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Fish consumption and PCB-associated health risks in recreational fishermen on the James River, Virginia ☆

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Abstract

Consumption of sport-caught fish contaminated with high levels of polychlorinated biphenyls (PCBs) may pose human health risks. To obtain estimates of fish consumption and fishing behaviors in recreational fishermen in Virginia, on-site interviews ($n = 143$; 134 men and 9 women) were conducted at seven public boat landings along the James River. Using existing PCB concentration data from James River fish tissue samples collected from 1997, and 1999 to 2001, default and point estimates were calculated and Monte Carlo analyses conducted to estimate potential risks under different consumption scenarios. A mean of 55 fish meals/yr and 14 James River sport-caught fish (JRSCF) meals/yr were reported. Caucasians fished less often (mean of 58 d), consumed less fish (mean of 43 meals/yr) and had smaller portion sizes (mean of 11.7 oz) compared to other races combined (130 d; 82 meals/yr; and 15.6 oz). On average, respondents reported consuming 10 meals of James River catfish a year (5 kg/yr). Risk estimates produced from Monte Carlo analysis were consistently lower than the default and point estimates. Several individuals exceeded acceptable risk levels and the mean cancer and non-cancer risks among catfish consumers exceeded acceptable levels. Eighteen percent of individuals had no knowledge of fish advisories in Virginia and 4% of the subjects indicated they would consume fish under advisory. Based on reported consumption, a significant risk to recreational fishermen, as a result of consuming PCB-contaminated catfish, was found. Risks associated with consuming other species were within acceptable limits.

Keywords: Risk assessment; Polychlorinated biphenyl (PCB); Fish consumption; James River; Monte Carlo analysis

1. Introduction

Polychlorinated biphenyls (PCBs) comprise a group of 209 congeners known to be stable, viscous compounds with high solubility in oils and organic solvents of low polarity (ATSDR, 1993). They are known to bioaccumulate in body fat and biomagnify along food chains (DiPinto and Coull, 1997; Zaranko et al., 1997). Toxic effects observed in laboratory animals and wildlife include alterations of the liver (Klaunig et al., 1979; Ndayibagira and Spear, 1999), alterations in thyroid hormone balance (Gould et al., 1999; Kato et al., 1999), immunotoxicity (Regala et al., 2001), and developmental effects in the offspring of animals exposed to PCBs (Ness et al., 1993; Seo et al., 1995). Oral exposure to PCBs in humans has been associated with cardiovascular effects, mild liver effects and effects on the skin, such as abnormal pigmentation and acne (ATSDR, 2000). PCBs are transferred through the placenta (Jacobson et al., 1984) and breast milk (Patandin et al., 1997), and may affect the development of fetuses and young children (Fein et al., 1984; Jacobson et al., 1990; Huisman et al., 1995). The United States Environmental Protection Agency (USEPA) has classified all PCB congeners as Group B2, probable human carcinogens of medium carcinogenic hazard, due to a lack of convincing evidence

☆The human subjects' research protocol and questionnaire were reviewed and approved by the Virginia Commonwealth University Institutional Review Board (IRB) in August 2001.

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regarding the carcinogenic effects of PCBs in humans (IRIS, 2002).

During the late 1970s, high levels of the organochlorine insecticide chlordecone (Kepone) were measured in James River estuarine sediments and in resident and migratory aquatic biota. At that time, several additional organochlorine contaminants, including PCBs, DDT, DDE, and chlordane compounds were present in James River sediments in the vicinity of Hopewell, Virginia. Additional sampling on the Lower James River indicated that 35 out of 45 fish tissue samples showed PCB levels greater than the Virginia Department of Environmental Quality's (VDEQ) screening level (50 ppb), but only one of the samples exceeded the Virginia Department of Health's (VDH) advisory level (600 ppb) (VDEQ, unpublished data). Approximately 20 yr later, PCB, DDT, TBT, and metal concentrations were monitored in blue catfish collected in a 1997 James River study. PCB concentrations in fish tissue ($n = 54$ samples) ranged from 2.52 to 1699 μg/kg wet weight for all locations (Garman et al., 1998). Several individual samples from the James River in the vicinity of Hopewell were exceptionally high compared to values reported elsewhere for piscivorous freshwater fishes: 15 samples exceeded the VDH level of concern (600 ppb). As a result of unacceptable contaminant levels in fish tissues, the VDH issued fish consumption advisories for several species, including channel and flathead catfish, along the Staunton, Dan, Shenandoah, Levisa, and Potomac Rivers.

The most rapidly growing consumptive fishery of the tidal James River focuses on two non-indigenous catfishes, blue catfish (*Ictalurus furcatus*) and flathead catfish (*Pylodictus olivaris*), which have increased dramatically in abundance during recent years (Garman et al., 1998). Channel catfish were introduced in 1893 and 1894; flathead catfish from 1965 to 1977; and blue catfish in 1975. Because predators such as blue catfish and largemouth bass are known to feed at the top of the food chain (Marchettini et al., 2001) and they support a substantial recreational fishery in the tidal freshwater James River, further evaluation of the potential human health effects of local fish consumption is necessary. Human consumption of sport-caught fish represents a significant route of exposure to aquatic contaminants since freshwater fish are the principal link between contaminants in the aquatic environment and humans (Humphrey, 1987).

The primary objective of this work was to obtain estimates of fish consumption (total, sports-caught fish on James River, and catfish) and fishing behavior for recreational fisherman on the tidal freshwater James River, and to use those estimates, along with existing PCB fish tissue monitoring data, to generate estimates of human health risk.

2. Materials and methods

2.1. Interviewer administered questionnaire

The questionnaire and study procedures were designed and pretested in a small sample of the target population ($n = 5$); these individuals were asked to provide critical feedback on the wording of the questions, as well as the format and presentation of the questionnaire. The study approach and instruments were then modified to develop the final questionnaire. One interviewer was trained and conducted all interviews.

The sample population was drawn from people fishing along the tidal freshwater James River, from the Benjamin Harrison Bridge near Hopewell, Virginia, to the Annabel Lee, near downtown Richmond. Using a structured questionnaire, in person interviews of 143 recreational fishermen were conducted during September and October 2001 at seven boat landings along the James River in Virginia, USA. Six public boat accesses and one private ramp on the Lower James River were included, and the sampling strategy was designed using randomization methods similar to an access point creel survey. Interviews were conducted 3 d/week (two weekdays and 1 d on the weekend) from September 16 to October 29, 2001. Interview days were selected randomly, and the seven sites were divided into two routes, north and south of the river. The interviewer traveled each route every other sampling day, visiting each site an equal number of times. The interviewer remained at each site for approximately 2 h each sampling day and approached all fishermen observed within that time period, including bank and boat fishermen. Only four people out of 147 declined the interview, largely because they did not have time to participate. On average, the voluntary interviews took approximately 5–10 min to complete.

The questionnaire had four sections: (1) current fishing effort (how often, seasonal nature, recreation or food) and food preparation methods (raw, smoke grill, etc., skin, fresh or frozen); (2) current fish consumption; (3) past consumption; and (4) knowledge of and behavior related to health advisory warnings.

Current fish consumption included measures of total fish consumption, and more specifically fish, and catfish consumed from the James River. Responses were coded on a weekly, monthly or annual basis, and participants were asked to estimate portion sizes. When asked about portion size, all participants were told that an 8 oz portion of fish fillet was approximately the size of the interviewer's hand (including fingers, female) and that there are 16 oz in a pound. Participants were asked about household size, children under 10 yr of age, and pregnant or breastfeeding women in the household along with their age, gender, and race. As a final question, participants were asked to state their annual income. However, due to the sensitive nature of the question and refusal from most participants to answer, the question was removed after the first round of interviews.

2.2. PCB concentrations in fish tissues

Data used to estimate PCB concentrations in fish tissues were obtained from two sources: the VDEQ and results from a study conducted by the Center for Environmental Studies (CES; Virginia Commonwealth University), on the Tidal James River for the USEPA (Garman et al., 1998).

The VDEQ data included PCB concentrations for James River fish tissue samples ($n = 55$) collected from 1999 to 2001. The composite fillet samples were analyzed by fish species for multiple chemicals and heavy metals using guidelines set by the USEPA. The fish contamination data included information on spot, smallmouth and largemouth basses, striped bass, rock bass, sunfishes, catfish (blue, flathead, channel, and bullhead), croaker, perch, and 'other' fish (mummichogs, creek chubsuckers, and carp) and descriptive statistics (for length and PCB concentrations) for the nine most commonly consumed species are presented in Table 1.

Data from the CES study on catfish contamination levels in the James River near Hopewell, Virginia, included information for 54 individual fillet samples that were collected in 1997 at three James River locations between the confluence of the Appomattox River and Tar Bay (Garman et al., 1998). The CES data included wet and dry weights of total PCBs (see Table 1) and percent water and lipids. Information from the VDEQ catfish samples was not included in this analysis due to different sampling methodologies. Wet weight PCB concentrations were used in all

Table 1
Descriptive statistics for fish species used in risk assessment

Species	No. of samples (no. of fish in sample)	Length (cm)		Total PCBs (wet weight; ppb)				
		Min	Max	Mean	Median	Min	Max	S.D.
Catfish	54 (54)[a]	30	107	398	267	54	1699	367
Black crappie	2 (7, 5)[b]	31	33	28	28	24	32	6
Bluegill sunfish	8 (12, 10, 10, 10, 5, 7, 5, 10)[b]	14	23	22	13	5	52	19
Croaker	2 (7, 8)[b]	20	37	33	33	14	52	27
Largemouth bass	4 (5, 10, 5, 5)[b]	30	52	108	98	80	155	33
Smallmouth bass	2 (8, 4)[b]	20	49	24	24	11	37	18
Spot	3 (4, 4, 7)[b]	15	24	27	27	23	29	3
Striped bass	3 (5, 10, 5)[b]	38	63	237	195	175	341	91
White perch	3 (7, 8, 10)[b]	11	29	55	69	28	70	24

[a]Individual samples, data obtained from Center for Environmental Studies.
[b]Composite samples, number of fish in each composite sample in brackets, data obtained from Virginia Department of Environmental Quality.

calculations because this measure best represented the concentration in the fillet as consumed by humans, prior to preparation and cooking.

2.3. Risk assessment methodology

The risk assessment methods used in this study follow EPA's Risk Assessment Guidance for Superfund (USEPA, 1989). An increased lifetime cancer risk (ILCR) and non-cancer hazard quotient (HQ) were calculated for each individual based on several models (see Table 2), using default values, point estimates and Monte Carlo simulation. Models were developed using estimates of overall reported fish consumption, James River sports-caught fish (JRSCF) consumption and James River catfish (JRC) consumption.

Point estimate calculations were performed in Microsoft Excel. Crystal Ball 4.0 was used within Microsoft Excel to perform probabilistic risk assessment using Monte Carlo simulations. Chronic daily intake (CDI) was calculated using the following equation (USEPA, 1991):

$$\mathrm{CDI}\,(\mathrm{mg/kg\,d}) = \frac{C \times \mathrm{IR} \times \mathrm{FI} \times \mathrm{ED} \times \mathrm{EF}}{\mathrm{BW} \times \mathrm{AT}},$$

where C is the concentration of PCB in tissue (mg/kg), IR the ingestion rate (kg/d or kg/meal), FI the fraction ingested from contaminated source, ED the exposure duration (yr), EF the exposure frequency (d/yr or meals/yr), BW the body weight (kg), and AT is the averaging time (d).

Default values used in risk assessment calculations were as follows: BW = 70 kg-adult, IR = 0.054 kg/d, FI = 1, AT-cancer = 25,550 d (70 yr × 365 d/yr), AT-non-cancer = 10,950 d (30 yr × 365 d/yr), ED = 30 yr and EF = 350 d/yr (USEPA, 1991). The 95% lognormal upper confidence limits (UCLs) were used for the estimate of PCB concentrations in the top four most frequently consumed fish (excluding catfish) (0.145 ppm) and catfish (0.526 ppm) for the default and point estimate models. ProUCL version 2.1, issued by the USEPA, was used to obtain the estimate of the appropriate UCL. Body weight (BW) was not asked on the questionnaire, so the default average lifetime body weight for adults (70 kg) was used in all calculations.

A cancer slope factor is used to estimate an upper-bound probability of an individual developing cancer as a result of a lifetime exposure to a carcinogen. The USEPA (Integrated Risk Information System, IRIS) recommends using the upper-bound slope factor for exposures that are high risk and persistent, such as food chain exposure; therefore, ILCRs were calculated by multiplying the CDI by the cancer slope factor (CSF = $2\,\mathrm{mg/kg\,d^{-1}}$) for PCBs. To assess non-cancer risks for PCBs, we selected the oral reference dose (RfD) for Aroclor 1254 (2×10^{-5} mg/kg d) because PCB congeners that bioaccumulate in fish tend to resemble the more chlorinated mixtures such as 1254 (IRIS, 2002). When not using default values, the averaging time for non-cancer (AT-NC) was calculated by multiplying the exposure duration (years consuming James River sports-caught fish (JRSCF)) by 365 d/yr. The values for CSF, RfD and AT-cancer remained constant in all models. According to the USEPA, the acceptable risk range for ILCR is 1×10^{-6} to 1×10^{-4}, and an HQ greater that one indicates that adverse non-carcinogenic effects may occur.

Table 2
Ten models used in human health risk assessment

Model	Scenario
1	Default model based on overall James River fish consumption
2	Default model based on overall James River catfish consumption
3	Point estimate model based on overall James River fish consumption, including zero consumption ($N = 142$)
4	Point estimate model based on overall James River catfish consumption, including zero consumption ($N = 142$)
5	Point estimate model based on James River fish consumption among JRSCF consumers only, not including James River catfish consumption ($N = 86$)
6	Point estimate model based on James River fish consumption among JRC consumers only, including JRF + JRC consumption ($N = 62$)
7	MC simulation based on overall James River fish consumption, including zero consumption ($N = 142$)
8	MC simulation based on overall James River catfish consumption, including zero consumption ($N = 142$)
9	MC simulation based on James River fish consumption among JRSCF consumers only, not including James River catfish consumption ($N = 86$)
10	MC simulation based on James River fish consumption among JRC consumers only, including JRF + JRC consumption ($N = 62$)

MC: Monte Carlo, JRF: James River fish (excluding catfish), JRC: James River catfish, JRSCF: James River sports-caught catfish.

In Table 2, the 10 models used in the risk assessment are presented. Models 1 and 2 utilized default values and the 95% lognormal UCL of the mean PCB concentrations to generate risk estimates based on overall consumption. Models 3 through 6 included reported values from each individual; however, the value for FI in Models 5 and 6 equaled one because the models were specific for consumption of James River fish. Models 7 through 10 were entered into Crystal Ball for Monte Carlo simulation. Assumption variables for the Monte Carlo analysis included

Table 3
Parameter inputs for Monte Carlo simulation models

Model	Parameter	Distribution	Mean	S.D.	Min	Max
7	EF (meals/yr)	Lognormal	54.99	54.74	0	365
	ED (yr)	Lognormal	13.17	17.58	0	71
	IR (kg/meal)	Lognormal	0.362	0.200	0	0.907
	FI	Triangular	0.22	0.32	0	1.00
	C_{JRF} (mg/kg)	Lognormal	0.046	0.066	0.070	0.306
8	EF (meals/yr)	Lognormal	10.12	23.60	0	156
	ED (yr)	Lognormal	13.17	17.58	0	71
	IR (kg/meal)	Lognormal	0.183	0.241	0	0.907
	FI	Triangular	0.22	0.32	0	1.00
	C_{JRC} (mg/kg)	Lognormal	0.398	0.367	0.054	1.699
9	EF_{JRF} (meals/yr)	Lognormal	5.23	16.17	0	112
	ED (yr)	Lognormal	21.01	18.25	0	71
	IR (kg/meal)	Lognormal	0.410	0.187	0.113	0.907
	C_{JRF} (mg/kg)	Lognormal	0.046	0.066	0.070	0.306
10	EF_{JRF} (meals/yr)	Lognormal	5.23	16.17	0	112
	EF_{JRC} (meals/yr)	Lognormal	23.20	31.42	0.25	156
	ED (yr)	Lognormal	21.30	18.11	0	71
	IR_{JRF} (kg/meal)	Lognormal	0.410	0.187	0.113	0.907
	IR_{JRC} (kg/meal)	Lognormal	0.409	0.192	0	0.907
	C_{JRF} (mg/kg)	Lognormal	0.046	0.066	0.070	0.306
	C_{JRC} (mg/kg)	Lognormal	0.398	0.367	0.054	1.699

JRF, James River fish (excluding catfish); JRC, James River catfish.

PCB concentration, portion size, ingestion rate, fraction ingested, exposure duration and exposure frequency (see Table 3). The distribution of most variables was found to be lognormal; however, a triangular distribution was used for fraction ingested (FI) because the minimum and maximum were fixed and values could not be less than zero or greater than 1.00. Forecast variables included IR, CDI, ILCR, and HQ. Models 5 and 9 represent fishermen who reported consuming fish from the James River, but did not report catfish consumption. Models 6 and 10 represent fishermen who reported eating both "other fish" and catfish from the James River; therefore, the intake equations in these models include exposure frequency and portion size for both categories of fish. Sensitivity analysis was conducted to determine which assumption variables were important contributors to the variance in the forecast variables. Each simulation was run with 10,000 trials at a 95% confidence level.

2.4. Statistical analysis

The questionnaire data were entered into Microsoft Excel 97 and imported into SAS version 8.0 for analysis. Normality plots were evaluated and when appropriate, continuous variables were natural log-transformed. Pre-planned comparisons were made between study participant characteristics and fish consumption data. The SAS procedure General Linear Models (GLM) was used for analysis of variance, and following a significant *F*-test, Tukey's test for multiple comparisons was used to evaluate mean differences between groups. Relationships between continuous variables were assessed using Pearson's correlation coefficient and associations between categorical variables were evaluated using χ^2 analyses. Multiple regression procedures were used to examine the significance of the independent variables (race, age, gender, perception, knowledge, etc.) in relation to the dependent variables that were important from a risk perspective (years consuming JRSCF, portion size and annual fish and JR catfish consumption). Backwards and stepwise selection techniques were used to evaluate which variables explained the most variation in annual fish and JR catfish consumption.

3. Results

3.1. Demographic information

Of the 143 participants surveyed, 94% were men, 70% were Caucasian and 28% were African American. The average age of the participants was 45 yr (range of 17–79) and 80% of the participants were age 55 or younger. Participants reported fishing an average of 80 d/yr on the James River. Twenty-five percent indicated that they fished seasonally, 72% fished year-round and 3% were fishing for the first time. Seasonal fishermen reported fishing most frequently during July, August, and September. Sixty-eight percent reported recreation as the primary reason for fishing, 29% reported fishing for recreation and food and 3% fished primarily for food.

The Caucasians sampled fished less often ($p = 0.015$), consumed smaller portion sizes ($p = 0.0024$) and had lower annual fish consumption ($p = 0.0003$) when compared to all other races combined. Due to small sample sizes, Hispanics and Asians were combined with African Americans for comparisons between groups. Caucasians fished an average of 58 d annually, less than half of the 130 d reported by other races. Caucasians reported eating an average of 43 fish meals/yr with an average portion size of 11.7 oz, while other races reported an average of 82 meals/yr and a 15.6 oz portion size.

At the Jordan Point Marina, fishermen had significantly higher ($p = 0.0006$) annual JRC consumption when compared to all other entry points. People that fished primarily for recreation reported significantly lower annual catfish consumption than those who also fished for food ($p = 0.001$). Gender was not significant in determining annual fish or catfish consumption, but only nine women were interviewed in the study.

3.2. Fish preparation and storage

Of the 131 fish consumers (92% of subjects) in the survey, 64% skinned the fish before eating, 24% did not skin fish, and 11% skinned only catfish. All consumers (100%) reported eating the fillet, but only 20% and 5% reported eating skin and fish broth, respectively. Only 3% of respondents froze fish for later use, while 41% usually ate fresh fish and 56% used both methods equally. Frying was the most popular method of cooking with 97 responses, while baking (42), broiling (33), and grilling (26) were also reported as common methods. Smoking, steaming, and blackening were less popular, and no one reported eating raw or boiled fish.

3.3. Fish consumption habits

Within the sample, 131 participants were fish consumers and 12 were non-consumers. Fishing behavior and consumption rates for the entire study population are shown in Table 4. Overall, participants reported eating an average of 55 fish meals/yr, of which approximately 14 meals came from the James River. Of consumers, 88 subjects reported eating JRSCF and 63 reported eating JRC in the last year. JRSCF consumers averaged 22 JRSCF meals/yr with a range of 0.24–216. JRC eaters consume an average of 22.6 JRC meals/yr and the average reported catfish portion size among JRC consumers was 14.4 oz. In Table 5, consumption patterns and other characteristics of JRSCF consumers and non-JRSCF consumers are presented. JRSCF consumers reported significantly higher annual fish consumption and portion size compared to fishermen who did not consume JRSCF; however, fishing effort was not significantly different between groups. Based on data from the 131 subjects, the following species were reported as the most frequently consumed fish from the James River (highest to lowest): catfish, striped bass, largemouth/smallmouth bass, perch, bluegill, rockfish, black crappie, croaker, and spot. Catfish were the most frequently consumed fish ($n = 97$, 74%), while the next most popular fish was the striped bass ($n = 28$, 21%). The self-reported average length of a catfish consumed was 18.4 in ($n = 57$), with a range of 10–36 in.

JRC consumers reported an average of two adults in the household consuming catfish from the James River and 32% reported sharing JRC with their families. Only 14 participants reported having children, under age 10, who consume JRC. Forty-five percent of all participants stated that their fish consumption habits had changed over the last 10 yr. Of the 65 people whose habits had changed, 48 had increased their fish consumption, while 16 had decreased. Two respondents reported pregnant or breast-feeding women in their household; however, they stated that the women did not consume JRSCF during these periods.

Table 4
Descriptive statistics for fishing behaviors and consumption variables for fishermen along the James River ($N = 142$)

	Means ± S.E.	Range
Annual fish consumption (meals/yr)	54.99 ± 4.58	0–365
Annual JRSCF consumption (meals/yr)	13.76 ± 2.38	0–216
Annual JRC consumption (meals/yr)	10.12 ± 1.98	0–156
Annual JR fishing effort (d/yr)	80 ± 8.20	1–365
Annual fish consumption (kg/yr)	24.11 ± 2.64	0–207
Annual JR catfish consumption (kg/yr)	5.05 ± 1.13	0–106
Percent of total fish consumed from JR	22.10 ± 2.71	0–100
Years eating JRSCF	13 ± 1.47	0–71
Fish portion size (oz)	12.85 ± 0.59	0–32
Catfish portion size (oz)	6.46 ± 0.71	0–32
Age	45 ± 1.10	17–79

JR, James River; JRSCF, James River sport-caught fish; JRC, James River catfish.

3.4. Risk perceptions

Eighty-two percent of the respondents reported general knowledge of fish consumption advisories in Virginia, while 18% had no advisory knowledge. The average age of people that reported knowledge of advisories was significantly higher than people that reported no knowledge of advisories ($p = 0.0420$). People with knowledge of advisories also consumed a significantly higher percent of catfish from the James River ($p = 0.0039$). No significant differences in portion sizes or annual fish consumption were found based on advisory knowledge. When asked if they would consume fish under an advisory, 91% answered no, 4% said yes and 5% said maybe. People who answered "yes" or "maybe" reported significantly higher catfish portion sizes ($p = 0.0015$) and annual catfish consumption ($p = 0.0009$) compared to those who answered "no." People that answered "yes" also had a significantly greater number of years consuming JRC ($p = 0.0047$). There was only a small correlation ($R^2 = 0.33$, $p < 0.0001$) between age and years consuming James River fish. Results of multiple regression analysis indicate that portion size, race and annual catfish consumption were significant predictors of annual fish consumption (meals/yr, model $R^2 = 0.40$), while percentage of fish consumed from James River, portion size and annual fish consumption were significant for predicting annual catfish consumption (meals/yr) ($R^2 = 0.88$).

3.5. Default and point estimate models

Default Models 1 and 2 generated ILCRs equal to 9.19×10^{-5} and 3.34×10^{-4} and HQs equal to 2.3 and 8.3, respectively. The ILCR for overall catfish consumption

Table 5
Consumption patterns among James River sport-fish consumers ($N = 86$) and non-sport fish consumers ($N = 62$)

	JR fish consumers		Non-JR fish-consumers		p
	Means ± S.E.	Range	Means ± S.E.	Range	
Portion size (oz)	14.4 ± 0.71	4–32	13.16 ± 0.73	0–24	0.0004
Annual JR fishing effort (d/yr)	83.18 ± 9.9	1–365	81.40 ± 17.58	1–365	NS
Annual fish consumption (meals/yr)	65.62 ± 5.92	4–365	48.56 ± 7.77	0–208	< 0.0001
Annual fish consumption (kg/yr)	29.68 ± 3.72	1.36–207	19.56 ± 3.79	0.34–106	< 0.0001
Age (yr)	46.00 ± 1.53	17–79	43.53 ± 1.75	24–76	NS

NS, not significant ($p > 0.05$); S.E., standard error.

Table 6
Risk estimates generated from Models 3 through 10

Model	Parameter	N	Mean	Median	Min	Max
3	ILCR	142	3.20E−05	6.46E−07	0.00E+00	**9.47E−04**
	HQ		**1.89E+00**	5.73E−02	0.00E+00	**3.48E+01**
4	ILCR	142	6.83E−05	0.00E+00	0.00E+00	**3.43E−03**
	HQ		**3.71E+00**	0.00E+00	0.00E+00	**1.09E+02**
5	ILCR	86	1.02E−05	1.68E−07	0.00E+00	**2.22E−04**
	HQ		6.54E−01	5.18E−02	0.00E+00	**8.03E+00**
6	ILCR	62	**2.13E−04**	3.84E−05	2.86E−07	**3.43E−03**
	HQ		**1.27E+01**	**5.64E+00**	9.25E−02	**1.09E+02**
7	ILCR	142	4.06E−06	8.70E−07	5.82E−10	**7.63E−04**
	HQ		6.24E−01	2.00E−01	1.43E−04	**4.79E+01**
8	ILCR	142	3.05E−06	3.79E−07	4.16E−11	**6.76E−04**
	HQ		4.67E−01	8.62E−02	3.20E−05	**6.92E+01**
9	ILCR	86	2.85E−06	4.25E−07	8.94E−11	**7.09E−04**
	HQ		2.28E−01	4.68E−02	3.80E−05	**5.68E+01**
10	ILCR	62	6.88E−05	2.68E−05	8.02E−08	**2.60E−03**
	HQ		**6.24E+00**	**2.97E+00**	2.05E−02	**1.97E+02**

Bold indicates value exceeds EPA acceptable risk level (ILCR = 1×10^{-4} and HQ = 1).

from the James River (Model 2) exceeds the acceptable risk range set by EPA, and both models exceed unity (HQ = 1). This risk level indicates that the increased probability of an individual developing cancer risk associated with consumption of JRC is approximately three additional cases of cancer for every 10,000 people exposed. Risk levels generated from the point estimate models (Models 3–6) are presented in Table 6. The mean HQs in Models 3, 4, and 6 exceeded 1 and the mean ILCR in Model 6 exceeded 1.00×10^{-4}. The median HQ for Model 6 and maximum ILCRs and HQs for all models exceeded acceptable levels. On an individual basis, 11 persons exceeded the acceptable ILCR range and 41 exceeded the acceptable HQ using Model 3; using Model 4, 11 persons exceeded the ILCR and 32 persons exceed the HQ; using Model 5, two persons exceeded ILCR and 17 exceeded the HQ; and Model 6 had 19 persons exceed ILCR and 48 persons exceed the HQ.

3.6. Monte Carlo simulation

The results of the Monte Carlo simulation models are presented in Table 6.

The mean and median ILCR and HQ exceeded acceptable levels in Model 10 and maximum ILCRs and HQs exceeded acceptable levels for all models. Monte Carlo analysis indicated that approximately 19% of JRC (Model 10) consumers in this study have non-cancer risks below 1 and Model 6 estimated that 23% of JRC consumers are below the acceptable HQ. Model 10 revealed that approximately 18% of JRC consumers have an ILCR above acceptable limits, while Model 6 estimated that 31% of JRC consumers exceed the acceptable ILCR range.

Sensitivity analysis revealed that exposure frequency (annual fish/catfish consumption) was the most important contributor to risk level variations in Monte Carlo Models 8 through 10, ranging from 43.7% in Model 10 to 52.3% in Model 9. In Model 7, the concentration of PCBs in fish contributed 33.2%, exposure duration 27.2% and exposure frequency 20.5%. In Model 10, annual JRC consumption contributed to 43.7% of the variation in risk, while JRF consumption contributed only 0.4%. The PCB concentration in catfish contributed 24.6%, while the PCB concentration in other James River fish accounted for only 0.2% of the variation in risk.

4. Discussion

This research represents the first attempt to quantify fish consumption habits among recreational fishermen on the tidal freshwater James River. In this study, we observed higher total fish consumption rates (66.05 g/d overall and 81.31 g/d among JRSCF consumers) than several other published studies, which may be a result of the close proximity to the Chesapeake Bay area. Burger et al. (1999) reported an average of 48 g/d among Savannah River fishermen, West et al. (1993) reported an average of 26.5 g/d in Michigan sport anglers, and Jacobs et al. (1998) reported 20 g/d in the general US population. We observed a mean of 14 JRSCF meals/yr, which is similar to 18 sport-caught fish (SCF) meals/yr reported by Fiore et al. (1989) and 12 SCF meals/yr by Kosatsky et al. (1999). Among JRSCF consumers, the number of JRSCF meals/yr averaged 22, which was approximately half the average reported by other studies (Fiore et al., 1989; Falk et al., 1999; Kosatsky et al., 1999). This is most likely because most studies have been conducted in the Great Lakes region, where sport-fishing is a much larger commodity than on the tidal freshwater James River. An average of 21 yr consuming JRSCF was similar to averages of 24, 26, and 33 yr reported in other studies (Cole et al., 1997; Burger et al., 1999; Falk et al., 1999) and of course this was reflective of the age of the sample. Because 80% of our participants were under the age of 55, the majority of the participants will likely continue to fish the James River for many more years.

A number of studies have found that females consume significantly less fish than males (Jacobs et al., 1998; Falk et al., 1999; Kearney et al., 1999; Burger, 2000); however, no association was observed between gender and fish consumption in this study. We lacked the statistical power to detect such an association due to the small number of females in the study group. In our study we did, however, find a relationship between race and fish consumption similar to that reported in a study by Burger et al. (1999), which found that African Americans consumed significantly more fish and larger portion sizes than Caucasians. Fishermen at Jordan Point reported higher catfish consumption, which was expected since the area around Hopewell and the Benjamin Harrison Bridge is known for producing more trophy blue catfish than any river in the state (James River Association, 2002).

We found that 82% of the study population had general knowledge of advisories, compared to 72% reported by Fiore et al. (1989) and 85% by Kearney et al. (1999). Because there was no advisory in effect at the time of the interviews, we could not obtain data on whether the population follows advisory recommendations; however, Kearney et al. (1999) found that only 20–38% followed advisories at least sometimes. Age was positively correlated with advisory knowledge most likely because older fishermen lived in the area during the 1970s Kepone incident that closed fishing on the James River for several years. Several participants mentioned Kepone during the interview and stated that they had not consumed fish from the James River since the ban was lifted. The correlation between age and knowledge of advisories was only moderate likely because several older fishermen had recently moved to the area.

In this study, we found that people with knowledge of advisories also consumed more JRC. This indicates that catfish consumers in the area may be more aware of contaminant problems related to the James River or other rivers since the majority (8 of 11) of advisories issued in Virginia at that time restricted catfish consumption. However, these participants also reported eating a higher percentage of catfish from the James River and larger portion sizes, which may indicate that many catfish consumers do not heed advisory warnings.

The accumulation of coplanar (non- and mono-ortho) PCB congeners in aquatic food webs is of special interest due to their dioxin-like toxicity. Several studies have observed a *chlorine shift*, a significantly higher proportion of highly chlorinated congeners, as PCBs move up the food chain (Willman et al., 1997; Feldman and Titus, 2001). Large predatory fish, such as blue catfish, contain higher PCB levels than smaller fish (Garman et al., 1998; Stow and Qian, 1998). Burger et al. (1998) found that fishermen on Barnegat Bay, New Jersey, had difficulty understanding the relationship between trophic levels and contaminant levels, but participants in this survey seem to have some understanding of the concept based on reported consumption habits. The majority of participants reported consuming small to medium-size catfish, and several stated that they either mount large trophy catfish or release them. Two participants from Jordan Point reported consumption of catfish weighing 30–40 lb; however, they reported only one meal per year following a yearly trip to the James River. Consequently, their estimated risk was low based on reported annual consumption.

Overall, no significant risk to the overall population of recreational fishermen on the tidal freshwater James River was found; however, unacceptable risk levels among fishermen consuming PCB-contaminated catfish where observed. Default Model 2 and point estimate Model 6 produced mean ILCRs greater than 1×10^{-4}, although Monte Carlo models had mean ILCRs above the acceptable level. Several individuals had risks above the acceptable levels. In Models 6 and 10, the majority of the variability in risk was attributable to annual catfish consumption and PCB concentration in catfish. Using point estimates, Model 5 indicated a mean ILCR among JR fish consumers of 1.02×10^{-5}; however, the addition of catfish consumption to the model increased the risk an order of magnitude to 2.13×10^{-4}, which is greater than the acceptable risk range. This translates into 1 excess cancer in 100,000 persons exposed versus 2 in 10,000. Similarly, in Model 9, the ILCR for consumers averaged 2.85×10^{-6} and the addition of catfish consumption increased the ILCR to 6.88×10^{-5}. In this case, both risks were within acceptable limits. Concentrations of PCBs were higher in catfish than in other species; therefore, the elevated PCB concentrations increased the risk estimates for catfish consumers. Models 3, 4, 7, and 8 were included only as a means of assessing the entire survey group; however, Models 5, 6, 9, and 10 were used to assess consumers since they are most at risk from PCB-contamination in fish. On the whole, Monte Carlo simulation models produced consistently lower risk estimates than the default and point estimate models because they drew from the entire distribution of each assumption variable rather than using single point estimates. The value of Monte Carlo simulations in estimating exposure or risk probability distributions diminishes if one or more parameters are poorly defined. Not all of the sources of uncertainty can be accounted for or all of the parameter codependencies recognized (USEPA, 1991).

The sensitivity analysis for Model 7 revealed that PCB concentration in fish contributed to the most variation in risk, while other models indicated that exposure frequency was the major contributor. Model 7 represented all participants, including non-consumers, and the concentration used for "other fish" was an average among several species that were reported as frequently consumed from the James River. Using an average across species increases the variability in risk because an individual's risk is based solely upon the species he/she consumes, which may contain higher or lower PCBs than the average used in this model. As expected, annual consumption (exposure frequency) contributed to the most variation in the forecast risk estimates. When exposure distributions are right-skewed and/or follow a lognormal distribution, exposure will usually be over-estimated for percentiles above the median by direct use of exposure study empirical data, since biologic exposure periods are generally longer than the exposure periods in the survey (Stanek et al., 1998). In this case, respondents were asked to recall their fish consumption over the last year and that data were converted into a lifetime exposure. Changes in consumption rates over a lifetime were not quantified and consequently, total exposure may have been over-estimated.

Research has shown that sport-fishers interviewed during their seasonal fishing period may overestimate their consumption during the rest of the year (Shatenstein et al., 1999). Such overestimates, along with difficulties conceptualizing frequency and quantity, may have contributed to portion size overestimates in the survey. In addition, the social desirability of the sport and frequency of fishing are bias factors; successful anglers are among the highest consumers of freshwater fish (USEPA, 1997). In surveys, researchers generally ask about the number of meals eaten in a given time frame, but the size of those meals is generally imprecisely estimated (USEPA, 1998). Consequently, annual fish consumption may be under- or overestimated. One individual reported a 32 oz portion size; however, it remained in the models as an upper bound rather that being disregarded as an outlier. Sampling design may also create bias. Although all people were approached, and 97% agreed to participate, the sample may not have captured individuals that fish during later hours of the day or different seasons of the year.

Although there was no advisory in effect for the James River near the sampling sites at the time of the interviews, the VDH issued a fish consumption advisory in July 2002 for blue catfish and carp. The advisory resulted from PCB samples taken by VDEQ in May 2001, which exceeded the VDH level of concern for PCBs (600 ppb). The advisory area included the sample area, covering a 43-mile stretch of the James River beginning at the I-95 bridge in downtown Richmond to Flowerdew Hundred, about 7 mile downstream of the Benjamin Harrison Bridge. Data from the 2001 DEQ sampling round was not included in the risk assessment due to different sampling methodologies. The CES samples were individual fillets, whereas VDEQ collected composite samples from three fillets. VDEQ found PCB concentrations as high as 3212 ppb in blue catfish near the I-95 bridge (VDEQ, unpublished data), which could increase the risk to catfish consumers fishing upstream at entry points near Annabel Lee and Ancarrows.

Based on studies that showed a 30–40% reduction in PCBs after frying and smoking (Zabik et al., 1996; Jacobs et al., 1998; Moya et al., 1998), several studies include a contaminant loss factor in the risk assessment to account PCB loss during cooking or trimming (Pellettieri et al., 1996; TAMS Consultants, 2000; Wilson et al., 2001). We chose not to include such a factor in this risk assessment and therefore, risks may be decreased depending on preparation techniques. The extent of cooking losses has not been well characterized, and it is difficult to make comparisons between different species, as preparation and cooking methods vary with fish type. For instance, many participants noted that they usually skin and fry catfish, while other species are scaled and baked, broiled or grilled. Skea et al. (1979) found that trimming the skin and subcutaneous fat from the fillets reduced PCB concentrations 43–64% in Lake Ontario smallmouth bass and brown trout. Therefore, it is likely that the risk may be overestimated based on reported preparation and cooking methods. Approximately 68% of consumers reported frying as the primary cooking method, which has been shown to reduce PCB concentrations up to 46% (Skea et al., 1979).

A large uncertainty in any risk assessment pertains to the dose–response criteria applied to estimate the ILCR and HQ from the average dose rates developed in the exposure assessment. The cancer slope factor and oral RfD for PCBs are based on laboratory studies. Estimates based on animal studies benefit from controlled exposures and absence of confounding factors; however, there is uncertainty in extrapolating dose and response rates across species. The principal uncertainty is using commercial mixtures to make inferences about environmental mixtures (IRIS, 2002). Through the food chain, organisms selectively bioaccumulate persistent congeners, but commercial mixtures tested in laboratory animals were not subject to prior selective retention. The pattern of relative proportions of PCBs in environmental mixtures is variable and may not resemble the original mixture. These differences are caused by several factors, including differential rates of degradation, differences in physiochemical and biological properties and changes in PCB congener composition in the food chain (Giesy and Kannan, 1998). RfDs derived from laboratory studies for Aroclor mixtures may not be appropriate for the PCB mixture found in environmental samples.

The calculated risks in this study were based on total PCBs, which may underestimate cancer risk if the congeners present in James River fish consist of a high percentage of dioxin-like congeners (USEPA, 2000). The potential importance of dioxin-like PCB congeners was not evaluated in this study due to limited analytical data. Animals exhibit interspecies differences in their abilities to metabolize specific congeners (Giesy and Kannan, 1998), but the metabolism of PCBs in catfish has not been well characterized. Tissue concentrations in fish predicted from an equilibrium partitioning model showed an exponential increase in potential cancer risk to humans as the hydrophobicity of the PCB increased (Barron et al., 1994). Note that this assessment focused only on PCBs in James River fish samples. Other organic compounds such as DDT, DDE, chlordane, PAHs, and heavy metals also have been detected in tissue samples (Garman et al., 1998 and VDEQ, unpublished data) and may act alone or in combination with PCBs to increase risk. Environmental degradation of PCBs was not evaluated in the risk assessment due to uncertainty regarding biotransformation and selective loss or accumulation of specific congeners. Barron et al. (1994) found that 3.3 degradation half-lives would be necessary to reduce cancer risk by an order of magnitude as a result of biotransformation to non-genotoxic metabolites by aquatic organisms, but the study did not account for differences in selectivity among organisms and trophic levels.

In conclusion, our analysis has shown that exposure frequency (annual fish consumption) and contaminant concentration are the most important factors in predicting personal exposure to PCBs from fish consumption. Therefore, when resources are available, local and/or regional fishing behavior and consumption data can be useful in generating more realistic risk estimates for a recreational population, while the most conservative models present a reasonable maximum exposure. There has been a shift in the risk assessment paradigm from deterministic point estimates to probabilistic methods. In this study, we have presented a probabilistic approach to accommodate parameter uncertainty in risk assessment, and the results were generally an order of magnitude less than the risk estimates obtained by point estimate methods. The Monte Carlo method used in this work is shown to be a good candidate for conducting public health risk assessments. This method can be used to complement other methods in an effort to better quantify the impact of uncertainty and variability.

Overall, our assessment indicates that PCB levels in catfish pose a significant risk to recreational anglers consuming these fish from the tidal freshwater James River, based on reported consumption habits. Individuals with the highest annual fish consumption rates have unacceptable cancer and non-cancer risks. PCB concentrations in fish samples from VDEQ and CES exceeded several human health criteria, including the USEPA Region III risk-based concentration of 0.0016 ppm, the FDA action level of 2 ppm, the VDH advisory level of 600 ppb, and the VDEQ screening level of 54 ppb. Risk management for contaminant exposure from fish consumption can include reduction in fish consumption, reduction in consumption of predatory fish, reduction in size of fish consumed and changes in cooking methods. Sensitive populations, including pregnant and/or breast-feeding women and young children should refrain from eating catfish from the James River. Recreational fishermen should follow current consumption advisory recommendations on the James River which call for zero blue catfish meals and no more than two 8 oz meals of carp per month in order to minimize future risk.

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References

ATSDR, 1993. Toxicological Profile for Selected PCBs (Aroclor 1260, 1254, 1248, 1242, 1232, 1221, and 1016). Update. ATSDR/TP-92/16. US Department of Health and Human Services, Public Health Services, Agency for Toxic Substances and Disease Registry, Atlanta, GA.

ATSDR, 2000. Toxicological Profile for Polychlorinated Biphenyls (PCBs). Update. US Department of Health and Human Services, Public Health Services, Agency for Toxic Substances and Disease Registry, Atlanta, GA.

Barron, M.G., Yurk, J.J., Crothers, D.B., 1994. Assessment of potential cancer risk from consumption of PCBs bioaccumulated in fish and shellfish. Environ. Health Perspect. 102, 562–567.

Burger, J., 2000. Gender differences in meal patterns: role of self-caught fish and wild game in meat and fish diets. Environ. Res. 83, 140–149.

Burger, J., Sanchez, J., Gochfeld, M., 1998. Fishing, consumption, and risk perception in fisherfolk along an East Coast estuary. Environ. Res. 77, 25–35.

Burger, J., Stephens Jr., W.L., Boring, C.S., Kuklinski, M., Gibbons, J.W., Gochfeld, M., 1999. Factor in exposure assessment: ethnic and socioeconomic differences in fishing and consumption of fish caught along the Savannah River. Risk Anal. 19, 427–438.

Cole, D.C., Kearney, J., Ryan, J.J., Gilman, A.P., 1997. Plasma levels and profiles of dioxin and dioxin-like compounds in Ontario Great Lakes anglers. Chemosphere 34, 1401–1409.

DiPinto, L.M., Coull, B.C., 1997. Trophic transfer of sediment associated polychlorinated biphenyls from meiobenthos to bottom-feeding fish. Environ. Toxicol. Chem. 16, 2568–2575.

Falk, C., Hanrahan, L.P., Anderson, H.A., Kanarek, M.S., Draheim, L., Needham, L., Patterson, D., 1999. Body burden levels of dioxin, furans, and PCBs among frequent consumers of Great Lakes sport fish. Environ. Res. 80, S19–S25.

Fein, G.G., Jacobson, J.L., Jacobson, S.W., Schwartz, P.M., Dowler, J.K., 1984. Prenatal exposure to polychlorinated biphenyls: effects on birth size and gestational age. J. Pediatr. 105, 315–320.

Feldman, R.S., Titus, J.E., 2001. Polychlorinated biphenyl accumulation differs among pumpkinseed sunfish during experimental field exposure: the role of invertebrate prey. Aquat. Toxicol. 51, 389–404.

Fiore, B.J., Anderson, H.A., Hanrahan, L.P., Olson, L.J., Sonzogni, W.C., 1989. Sport fish consumption and body burden levels of chlorinated hydrocarbons: a study of Wisconsin anglers. Arch. Environ. Health 44, 82–88.

Garman, G.C., Hale, R.C., Unger, M.A, Rice, G., 1998. Fish Tissue Analysis for Chlordecone (Kepone) and Other Contaminants in the Tidal James River, Virginia: A Report to the United States Environmental Protection Agency, p. 38.

Giesy, J.P., Kannan, K., 1998. Dioxin-like and non-dioxin-like effects of polychlorinated biphenyls (PCBs): implications for risk assessment. Crit. Rev. Toxicol. 28, 511–569.

Gould, J.C., Cooper, K.R., Scanes, C.G., 1999. Effects of polychlorinated biphenyls on thyroid hormones and liver type I monodeiodinase in the chick embryo. Ecotoxicol. Environ. Saf. 43, 195–203.

Huisman, M., Eerenstein, S.E., Koopman-Esseboom, C., Brouwer, M., Fidler, V., Muskiet, F.A., Sauer, P.J., Boersma, E.R., 1995. Perinatal exposure to polychlorinated biphenyls and dioxins through dietary intake. Chemosphere 31, 4273–4287.

Humphrey, H.E.B., 1987. The human population—an ultimate receptor for aquatic contaminants. Hydrobiology 149, 75–80.

IRIS, 2002. Online. Integrated Risk Information System, Cincinnati, OH. Office of Health and Environmental Assessment, Environmental Criteria Office, US Environmental Protection Agency.

James River Association, 2002. State of the James. James River Association, Mechanicsville, VA, p. 48.

Jacobs, H.L., Kahn, H.D., Stralka, K.A., Phan, D.B., 1998. Estimates of per capita fish consumption in the US based on the Continuing Survey of Food Intake by Individuals (CSFII). Risk Anal. 18, 283–291.

Jacobson, J.L., Fein, G.G., Jacobson, S.W., Schwartz, P.M., Dowler, J.K., 1984. The transfer of polychlorinated biphenyls (PCBs) and polybrominated biphenyls (PBBs) across the human placenta into maternal milk. Am. J. Public Health 74, 378–379.

Jacobson, J.L., Jacobson, S.W., Humphrey, H.E., 1990. Effects of in utero exposure to polychlorinated biphenyls and related contaminants on cognitive functioning in young children. J. Pediatr. 116, 38–45.

Kato, Y., Haraguchi, K., Shibahara, T., Yumoto, S., Masuda, Y., Kimura, R., 1999. Reduction of thyroid hormone levels by methysulfonyl metabolites of tetra- and penta-chlorinated biphenyls in male Sprague-Dawley rats. Toxicol. Sci. 48, 51–54.

Kearney, J.P., Cole, D.C., Ferron, L.A., Weber, J.P., 1999. Blood PCB, *p,p′*-DDE and Mirex levels in Great Lakes fish and waterfowl consumers in two Ontario communities. Environ. Res. 80, S138–S149.

Klaunig, J.E., Lipsky, M.M., Trump, B.F., Hinton, D.E., 1979. Biochemical and ultrastructural changes in teleost liver following subacute exposure to PCB. J. Environ. Pathol. Toxicol. 2, 953–963.

Kosatsky, T., Przybysz, R., Shatenstein, B., Weber, J.P., Armstrong, B., 1999. Fish consumption and contaminant exposure among Montreal-area sportfishers: pilot study. Environ. Res. 80, S150–S158.

Marchettini, N., Panzieri, M., Tiezzi, E.B., 2001. Effects of bioaccumulation of PCBs on biodiversity and distribution of fish in two creeks in East Tennessee (USA). Anal. Chim. 91, 435–443.

Moya, J., Garrahan, K.G., Poston, T.M., Durell, G.S., 1998. Effects of cooking on levels of PCBs in the fillets of winter flounder. Environ. Contam. Toxicol. 60, 845–851.

Ndayibagira, A., Spear, P.A., 1999. Esterification ad hydrolysis of vitamin A in the liver of brook trout (*Salvelinus fontinalis*) and the influence of a coplanar polychlorinated biphenyl. Comp. Biochem. Physiol. 122, 317–325.

Ness, D.K., Schantz, S.L., Moshtaghian, J., Hansen, L.G., 1993. Effects of perinatal exposure to specific PCB congeners on thyroid hormone concentrations and thyroid histology in rats. Toxicol. Lett. 68, 311–323.

Patandin, S., Weisglas-Kuperus, N., de Ridder, M.A., Koopman-Esseboom, C., van Staveren, W.A., van der Paauw, C.G., Sauer, P.J., 1997. Plasma polychlorinated biphenyl levels in Dutch preschool children either breast-fed or formula-fed during infancy. Am. J. Public Health 87, 1711–1714.

Pellettieri, M.B., Hallenbeck, W.H., Brenniman, G.R., Cailas, M., Clark, M., 1996. PCB intake from sport fishing along the northern Illinois shore of Lake Michigan. Bull. Environ. Contam. Toxicol. 57, 766–770.

Regala, R.P., Rice, C.D., Schwedler, T.E., Dorociak, I.R., 2001. The effects of tributyltin (TBT) and 3,3′,4,4′,5-pentachlorobiphenyl (PCB-126) mixtures on antibody responses and phagocyte oxidative burst activity in channel catfish, *Ictalurus punctatus*. Arch. Environ. Contam. Toxicol. 40, 386–391.

Seo, B.W., Li, M.H., Hansen, L.G., Moore, R.W., Peterson, R.E., Schantz, S.L., 1995. Effects of gestational and lactational exposure to coplanar polychlorinated biphenyl (PCB) congeners or 2,3,7,8-tetrachlorodibenzo-*p*-dioxin (TCDD) on thyroid hormone concentrations in weanling rats. Toxicol. Lett. 78, 253–262.

Shatenstein, B., Kosatsky, T., Nadon, S., Lussier-Cacan, S., Weber, J.P., 1999. Reliability and relative validity of fish consumption data obtained in an exposure assessment study among Montreal-area sportfishers. Environ. Res. 80, S71–S86.

Skea, J.C., Simonin, H.A., Harris, E.J., Jackling, S., Spagnoli, J.J., 1979. Reducing levels of mirex, Aroclor 1254 and DDE by trimming and cooking Lake Ontario brown trout (*Salmo trutta* Linnaeus) and smallmouth bass (*Micropterus dolomieui* Lacepede). J. Great Lakes Res. 5, 153–159.

Stanek, E.J., Calabrese, E.J., Xu, L., 1998. A caution for Monte Carlo risk assessment of long-term exposures based on short-term exposure study data. Hum. Ecol. Risk Assess. 4, 409–422.

Stow, C.A., Qian, S.S., 1998. A size-based probabilistic assessment of PCB exposure from Lake Michigan fish consumption. Environ. Sci. Technol. 32, 2325–2330.

TAMS Consultants, 2000. Volume 2F-Revised Human Health Risk Assessment Hudson River PCBs Reassessment RI/FS, for USEPA Region 2 and USACE Kansas City District. TAMS Consultants and Gradient Corporation.

USEPA, 1989. Risk Assessment Guidance for Superfund (RAGS), vol. 1. Human Health Evaluation Manual (Part A) Interim Final, EPA/540/1-89/002. United States Environmental Protection Agency, Washington, DC, Office of Emergency and Remedial Response.

USEPA, 1991. Risk Assessment Guidance for Superfund (RAGS), vol. 1. Human Health Evaluation Manual Supplemental Guidance: Standard Default Exposure Factors. OSWER Directive 9285.6-03. United States Environmental Protection Agency, Washington DC, Office of Emergency and Remedial Response.

USEPA, 1997. Exposure Factors Handbook. EPA/600/P-95/002Fa, National Center for Environmental Assessment. United States Environmental Protection Agency.

USEPA, 1998. Guidance for Conducting Fish and Wildlife Consumption Surveys. United States Environmental Protection Agency, Washington, DC US EPA, Office of Water.

USEPA, 2000. Guidance for Assessing Chemical Contaminant Data for Use in Fish Advisories Volume 2: Risk Assessment and Fish Consumption Limits, third ed. United States Environmental Protection Agency, Office of Water.

West, P.C., Fly, J.M., Marans, R., Larkin, F., Rosenblatt, D., 1993. 1991–92 Michigan Sport Anglers Fish Consumption Study. Final Report to the Michigan Great Lakes Protection Fund, Michigan Department of Natural Resources. Technical Report No. 6, School of Natural Resources Sociology Research Lab, University of Michigan.

Willman, E.J., Manchester-Neesvig, J.B., Armstrong, D.E., 1997. Influence of *ortho*-substitution on patterns of PCB accumulation in sediment, plankton, and fish in a freshwater estuary. Environ. Toxicol. Chem. 31, 3712–3718.

Wilson, N.D., Price, P.S., Paustenback, D.J., 2001. An event-by-event probabilistic methodology for assessing the health risks of persistent chemicals in fish: a case study at the Palos Verde Shelf. J. Toxicol. Environ. Health 62, 595–642.

Zabik, M.E., Booren, A., Zabik, M.J., Welch, R., Humphrey, H., 1996. Pesticide residues, PCBs and PAHs in baked, charbroiled, salt boiled and smoked Great Lakes lake trout. Food Chem. 55, 231–239.

Zaranko, D.T., Griffiths, R.W., Kaushik, N.K., 1997. Biomagnification of polychlorinated biphenyls through a riverine food web. Environ. Toxicol. Chem. 16, 1463–1471.