Application of Probabilistic Risk Assessment: Evaluating Remedial Alternatives at the Portland Harbor Superfund Site, Portland, Oregon, USA

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EDITOR’S NOTE:
This is 1 of 5 articles generated from the Portland Harbor Sustainability Project (PHSP). The Portland Harbor Superfund Site is one of the “mega-sediment sites” in the United States, comprising about 10 miles of the Lower Willamette River, running through the heart of Portland, Oregon. The primary aim of the PHSP was to conduct a comprehensive sustainability assessment, integrating environmental, economic, and social considerations of a selection of the remedial alternatives laid out by the US Environmental Protection Agency. A range of tools was developed for this project to quantitatively address environmental, economic, and social costs and benefits based upon diverse stakeholder values. In parallel, a probabilistic risk assessment was carried out to evaluate the risk assumptions at the core of the remedial investigation and feasibility study process.

ABSTRACT
A probabilistic risk assessment (PRA) was performed to evaluate the range of potential baseline and postremedy health risks to fish consumers at the Portland Harbor Superfund Site (the “Site”). The analysis focused on risks of consuming fish resident to the Site containing polychlorinated biphenyls (PCBs), given that this exposure scenario and contaminant are the primary basis for US Environmental Protection Agency’s (USEPA’s) selected remedy per the January 2017 Record of Decision (ROD). The PRA used probability distributions fit to the same data sets used in the deterministic baseline human health risk assessment (BHHRA) as well as recent sediment and fish tissue data to evaluate the range and likelihood of current baseline cancer risks and noncancer hazards for anglers. Areas of elevated PCBs in sediment were identified on the basis of a geospatial evaluation of the surface sediment data, and the ranges of risks and hazards associated with pre- and postremedy conditions were calculated. The analysis showed that less active remediation (targeted to areas with the highest concentrations) compared to the remedial alternative selected by USEPA in the ROD can achieve USEPA’s interim risk management benchmarks (cancer risk of $10^{-4}$ and noncancer hazard index [HI] of 10) immediately postremediation for the vast majority of subsistence anglers that consume smallmouth bass (SMB) fillet tissue. In addition, the same targeted remedy achieves USEPA’s long-term benchmarks ($10^{-5}$ and HI of 1) for the majority of recreational anglers. Additional sediment remediation would result in negligible additional risk reduction due to the influence of background. The PRA approach applied here provides a simple but adaptive framework for analysis of risks and remedial options focused on variability in exposures. It can be updated and refined with new data to evaluate and reduce uncertainty, improve understanding of the Site and target populations, and foster informed remedial decision making. Integr Environ Assess Manag 2018;14:63–78. © 2017 The Authors. Integrated Environmental Assessment and Management published by Wiley Periodicals, Inc. on behalf of Society of Environmental Toxicology & Chemistry (SETAC)

Keywords: Probabilistic risk assessment Fish consumption Sediment Portland Harbor Superfund Site

INTRODUCTION
Risk assessment is a key tool in the evaluation of contaminated sites. Chemistry, toxicity, and exposure information are integrated using quantitative models to estimate the potential for human health and environmental impacts. Risk assessment is well suited to probabilistic
methods because the inherent variability and uncertainty in environmental data and the characteristics and behaviors of populations (human and ecological) are explicitly taken into account (USEPA 2001, 2014a). Probabilistic risk assessment (PRA) uses probability distributions that encompass the range of possible values of variables in a risk equation to quantify the probability of the full range of potential outcomes (USEPA 2001, 2004, 2014a). Thus, the cancer risk or noncancer hazard associated with a specific percentile (e.g., 50th, 95th percentile) of the population distribution is known.

Deterministic assessments, on the other hand, are more commonly used at contaminated sites but can be overly conservative when based on multiple high-end point values. The cumulative effect of combining multiple upper-bound assumptions can be implausible estimates of health risk that fall well above the 90th or 95th percentile of the distribution, although the degree of overestimation is unknown (Nichols and Zeckhauser 1986; Burmaster and Harris 1993; Cullen 1999). Several retrospective analyses of fish consumption and other exposures at Superfund sites have compared deterministic and probabilistic risk outcomes and shown the effect of “compounding conservatism” to be as much as 1 or more orders of magnitude (Keenan et al. 1996; Vissusi et al. 1997; Simon 1999; Wilson et al. 2001). When cleanup costs range upwards of billions of dollars, risk-based goals that are overly protective for all but a tiny fraction of a population and achieve marginal additional risk reduction for disproportionately higher net social, environmental, and economic costs, are neither sustainable nor consistent with the National Contingency Plan and guidance (USEPA 2002a, 2005, 2017a). Detailed analyses of the social, environmental, and economic impacts of the US Environmental Protection Agency’s (USEPA’s) remedial alternatives for the Portland Harbor Superfund Site (the “Site”), Portland, Oregon, USA, are discussed in companion articles of this series (Apitz et al. 2018 this issue; Harrison et al. 2018 this issue; McNally et al. 2018 this issue). Use of PRA is consistent with a tiered and iterative risk assessment approach that often begins with conservative assumptions and methods, and uses site-specific information and more refined analyses to reduce uncertainty and inform the decision process (USEPA 1991, 2001, 2004, 2014b; NAVFAC 2008; NRC 2009). In short, PRA is a valuable option in the risk assessment tool box because of “its ability to support the refinement and improvement of the information leading to decision making by incorporating known uncertainties” (USEPA 2014a). When coupled with spatial data analysis, PRA can be used to predict the range of probable postremedy risks and hazards achieved by remedial alternatives.

Since 2000, the Site has been the subject of a Remedial Investigation and Feasibility Study (RI/FS) under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA 1980) (USEPA 2016a, 2016b). The Site consists of approximately 10 miles (River Mile [RM] 1.9 to 11.8) of the Lower Willamette River (LWR) in Portland, Oregon. A deterministic baseline human health risk assessment (BHHRA) performed as part of the RI/FS found consumption of fish poses risks in excess of federal and state acceptable risk benchmarks (Kennedy/Jenks 2013a). In early 2017, USEPA released a Record of Decision (ROD) that identified a cleanup remedy for the Site, including remediation of sediment to contaminant levels that support subsistence-level consumption of resident fish or background concentrations if higher than risk-based goals (USEPA 2017b). The remedy includes 394 acres of active remediation, with an estimated duration of 13 years (y) and an estimated cost of US$1.1 billion (7% net present value) (USEPA 2017b). Consideration of uncertainty was largely qualitative and did not address risk reduction as a function of remediation area (and cost) or the significance of the more recent data with respect to natural recovery. The present paper fills a gap by using more recent Site data than were used in the RI/FS (post-2011) in conjunction with probabilistic and geospatial techniques to characterize current (preremed) and postremedy risk.

**METHODS**

As a complement to the sustainability evaluation of USEPA’s remedial alternatives analysis for the Site (see companion articles in this special series: Apitz et al. 2018 this issue; Harrison et al. 2018 this issue; McNally et al. 2018 this issue), the present article describes a PRA performed to estimate the probable distributions of human health risks from consuming Portland Harbor fish under both current and postremedy conditions.

The PRA was performed in accordance with USEPA Superfund guidance for human health risk assessments and standard practice for this type of analysis (USEPA 1989, 2001; Burmaster and Anderson 1994; Cullen and Frey 1999; Maddalena and McKone 2002). The analysis focused on human exposure to polychlorinated biphenyls (PCBs) via consumption of fish because these are the principal contaminant and exposure pathways driving Site risk and the primary basis for the selected remedy (USEPA 2016a, 2016b, 2017b). The deterministic BHHRA performed for the RI/FS evaluated 3 angler populations: tribal, subsistence, and recreational. This analysis focused on the subsistence angler because fish consumption by this receptor group drives the remedy for Portland Harbor. Using probability distributions for media concentrations and key exposure parameters, the ranges of current cancer risks and noncancer hazards were estimated on a site-wide basis and for smaller spatial scales. The risk results were used with a geospatial analysis to identify targeted sediment remediation areas that could achieve the same risks as USEPA’s selected remedy at Time 0 (immediately postremed). The percentiles of postremedy risk and hazard that correspond to USEPA’s interim and long-term risk management benchmarks were identified to evaluate the protectiveness of the targeted remedy.

**Probabilistic risk assessment approach**

A 1-dimensional probabilistic approach was used, whereby variability in parameters of exposure were evaluated using distributions that encompass the range of possible values instead of single point estimates for key parameters of...
exposure (USEPA 2001, 2014a). Except for updated sediment and fish tissue data sets, the PRA relied on the same data sources used to derive the exposure assumptions for the deterministic BHHRA to allow for comparison of the 2 sets of risk results. The calculation of intake from fish consumption was performed using the following equation (USEPA 1989):

\[
\text{Intake} = C_{\text{tiss}} \times \text{IR} \times \text{LHF} \times \text{FI} \times \left(1 - \text{Loss}\right) \times \text{AAF}_o \times \text{EF} \times \text{ED} \times \frac{\text{AT} \times \text{BW}}{\text{C} \quad \text{BW}},
\]

where \( \text{Intake} = \text{intake (mg/kg}^{-1} \cdot \text{d}^{-1}) \), \( C_{\text{tiss}} = \text{concentration in fish tissue (mg/kg)} \), \( \text{IR} = \text{fish ingestion rate (kg/d)} \), \( \text{LHF} = \text{life history factor (unitless)} \), \( \text{FI} = \text{fraction ingested from Site (unitless)} \), \( \text{Loss} = \text{preparation/cooking loss (unitless)} \), \( \text{AAF}_o = \text{absorption adjustment factor (oral bioavailability) (unitless)} \), \( \text{EF} = \text{exposure frequency (d/y)} \), \( \text{ED} = \text{exposure duration (y)} \), \( \text{BW} = \text{body weight (kg)} \), and \( \text{AT} = \text{averaging time (d)} \).

Both potential carcinogenic risks and noncarcinogenic hazards from exposure to PCBs were evaluated. Consistent with the RI/FS BHHRA, adults were the target age group for assessment of potential carcinogenic effects and young children were the target age group for assessment of noncarcinogenic effects.

Initially, probability distributions were fit to 2 of the key variables used to estimate fish consumption risk and hazard: 1) fish tissue concentration and 2) angler fish consumption rate. For the remaining exposure parameters identified in Equation 1, the point values used in the RI/FS BHHRA were also used in this “baseline” analysis, including the assumptions that 1) all fish consumed comes from the Site, 2) all cooking juices and fat are consumed, and 3) exposure occurs for 30 y.

These assumptions can also be represented by distributions that include the range of possible values. Therefore, a supplemental analysis was performed that included probability distributions for other exposure factors, including the realistic assumptions that fish is typically cooked and cooking juices and fat are not always consumed (USEPA 2000; Ruffle 2015), not everyone resides in the county for 30 y (Johnson and Capel 1992; Sedman et al. 1998; USEPA 2011), and not everyone weighs the same (Burnmaster and Crouch 1997; USEPA 2011). The supplemental analysis evaluated the impact of these additional probability distributions on risk outcomes.

Several variables were held constant, including the fish LHF, the FI, and the AAF_0; the default point estimates from the RI/FS BHHRA were used for these variables. The assumption that all of a smallmouth bass’ (SMB) lifetime is spent in the study area is consistent with it being considered a resident species (Friesen 2005). The assumption that all of the subsistence angler’s catch comes from the study area is likely to be an overestimate, but is assumed for simplicity and lack of site-specific data to support an alternate FI assumption. Although oral bioavailability likely varies across individuals, it is generally assumed that gastrointestinal absorption of ingested PCBs is the same as absorption in the dose–response studies, such that no adjustment is made (USEPA 1989). Table 1 presents the data sources for the exposure variables included in the PRA.

The commercial software @Risk Professional (Version 6.0) (Palisades 2012) was used to fit distributions and perform simulations. In general, the simplest probability model that adequately characterizes variability and is consistent with the underlying mechanism or pattern of the exposure variable was selected (USEPA 2001). In many cases, this was a lognormal distribution (e.g., concentration, consumption rate). Discrete distributions were used where the intervals and associated probabilities were sufficiently fine to provide a robust distribution and the parameters needed to fit a continuous distribution were not available (e.g., exposure duration).

**Summary of data used**

The data sets, distribution fits, input parameters, and select output statistics for the exposure variables included in the PRA are summarized in Table 1. The input data and output statistics for the full probability distributions are provided in Supplemental Data Tables 1 through 10.

**Fish tissue concentration.** Concentrations of PCBs in fish tissue were based on recent empirical and modeled data sets that were not available for inclusion in the RI/FS BHHRA. In 2012, 92 samples of whole body SMB were collected from the Site and the “near upriver” background reach located above the Site (RM 12 to 16) (Kennedy/Jenks 2013b). These data provide a direct measure of PCB concentrations in SMB tissue and were used to estimate current baseline risk. Fillet concentrations were estimated from the empirical whole body concentrations using a site-specific whole body to fillet ratio of 8.02 (USEPA 2016a, 2016b). Only SMB were included in the PRA due to the lack of recent tissue chemistry data on other resident or migratory species.

In order to explore the impact of sediment remedial alternatives on fish consumption risk, the relationship between sediment and fish tissue must be understood. A mechanistic food web model (FWM) based on the Amot and Gobas (2004) model was developed for the RI/FS that related concentrations of PCBs in SMB to concentrations in sediment and water (Windward 2015). Under current conditions, an estimated 90% of the PCBs in SMB tissue comes from sediment exposure (both direct exposure and dietary uptake) and 10% from surface water (Windward 2015). A regression indicates the model is linear over its domain, and the relationship between total PCBs in SMB tissue and sediment at the Site is described by the following equations (Wolf 2015b):

\[
C_{\text{whole body}} = 13.6 \times C_{\text{sed}} + 142.5, \quad (2)
\]

\[
C_{\text{fillet}} = 1.7 \times C_{\text{sed}} + 17.86, \quad (3)
\]

where \( C_{\text{whole body}} = \text{concentration in whole body tissue,} \)

\( C_{\text{sed}} = \text{concentration in sediment,} \)

\( C_{\text{fillet}} = \text{concentration in fillet tissue.} \)

Recent surface sediment data collected in 2013 to 2016 are available for the Site, the upriver background reach, and 3
Table 1. Exposure parameter data sources and probability distributions for subsistence angler*

| Parameter | Specification for PRA | Source | Distribution fit | Input parameters | Output statistics | RI/FS | Location of RME on distribution |
|-----------|-----------------------|--------|------------------|------------------|------------------|-------|--------------------------------|
| Fish consumption rate (g/d) | Adult subsistence angler | USEPA (2002b); Section 5.1.1.1, Table 4, per capita consumption of freshwater and estuarine finfish and shellfish, 18+ y | Lognormal (alternate) | 5th percentile = 7.5 50th percentile = 49 95th percentile = 142 | mean = 60 90th = 120 95th = 143 | 142 g/d | 95th percentile |
| | Alternate rate for adult subsistence angler | USEPA (2014c); Table E-1, total finfish and shellfish usual fish consumption, 21+ y | Lognormal (alternate) | 25th percentile = 7.6 50th percentile = 17.6 95th percentile = 68.1 | mean = 26 90th = 54 95th = 70 | 142 g/d | >99th percentile |
| | Child subsistence angler | BHHRA (Kennedy/Jenks 2013a) | Lognormal (alternate) | 42% of adult rates | mean = 25 90th = 48 95th = 60 | 60 g/d | 95th percentile |
| Body weight (kg) | Adult | USEPA’s EFH (2011); Overall male/female mean and SD for age groups 21–22 through 79–80 | Lognormal | $\mu = 80.30327$, $\sum = 19.99$ | mean = 80.3 90th = 107 95th = 117 | 70 kg | 33rd percentile |
| | Child | USEPA’s EFH (2011); Overall male/female mean and SD for age groups 0–1 through 5–6 | Uniform to combine lognormal distribution for each year of age | $\mu = 9.3$, $\sum = 1.5$ $\mu = 11.4$, $\sum = 1.8$ $\mu = 13.5$, $\sum = 2$ $\mu = 15.9$, $\sum = 2.2$ $\mu = 18.5$, $\sum = 3.3$ $\mu = 20.6$, $\sum = 4.9$ | mean = 14.8 90th = 20.8 95th = 23.2 | 15 kg | 56th percentile |
| Exposure duration (y) | Adult | USEPA’s EFH (2011); Johnson and Capel (1992), Table 3, cumulative percentiles for ROP of US population | Discrete | 1-y ROP for 0–75 y | mean = 12 90th = 26 95th = 33 | 30 y | 94th percentile |
| | Child | BHHRA (Kennedy/Jenks 2013a); USEPA (2014d) | Point estimate | 6 | NA | 6 y | NA |
| Cooking loss (unitless) | Loss of PCBs from fish tissue due to cooking | Ruffle (2015); 79 cooking loss estimates for PCBs in fish from 14 published studies | Gamma | $\mu = 19.1$, $\sum = 0.0373$ Min of 0 and Max of 0.74 | mean = 32 10th = 13 5th = 8.5 | Zero | 0 percentile |
| Fraction caught from study area (unitless) | Fraction ingested = 1 (all fish from study area) | BHHRA (Kennedy/Jenks 2013a) | Point estimates from RI/FS BHHRA used for PRA. |
| Life history factor (unitless) | LHF = 1 (lifetime of fish spent in study area) |
| Oral bioavailability (unitless) | $\text{AAF}_o = 1$ |

$\text{AAF}_o$ = absorption adjustment factor for oral exposure; BHHRA = baseline human health risk assessment; EFH = exposure factors handbook; LHF = life history factor; NA = not applicable; PRA = probabilistic risk assessment; RI/FS = remedial investigation/feasibility study; RME = reasonable maximum exposure; ROP = residential occupancy period; SD = standard deviation; USEPA = US Environmental Protection Agency.

*See Supplemental Data for additional details on input parameters and output distribution statistics.
subareas within the Site, RM 11 East (RM 11E), RM 5–6, and Swan Island Lagoon (GSI 2014; Kleinfelder 2015; Newfields 2015; Geosyntec 2016). The simplified equations were used to estimate PCB concentrations in SMB tissue from the surface sediment data sets. Comparison of the empirical SMB concentrations with tissue concentrations modeled from sediment support the model’s reliability for predicting PCB concentrations in SMB. The 2012 empirical site-wide mean concentration of PCBs in whole body SMB of 649 μg/kg is nearly the same as the whole body concentration of 663 μg/kg modeled from the site-wide PCB sediment surface weighted average concentration (SWAC) of 39 μg/kg (discussed in Geospatial analysis). Other model validation analyses support its appropriateness for predicting PCBs in SMB and evaluating fish consumption risk under postremedy conditions (Toll et al. 2015; Wolf 2015a, 2015b). The modeled SMB fillet concentrations were also used to estimate current baseline risk.

Fish tissue concentration was evaluated on a site-wide basis and a smaller spatial scale. The site-wide scale accounts for the fact that anglers may fish at multiple locations throughout the Site and is consistent with the scale used in the RI/FS BHHRA for the subsistence angler. A smaller spatial scale (2- to 3-mile segments) was also evaluated to account for spatial variability in fish and sediment concentrations and a potential SMB home range that may be smaller than the 10-mile Site (Scott and Crossman 1998; Friesen 2005). Probability distributions were fit to the empirical and modeled SMB PCB concentrations in each spatial domain (Table 2).

Fish consumption rate. The RI/FS BHHRA used a fish consumption rate of 142 g/d for the adult subsistence angler under the “reasonable maximum exposure” (RME) scenario. The rate is based on the 1994 to 1996 and 1998 US Department of Agriculture Continuing Survey of Food Intakes by Individuals (CSFII) (USDA/ARS 2000) and represents the 99th percentile of per capita consumption of uncooked freshwater and estuarine finfish and shellfish by the US population (USEPA 2002b). In 2014, USEPA published an updated analysis of fish intake by the US population (conducted from 2003 to 2010) that uses a more accurate method of extrapolating short-term survey data to long-term consumption rates (USEPA 2014c). The 2014 study provides means and percentiles for a variety of “usual fish consumption rates” based on species, demographics, and region of the country. To estimate high-end consumption for someone for whom self-caught fish contributes significantly to the overall diet, the usual fish consumption rates for “all finfish and shellfish” (USEPA 2014c) were used to develop an alternative probability distribution of fish consumption rates for the subsistence angler. Because the “all finfish and shellfish” group includes marine fish and shellfish species not present in the LWR, the upper percentiles of the distribution are expected to provide a very conservative estimate of subsistence consumption rates.

Both fish consumption survey data sets (USEPA 2002b, 2014c) were fit to lognormal probability distributions. Using the outdated survey data (USEPA 2002b), the mean and 95th percentile fish consumption rates for the subsistence angler are 60 and 143 g/day, respectively (Table 1). Using the updated survey data (USEPA 2014c), the mean and 95th percentile fish consumption rates are 26 and 70 g/d, respectively (Table 1). The 99th percentile of 111 g/d of all fish and shellfish is also below the 142 g/d rate used in the RI/FS BHHRA, suggesting this default overestimates consumption by anglers who may frequently eat fish from the Site. Consistent with the RI/FS BHHRA, the distribution of consumption rates for children was set to 42% of the adult rates. While the amount of fish consumed by children relative to adults varies, for simplicity, a fixed value was used in the present analysis.

Body weight. The supplemental PRA included a probability distribution for body weight, recognizing that not all individuals weigh the same. It was assumed that the body weights of anglers who may fish in the LWR for recreation or to supplement their diet are comparable to the general US population, and that national statistics for body weight are representative. Body weight is reasonably well represented by a lognormal distribution (Brainard and Burmaster 1992; Burmaster and Crouch 1997; Portier et al. 2007). Body weight data for the general US population were fit to lognormal distributions for adults and for young children 0 to 6 y of age using the average of males and females (USEPA 2011). Because child body weight changes annually, each year of child body weight data was fit to a lognormal distribution and integrated over the 6-y age group using a uniform distribution. The means of the distributions of body weight are 80 kg for adults and 15 kg for the young child, which are consistent with current default values (USEPA 2014d) (Table 1).

Cooking loss. Loss of hydrophobic chemicals upon cooking is a recognized phenomenon and can have a significant effect on exposure dose from fish consumption (Sherer and Price 1993; Wilson et al. 1998; Zabik and Zabik 1999; USEPA 2000). The supplemental PRA included loss of PCBs from fish tissue due to cooking. Fourteen studies representing a variety of cooking methods were identified in the literature, with estimates of mass loss of PCBs ranging from no loss up to 74% loss (Ruffle 2015; details on studies used are provided in Supplemental Data Tables 9a and 9b). The data were fit to a gamma distribution with a minimum of 0 and a maximum of 0.74 (74% loss). The mean and lower 5th percentile estimates of cooking loss (lower values represent less loss of contaminant and are more conservative) are 32% and 8.5%, respectively (Table 1).

Exposure duration. The supplemental PRA included a probability distribution for exposure duration, as represented by the number of years of eating fish from the Site. Residential occupancy period, or the number of years living in the same residence, can be used to estimate exposure duration in the absence of site-specific angler survey data. The RME default for time residing at the same location is 26 y (USEPA 2014d),
Table 2. Data sets and domains for PCB concentrations in smallmouth bass fillet tissue for baseline analysis

| Parameter | Domain for baseline analysis | Source | River miles represented | Nr of data points | Distribution fit | Input parameters (mg/kg) | Output statistics (mg/kg) |
|-----------|-----------------------------|--------|-------------------------|-------------------|-----------------|-------------------------|--------------------------|
| Empirical smallmouth bass tissue (mg/kg) | | | | | | | |
| Site-wide | | | 2–12 | 83 | Lognormal | $\mu = 0.057975$ $\sum = 0.095051$ RiskShift (0.010602) | mean = 0.069 90th = 0.141 95th = 0.208 |
| Segment 1 | | | 9–12 | 22 | Lognormal | $\mu = 0.23277$ $\sum = 0.88748$ RiskShift (0.015424) | mean = 0.248 90th = 0.509 95th = 0.916 |
| Segment 2 | 2012 SMB site-wide and near upriver background fish sampling (Kennedy/Jenks 2013b); fillet concentrations calculated using USEPA's | | 7.5–9 | 23 | Lognormal | $\mu = 0.031391$ $\sum = 0.024527$ RiskShift (0.0098099) | mean = 0.041 90th = 0.070 95th = 0.087 |
| Segment 3 | SMB whole body to fillet ratio: $C_{fillet} = C_{whole\ body}/8.02$ | | 5–7.5 | 19 | Lognormal | $\mu = 0.028058$ $\sum = 0.010303$ RiskShift (-0.00000311982) | mean = 0.028 90th = 0.042 95th = 0.047 |
| Segment 4 | | | 2–5 | 19 | Lognormal | $\mu = 0.040878$ $\sum = 0.055644$ RiskShift (0.015649) | mean = 0.057 90th = 0.106 95th = 0.146 |
| Near upriver background | | | 12–16 | 9 | Lognormal | $\mu = 0.027204$ $\sum = 0.028285$ RiskShift (0.0026503) | mean = 0.030 90th = 0.059 95th = 0.080 |
| Modeled smallmouth bass tissue (mg/kg) | | | | | | | |
| Site-wide | | | 2–12 | 96 | Lognormal | $\mu = 0.053288$ $\sum = 0.18157$ RiskShift (0.018775) | mean = 0.072 90th = 0.134 95th = 0.225 |
| Segment 1 | | | 9–12 | 25 | Lognormal | $\mu = 0.077841$ $\sum = 0.40013$ RiskShift (0.018386) | mean = 0.097 90th = 0.172 95th = 0.315 |
| Segment 2 | Modeled from site-wide and near upriver background surface sediment data (Kleinfelder 2015) using $C_{fillet} = 1.7 \times C_{sed} + 17.86$ | | 7.5–9 | 20 | Lognormal | $\mu = 0.15019$ $\sum = 0.57905$ RiskShift (0.018936) | mean = 0.169 90th = 0.336 95th = 0.599 |
| Segment 3 | | | 5–7.5 | 19 | Lognormal | $\mu = 0.080049$ $\sum = 1.083$ RiskShift (0.010602) | mean = 0.10 90th = 0.13 95th = 0.27 |
| Segment 4 | | | 2–5 | 32 | Lognormal | $\mu = 0.019332$ $\sum = 0.027896$ RiskShift (0.01834) | mean = 0.038 90th = 0.061 95th = 0.081 |
| Near upriver background | | | 12–16 | 27 | Pareto | $\mu = 3.7591$ $\sum = 0.019303$ | mean = 0.026 90th = 0.035 95th = 0.042 |
| RM 5–6 | Modeled from sediment data (Kleinfelder 2015 and NewFields 2015) using $C_{fillet} = 1.7 \times C_{sed} + 17.86$ | | 5–6 | 20 | Lognormal | $\mu = 0.010403$ $\sum = 0.026182$ RiskShift (0.017914) | mean = 0.028 90th = 0.041 95th = 0.057 |

(Continued)
and is based on an analysis of mobility and mortality data for the general US population from 0 to 90 y of age (Johnson and Capel 1992). Based on a comparison of national mobility and mortality data with that of Multnomah County, Oregon, USA, the use of national statistics is conservative for Multnomah County. The cumulative percentiles for residential occupancy are successively targeted for remediation.

Geospatial analysis

Evaluations of remedial alternatives rely on estimates of the sediment SWAC before and after remediation. A geospatial analysis was performed using the recent surface sediment data from the Site. The spatial interpolation estimated unknown values from sample points with known values using Thiessen polygons. Site-wide PCB SWACs were calculated as the sum of a series of products of normalized Thiessen polygon areas as a function of sample location and associated sediment concentrations. A site-wide SWAC of 39 μg/kg was calculated from the interpolated surface of the 2013 to 2016 sediment data (Figure 1). The interpolated surface was also used to evaluate SWAC reduction that could be achieved using an incremental “hill-topping” approach, in which areas of elevated concentration are successively targeted for remediation.

The current site-wide SWAC estimate of 39 μg/kg contrasts with the SWAC estimate in the ROD of 87 μg/kg, primarily due to USEPA’s reliance on older sediment data, some dating to 1997. The difference in SWAC estimates suggests that the system is undergoing natural recovery and that surface sediment concentrations are improving in many areas. The 2012 SMB tissue data provide another line of evidence of natural recovery. The site-wide mean concentration of PCBs in whole body SMB of 649 μg/kg in 2012 is about 40% lower than the site-wide mean of 1100 μg/kg for combined 2002 and 2007 whole body SMB, and the difference is statistically significant (Wolf 2015a, 2015b).

RESULTS AND DISCUSSION

With a probabilistic approach, the output of the risk assessment is a distribution of risks across the members of a population. Graphical depictions of the distribution include the probability density function (PDF), cumulative density function (CDF), and box plot format. The PDF is useful for showing the relative probability of values and the shape of the distribution (e.g., skewness and kurtosis), whereas the CDF is useful for identifying where specific percentiles (e.g., 50th, 90th) fall on the distribution. The box plot format is useful for illustrating the range of results and specific statistics of interest (e.g., median, 90th percentile).

Summary of baseline risks

Site-wide. Figure 2 illustrates the cumulative probability of site-wide baseline cancer risks for the subsistence angler who consumes SMB fillet tissue from the Site. For this analysis, probability distributions were used for fish tissue concentration (based on the 2012 empirical data) and fish consumption rate only; other exposure variables were set to the RI/FS BHHRA point estimates, including an adult body weight of 70 kg, 30 y of exposure, and no contaminant loss due to cooking. As shown in Figure 2, the 90th percentile corresponds to a risk of approximately 1 in 1000 (1 × 10⁻⁵), which is USEPA’s interim cancer risk target for the Site. When USEPA’s updated fish consumption rate distribution is used (USEPA 2014c), the 90th percentile site-wide risk is 4 × 10⁻⁵.

By comparison, the RME point estimate site-wide risk from the RI/FS BHHRA for the subsistence angler of 9 × 10⁻³ falls at the 99.9th percentile of the distribution. The RI/FS BHHRA assumed a mixed fish diet that included carp, and the PCB body burden in this species is generally higher than in SMB. Assuming a subsistence diet of only SMB fillet for direct comparison with the PRA results, the RME point estimate...
site-wide risk based on the RI/FS data set would be $9 \times 10^{-4}$, which still falls above the 99th percentile of the distribution (Figure 2). Such tails of the distribution are unstable and can vary substantially from 1 PRA simulation to the next. The findings suggest that the deterministic risk estimates presented in the RI/FS BHHRA represent only a tiny fraction of the population that may consume fish from the river. Table 3 presents the range and percentiles of site-wide baseline risks and hazards calculated using the empirical and modeled SMB tissue concentrations.

Figures 3a and 3b present distributions in box plot format of site-wide baseline risk and hazard for the adult and child subsistence angler, respectively, when distributions for body weight, exposure duration (adult only), and cooking loss are also included in the PRA. As shown, there is negligible change in risk or hazard when the distribution for body weight is added. When distributions for exposure duration and cooking loss are added, potential cancer risks for more than 95% of the population of adult subsistence anglers fall below $10^{-4}$. When the distribution for cooking loss is added, HI for 90% of the population of child subsistence anglers fall below USEPA’s interim target of 10 (see Supplemental Data Table 11 in for impact of additional distributions on baseline risk and hazard output). A sensitivity analysis of the 5 probability distributions included in the supplemental analysis indicates that fish consumption rate and fish tissue concentration have the greatest impact on risk outcomes. The use of updated SMB tissue data in lieu of the historical RI/FS SMB tissue data accounts for half of the change in risk.
In summary, by using more recent Site data and probability distributions for key exposure variables, the present analysis suggests that current site-wide risks and hazards for the vast majority of subsistence anglers meet USEPA's interim risk management targets for the Site. Although the recreational angler is not discussed here, a similar analysis performed for this receptor group revealed that the majority of recreational anglers meet USEPA's long-term risk targets of $1 \times 10^{-5}$ and HI of 1 (see Supplemental Data Table 12b).

**Background contributes significantly to Site risks.** When the concentration of PCBs in SMB tissue is modeled from USEPA's background surface sediment concentration of 9 µg/kg for the Site, background risks for the subsistence angler range from approximately $10^{-6}$ to $10^{-4}$ (cancer) and from approximately 0.1 to 10 (noncancer), with 90th percentile risk and hazard estimates of approximately $5 \times 10^{-5}$ and 5, respectively. Fish consumption risks and hazards associated with USEPA's background sediment concentration of 9 µg/kg fall within the range of current risks and hazards at the Site for the subsistence angler. As shown in Table 3, the background risk and hazard estimates for 80% of the subsistence angler population exceed the long-term risk management goals of $1 \times 10^{-5}$ and an HI of 1 identified for the Site (USEPA 2016b). Consequently, for frequent consumers of Lower Willamette River (LWR) fish, the long-term risk management goals established by USEPA for the Site will not be met regardless of the remedy selected because of ongoing background contributions, and fish consumption advisories will be required for the long term.

**Smaller spatial scales.** The baseline analysis also included an evaluation of risks and hazards after dividing the Site into smaller domains:

- Segment 1: RM 9 to 11.8
- Segment 2: RM 7.5 to 9
- Segment 3: RM 5 to 7.5
- Segment 4: RM 1.8 to 5
- Near upriver background: RM 12 to 18
- Subarea: RM 5–6
- Subarea: Swan Island Lagoon (SIL)
- Subarea: RM 11E.

The identification of these domains was based on prior analysis of the data (Wolf 2015a), the availability of recent

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**Table 3.** Range and percentiles of site-wide baseline and background cancer risks and hazards for subsistence angler

| Statistic | Adult subsistence angler cancer risks | Child subsistence angler noncancer hazards |
|-----------|-------------------------------------|-------------------------------------------|
|           | Source of smallmouth bass concentrations | Modeled from 2014 surface sediment data | Modeled from USEPA's background PCB sediment concentration of 9 µg/kg | Source of smallmouth bass concentrations | Modeled from 2014 surface sediment data | Modeled from USEPA's background PCB sediment concentration of 9 µg/kg |
|           | 2012 SMB empirical tissue data | Modeled from USEPA's background PCB sediment concentration of 9 µg/kg | | 2012 SMB empirical tissue data | Modeled from USEPA's background PCB sediment concentration of 9 µg/kg |
| Minimum   | 3E–09 | 1E–09 | 4E–09 | 0.001 | 0.002 | 0.0007 |
| Maximum   | 2E–03 | 4E–03 | 2E–04 | 211 | 663 | 22 |
| Mean      | 5E–05 | 5E–05 | 2E–05 | 6 | 6 | 3 |
| 1<sup>st</sup> | 1E–06 | 1E–06 | 1E–06 | 0.1 | 0.1 | 0.1 |
| 10<sup>th</sup> | 6E–06 | 6E–06 | 6E–06 | 0.7 | 0.7 | 0.7 |
| 20<sup>th</sup> | 1E–05<sup>b</sup> | 1E–05<sup>b</sup> | 1E–05<sup>b</sup> | 1<sup>b</sup> | 1<sup>b</sup> | 1<sup>b</sup> |
| 30<sup>th</sup> | 1E–05 | 1E–05 | 1E–05 | 2 | 2 | 2 |
| 40<sup>th</sup> | 2E–05 | 2E–05 | 2E–05 | 2 | 2 | 2 |
| 50<sup>th</sup> | 3E–05 | 2E–05 | 2E–05 | 3 | 3 | 2 |
| 60<sup>th</sup> | 3E–05 | 3E–05 | 2E–05 | 4 | 3 | 3 |
| 70<sup>th</sup> | 4E–05 | 4E–05 | 3E–05 | 5 | 5 | 3 |
| 80<sup>th</sup> | 7E–05 | 6E–05 | 4E–05 | 7 | 6 | 4 |
| 90<sup>th</sup> | 1E–04<sup>c</sup> | 1E–04<sup>c</sup> | 5E–05 | 12 | 12 | 5 |
| 95<sup>th</sup> | 2E–04 | 2E–04 | 6E–05 | 20 | 21 | 7 |
| 99<sup>th</sup> | 4E–04 | 5E–04 | 8E–05 | 45 | 60 | 10 |

BHHRA = baseline human health risk assessment; FS = feasibility study; HI = hazard index; PRA = probabilistic risk analysis; RI = remedial investigation; SMB = smallmouth bass; USEPA = US Environmental Protection Agency.

<sup>a</sup>Site-wide baseline risks and hazards calculated using probability distributions for tissue concentrations and fish consumption rate. Background risks and hazards calculated using probability distribution for fish consumption rate only.

<sup>b</sup>USEPA's long-term risk management targets ($10^{-5}$ and HI of 1).

<sup>c</sup>USEPA's interim risk management targets ($10^{-4}$ and HI of 1).
sediment data in the 3 subareas, as well as consideration of the home range of SMB. By evaluating risk on a smaller spatial scale, localized areas of greater variability and elevated concentrations can be identified. Fillet tissue concentrations were modeled from the available sediment data in each domain using the simplified sediment–fillet bioaccumulation equation and then fit to probability distributions. Figures 4a and 4b present box plots of subsistence angler risk and hazard, respectively, for each domain (see Supplemental Data Table 13 for baseline risk or hazard output distributions by domain). For the present analysis, probability distributions were used only for tissue concentration and fish consumption rate. As shown in Figures 4a and 4b, risks and hazards in SIL and RM 11E subareas are elevated relative to the Site as a whole and the respective segments where they are located. Many of the highest PCB tissue concentrations measured in the 2012 study were for SMB caught in these 2 subareas of the Site.

Targeted remedy evaluation

The subsistence angler is the focus of the targeted remedy evaluation because fish consumption by this receptor group drives the remedy for Portland Harbor. To evaluate the impact of remedy on risk, postremedy risks or hazards associated with a range of remedial action limits (RALs) and postremedy SWACs were calculated on a site-wide basis using an incremental hill-topping approach. For each scenario, SMB tissue concentrations were modeled from the postremedy SWAC using the simplified Equation 3. Figure 5 plots the postremedy site-wide PCB risk for incrementally larger remedial footprints (acres remediated). As shown, rapid risk reduction is achieved with removal of areas with the highest PCB concentrations.

Remediation (removal) of approximately 150 Thiessen polygon acres with the highest concentrations of PCBs (above a remedial action level of 200 μg/kg, including areas within and proximal to SIL and RM 11E, and a polygon with

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Figure 3. Site-wide risks and hazards calculated using empirical SMB fillet tissue data for subsistence angler: adult (a) and child (b). EPA = US Environmental Protection Agency; FS = feasibility study.
elevated PCB detection limits near RM 7W) has the largest impact on risk reduction and reduces the site-wide SWAC from 39 μg/kg to 14 μg/kg (64% reduction), assuming a bed replacement value equal to USEPA’s PCB background estimate of 9 μg/kg. In contrast, the ROD identified an active remediation area of nearly 400 constructed acres and an estimated 72% reduction in the PCB SWAC (87 μg/kg to 24 μg/kg) (USEPA 2017b). However, this estimate was based on the older sediment data set used in the RI/FS, and does not reflect the more recent data and current lower SWAC.

Postremedy SWACs in the 4 segments range from 12 to 15 μg/kg (Table 4). Using the simplified sediment–tissue bioaccumulation relationship, fillet tissue concentrations were modeled from the 2013 to 2016 sediment data in each domain (GSI 2014; Kleinfelder 2015; Newfields 2015; Geosyntec 2016) using the simplified bioaccumulation equation for PCBs in SMB: \( C_{\text{fillet}} = 1.7 \times C_{\text{sed}} + 17.86 \). \( C_{\text{fillet}} \) = concentration in fillet tissue; \( C_{\text{sed}} \) = concentration in sediment; EPA = US Environmental Protection Agency; FS = feasibility study; SMB = smallmouth bass.

Figure 4. Baseline risks and hazards were calculated using probability distributions for tissue concentration and consumption rate only for subsistence angler: adult (a) and child (b). Fillet tissue concentrations were modeled from the 2013 to 2016 sediment data in each domain (GSI 2014; Kleinfelder 2015; Newfields 2015; Geosyntec 2016) using the simplified bioaccumulation equation for PCBs in SMB: \( C_{\text{fillet}} = 1.7 \times C_{\text{sed}} + 17.86 \). \( C_{\text{fillet}} \) = concentration in fillet tissue; \( C_{\text{sed}} \) = concentration in sediment; EPA = US Environmental Protection Agency; FS = feasibility study; SMB = smallmouth bass.

Postremedy SWACs in the 4 segments range from 12 to 15 μg/kg (Table 4). Using the simplified sediment–tissue bioaccumulation relationship, fillet tissue concentrations were modeled from the pre- and postremedy SWACs for the Site and each segment (Table 4). The modeled tissue concentrations were fit to a lognormal distribution and combined with the fish consumption rate distribution to calculate pre- and postremedy risks and hazards. As shown in Figure 6, remediation of the targeted PCB areas (approximately 150 polygon acres) reduces cancer risks for the Site as a whole and in the RM 9 to 12 and RM 7.5 to 9 segments by approximately 50% (Figure 6). Postremedy (Time 0) risks achieve the FS interim targets of \( 10^{-4} \) (cancer risk) for approximately 99% of the population of adult subsistence anglers (Figure 6). Similar results are obtained for noncancer; the FS interim target of 10 for noncancer hazard is achieved for approximately 99% of the population of child subsistence anglers (see Supplemental Data Tables 14 and 15 for pre- and postremedy output distributions of risk and hazard). For the selected remedy in the ROD, USEPA’s site-wide postconstruction risk and hazard estimates for the subsistence angler are \( 1 \times 10^{-4} \) and 15, respectively (USEPA 2017b).

The distributions of site-wide and segment-specific postremedy risks and hazards are generally consistent with USEPA’s background sediment target of 9 μg/kg, and slightly higher than risks for PCBs in near upriver background sediment. Given the background levels, negligible additional risk reduction is achieved with increased remediation acreage (Figure 5). Reductions in site-wide SWACs and risk begin to plateau with removal of more than approximately

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DOI: 10.1002/ieam.1999 © 2017 The Authors
Table 4. Pre- and postremedy SWACs and modeled concentrations of PCBs in smallmouth bass fillet tissue

| Domain                                      | Average (µg/kg) | SD (µg/kg) | Modeled fillet concentration in SMB (µg/kg) | SD (µg/kg) |
|---------------------------------------------|-----------------|------------|--------------------------------------------|------------|
| Preremedy                                   |                 |            |                                            |            |
| Superfund site reach (RM 2–12)              | 39.03           | 3.29       | 84.21                                      | 23.45      |
| River segment 1 (RM 9–12)                   | 66.29           | 9.42       | 130.55                                     | 33.87      |
| River segment 2 (RM 7.5–9)                  | 54.46           | 7.8        | 110.44                                     | 31.12      |
| River segment 3 (RM 5–7.5)                  | 14.82           | 3.49       | 43.05                                      | 23.79      |
| River segment 4 (RM 2–5)                    | 11.73           | 2.78       | 37.80                                      | 22.59      |
| Near upriver background reach (RM 12–15)    | 2.49            | 0.47       | 22.09                                      | 18.66      |
| Postremedy                                  |                 |            |                                            |            |
| Superfund site reach (RM 2–12)              | 14.10           | 1.16       | 41.83                                      | 19.83      |
| River segment 1 (RM 9–12)                   | 15.03           | 2.46       | 43.41                                      | 22.04      |
| River segment 2 (RM 7.5–9)                  | 13.90           | 2.04       | 41.49                                      | 21.33      |
| River segment 3 (RM 5–7.5)                  | 14.24           | 3.45       | 42.07                                      | 23.73      |
| River segment 4 (RM 2–5)                    | 11.73           | 2.78       | 37.80                                      | 22.59      |
| Near upriver background reach (RM 12–15)    | 2.49            | 0.47       | 22.09                                      | 18.66      |
| USEPA’s background concentration (point estimate) | 9               | —          | 33.16                                      | —          |

C<sub>fillet</sub> = concentration in fillet tissue; C<sub>sed</sub> = concentration in sediment; RM = river mile; SD = standard deviation; SMB = smallmouth bass; SWAC = surface weighted average concentration; USEPA = US Environmental Protection Agency.

*SWACs based on Thiessen polygons derived using available surface sediment data from 2013 to 2016. Postremedy scenario involves remediation of RM 11E area, part of Swan Island Lagoon, and Polygon 90 near RM 7W and replacement with 9 µg/kg. Tissue concentrations modeled using simplified bioaccumulation equation: C<sub>fillet</sub> = 1.7 × C<sub>sed</sub> + 17.86.

Figure 5. Risk reduction as a function of remediated acreage based on Thiessen polygon acres, which should not be viewed as equivalent to remedial cutlines or boundaries defined in remedial design. EPA = US Environmental Protection Agency.
150 polygon acres, such that disproportionately more acreage needs to be remediated to achieve additional small reductions in SWAC and risk. The PRA indicates that the majority of PCB risk reduction can be achieved with a targeted remedy that entails significantly less active remediation than USEPA’s selected alternative.

Uncertainty discussion

The present analysis focused on modeling variability in exposure parameters; however, there is also considerable uncertainty in estimating exposure, including predicting fish tissue concentrations from sediment (model and spatial uncertainty) and calculating SWACs (statistical uncertainty) (von Stackelberg, Burnistrov, Vorhees et al. 2002; von Stackelberg, Burmistrov, Linkov et al. 2002; Kern et al. 2009). A future area of work could consider how key elements of model and geospatial uncertainties affect the reliability of the estimated percentiles of risk. The present analysis focused solely on consumption of SMB due to the availability of recent and extensive data for this resident species and a validated sediment–SMB tissue relationship for the risk-driving contaminant PCBs. However, most anglers consume a variety of resident and migratory species, including salmon that spend only a part of their life in the study area. The results of the present analysis are expected to be conservative for the vast majority of LWR anglers who target salmon or a mix of species; however, with new fish tissue and sediment data, the analysis could be updated to evaluate a mix of species. The analysis could also be expanded to include tribal anglers. Last, while toxicity values are also a recognized source of variability and uncertainty in human health risk assessment, as recommended by guidance (USEPA 2001), probability distributions were not developed for these inputs; the same PCB toxicity values used in the deterministic BHHRA were used for the present analysis.

CONCLUSIONS

The findings of the present analysis, which utilized new data and a probabilistic approach, indicate that the earlier deterministic BHHRA overstated current baseline risks and hazards for the vast majority of anglers. The PRA results indicate that USEPA’s risk management targets are exceeded for only a very small fraction (less than 1%) of the population of subsistence anglers, as well as recreational anglers who may occasionally eat their catch. The PRA also indicates that a less aggressive remedial alternative than the selected remedy will achieve postremedy, site-wide risk comparable to USEPA’s postconstruction (Time 0) risk estimates for the vast majority of subsistence anglers. To achieve additional risk reduction will require disproportionately more remediation acreage. Remediation of targeted areas will achieve cancer risks and noncancer hazards that meet USEPA’s interim targets and provide protection for the vast majority of the angler populations that may consume fish from the LWR. Given regional background levels, none of the remedial alternatives will achieve USEPA’s long-term risk management goals, and continued fish consumption advisories will be necessary.

Risk assessment is an iterative (or tiered) process, and often involves the identification and filling of data gaps to develop a more refined understanding of the risk. The PRA presented here provides a framework for use in future analyses of Site risk and remedy evaluation and complements an adaptive management approach. The PRA can be updated and refined with new data focused on evaluating and reducing uncertainty and improving the overall understanding of the Site and target populations.
Acknowledgment—The authors acknowledge the financial support of ExxonMobil as well as helpful comments received from reviewers and the other members of the sustainability team—including Sabine E Apitz, Anne G Fitzpatrick, Amanda McNally, Sera Mirchandani, David Harrison, and Conor Coughlin. The views expressed in the paper and any conclusions are solely those of the authors and not necessarily those of any organization.

Data Accessibility—Data available upon request from the corresponding author Betsy Ruffle at Betsy.Ruffle@aecom.com.

SUPPLEMENTAL DATA
Supplemental Table 1. PCB concentrations in study area smallmouth bass probabilistic risk assessment for Portland Harbor Superfund Site
Supplemental Table 2. PCB concentrations in study area surface sediment (2014 data) and modeled concentrations in whole body and fillet smallmouth bass tissue
Supplemental Table 3a. River Mile 5 to 6 PCB concentrations in subarea surface sediment and modeled concentrations in whole body and fillet smallmouth bass tissue
Supplemental Table 3b. Swan Island Lagoon PCB concentrations in subarea surface sediment and modeled concentrations in whole body and fillet smallmouth bass tissue
Supplemental Table 3c. River Mile 11E PCB concentrations in subarea surface sediment and modeled concentrations in whole body and fillet smallmouth bass tissue
Supplemental Table 4. Smallmouth bass fillet fish tissue concentration percentiles (empirical tissue data) site-wide, segments, and near upriver background
Supplemental Table 5. Smallmouth bass fillet tissue concentration percentiles (modeled) site-wide, segments, and near upriver background
Supplemental Table 6. Smallmouth bass fillet tissue concentration percentiles (modeled) subareas
Supplemental Table 7. Percentiles for fish consumption rate probability distributions
Supplemental Table 8. Percentiles for adult and child body weight probability distributions
Supplemental Table 9a. Summary of PCB mass loss values from cooking loss studies
Supplemental Table 9b. Percentiles for cooking loss
Supplemental Table 10. Percentiles for exposure duration probability distribution (adult only)
Supplemental Table 11. Subsistence angler: Range of site-wide adult cancer risks and child noncancer hazard index impact of additional distributions based on empirical smallmouth bass fillet data
Supplemental Table 12a. Subsistence angler: Range and percentiles of baseline adult cancer risks and child noncancer hazard index based on empirical SMB fillet data for site-wide and segment domains
Supplemental Table 12b. Recreational angler: Range and percentiles of baseline adult cancer risks and child noncancer hazard index based on empirical SMB fillet data for site-wide and segment domains

Supplemental Table 13. Subsistence angler: Range of baseline adult cancer risks and child noncancer hazard index based on smallmouth bass fillet data modeled from sediment for all domains
Supplemental Table 14. Range and percentiles of PCB cancer risks for adult subsistence angler preremedy and postremedy conditions, site-wide and segment domains
Supplemental Table 15. Range and percentiles of PCB noncancer hazards for child subsistence angler preremedy and postremedy conditions, site-wide and segment domains

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