01	1.22E+03	3.09	4.68E-01
	128	2.06E+02	2.31	1.78E-01	2.42E+02	2.38	4.25E-01
	129/138	1.67E+03	3.22	2.66E-01	1.49E+03	3.17	4.01E-01
	146	2.81E+02	2.45	2.16E-01	1.73E+02	2.24	5.76E-01
	149	6.95E+01	1.84	2.72E-01	6.17E+00	0.79	9.61E-01
	151	2.65E+02	2.42	2.68E-01	1.27E+03	3.10	4.63E-01
	153	2.55E+03	3.41	2.32E-01	1.95E+03	3.29	3.59E-01
	156	1.62E+02	2.21	2.24E-01	-	-	-
	170	3.80E+02	2.58	3.08E-01	3.72E+02	2.57	3.89E-01
	177	-	-	-	-	-	-
	180	9.15E+02	2.96	2.97E-01	8.53E+02	2.93	3.46E-01
	183/185	2.40E+02	2.38	2.81E-01	2.33E+02	2.37	3.70E-01
	187	2.37E+02	2.37	2.21E-01	-	-	-
	194	1.66E+02	2.22	3.26E-01	1.29E+02	2.11	4.12E-01
	198/199	-	-	-	-	-	-
	203/196	1.22E+02	2.09	2.58E-01	1.39E+02	2.14	3.75E-01
	206	4.31E+02	2.63	7.54E-01	4.99E+01	1.70	4.71E-01
	209	-	-	-	-	-	-

"-" = not available

Reference: data supplied by Dr. John Elliott

Years collected: Cormorant eggs = 1994 & 1995; Heron eggs = 1994 to 2000

Table 6-19 Empirical seal data used to verify model predictions

		ADULT FEMALE SEAL (n = 4)			SEAL PUP (n = 10)		
		Geometric mean	**Log Geomean**	**Geometric SD**	**Geometric mean**	**Log Geomean**	**Geometric SD**
	Units -->	ng/g lipid	ng/g lipid	ng/g lipid	ng/g lipid	ng/g lipid	ng/g lipid
PCB	**8**	1.90E-01	-0.72	1.03E-01	-	-	-
Congener	**15**	8.29E-02	-1.08	4.55E-02	1.32E+01	1.12	3.50E-01
I	**18/30**	5.28E-01	-0.28	1.67E-01	1.32E+01	1.12	3.07E-01
I	**20/28/31**	6.91E+00	0.84	9.56E-02	2.10E+01	1.32	2.29E-01
V	**37**	9.31E-02	-1.03	1.07E-01	9.62E+00	0.98	3.39E-01
	44/47/65	1.62E+01	1.21	1.53E-01	9.32E+00	0.97	2.07E-01
	49/69	1.12E+01	1.05	1.08E-01	1.52E+01	1.18	1.35E-01
	52	3.67E+01	1.56	1.65E-01	9.22E+01	1.96	1.93E-01
	66	4.24E+00	0.63	4.24E-02	1.80E+01	1.26	1.44E-01
	61/70/74/76	2.02E+01	1.30	1.31E-01	1.63E+01	1.21	2.01E-01
	83/99	1.12E+02	2.05	1.97E-01	1.64E+02	2.22	2.43E-01
	101/90/113	9.05E+01	1.96	1.68E-01	1.52E+02	2.18	1.65E-01
	105	2.06E+01	1.31	1.40E-01	2.94E+01	1.47	1.20E-01
	110/115	2.11E+01	1.32	5.94E-02	1.37E+01	1.14	1.02E-01
	118	5.09E+01	1.71	1.44E-01	6.63E+01	1.82	1.27E-01
	128/166	3.35E+01	1.52	2.09E-01	2.19E+01	1.34	1.73E-01
	129/138/160/163	3.04E+02	2.48	2.04E-01	4.44E+02	2.65	2.53E-01
	146	6.34E+01	1.80	2.09E-01	9.65E+01	1.98	2.73E-01
	147/149	5.35E+01	1.73	1.38E-01	1.16E+02	2.06	1.32E-01
	135/151/154	2.40E+01	1.38	1.58E-01	1.43E+01	1.16	1.16E-01
	153/168	3.96E+02	2.60	2.16E-01	6.02E+02	2.78	2.73E-01
	156/157	1.76E+01	1.25	2.03E-01	6.17E+00	0.79	1.74E-01
	170	7.26E+01	1.86	2.30E-01	3.09E+01	1.49	2.61E-01
	177	3.09E+01	1.49	1.47E-01	2.05E+01	1.31	2.13E-01
	180/193	2.11E+02	2.32	2.43E-01	1.02E+02	2.01	2.65E-01
	183/185	6.64E+01	1.82	2.30E-01	3.49E+01	1.54	2.45E-01
	187	1.78E+02	2.25	2.16E-01	1.20E+02	2.08	2.46E-01
	194	5.05E+01	1.70	2.76E-01	8.93E+00	0.95	2.64E-01
	198/199	5.68E+01	1.75	2.43E-01	4.11E-01	-0.39	2.39E-01
	203	4.13E+01	1.62	2.71E-01	1.51E+01	1.18	2.20E-01
	206	1.80E+01	1.26	3.13E-01	2.79E+00	0.45	2.60E-01
	209	5.48E+00	0.74	3.60E-01	1.03E+00	0.01	2.35E-01

"-" = not available

Reference: data supplied by Dr. Peter Ross

Year collected: 2001

6.7 CD Copy of the Model

Please find attached a CD containing an electronic copy of the food web bioaccumulation model for PCBs described in this document. Microsoft Excel software with enabled Visual Basic will be required to run the model. The file size is approximately 5 MB. Instructions for use of the model are located in the model's first worksheet.

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