WILLAMETTE BASIN
TOTAL MAXIMUM DAILY LOAD (TMDL)

APPENDIX B: MERCURY

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TABLE OF CONTENTS

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Health Division Fish Mercury Policy and Assessment Assumptions

Due to the growing awareness of state agencies and Oregon citizens about the presence of natural mercury in numerous waterways in the state; and the impact that such mercury can have, the Health Division has been asked for a concise statement of the assumptions and criteria we use in determining the safety of fish taken from waterbodies in Oregon.

The first mercury advisory issued in Oregon was initiated by Lane County Health Department in 1978, and was brought about by mercury tests showing levels of mercury in some fish from Cottage Grove Reservoir well above the FDA market limit of 1 part per million. The advisory has been reviewed and modified slightly, but remains in effect. It recommends reduced consumption of Cottage Grove reservoir fish by all consumers, but with particular restrictions for children and pregnant women. Since that time fish-mercury advisories have been issued by the Health Division for Jordan Creek, Antelope Reservoir, Owyhee Reservoir and parts of Owyhee River (Malheur County), for East Lake (Deschutes County), for the Snake River along all of Oregon's border, for the Dorena Reservoir (Lane County) and for the Willamette River mainstem.

The Health Division is currently maintaining a fish testing database which includes all historical data available from any source, and which is updated as new mercury testing data becomes available. The basic criteria currently used by the agency in developing advisories are as follows:

1. The initial indication that fish from a particular waterbody may pose a hazard to consumers is when the overall average mercury level reaches or exceeds 0.35 ppm. This level is referred to as the "screen value" which serves as a red flag that fish from that waterbody may pose hazards to consumers. It is necessary that there be sufficient numbers of fish tested involving a number of different kinds of fish to ensure that the average level is meaningful. Rarely do we have enough test data to assure statistical accuracy, but we do not issue advisories unless we have a significant number of samples and a variety of species represented.

2. When the average mercury level is found to be at or above 0.35 ppm, a careful review of the data is made. The average mercury level of each species is reviewed; correlations of mercury levels with size (or age) of fish are reviewed; any information about fishing habits and characteristics of the consuming population are reviewed; and any other relevant factors are taken into account. If mercury levels are so high that fish consumption should be avoided entirely, or if there are especially susceptible populations that would be adversely effected by eating the fish; an advisory recommending against any consumption will be issued.

3. Frequently mercury levels are high enough to pose some hazard to high consumption users or to especially sensitive populations, but not so high as to require complete avoidance of consumption. In these cases the Health Division issues advisories stating how much fish can be safely eaten.

4. If there is sufficient evidence that a particular kind or size of commonly eaten fish does not have dangerous levels of mercury, the advisory may exclude them.

5. Where the amount of test data is sufficient to warrant it, the Health Division may also include advisory information about species or sizes that pose unique hazards. For example, the advisory may recommend that a certain species of fish larger than a specified size should not be used for food.

6. In cases in which the average mercury level for fish from a given body of water does not exceed the 0.35 ppm screen value, but there is significant test data for one or more species indicating that they contain excessive levels of mercury, an advisory may be issued for the affected fish. In cases in which the average mercury level is less than the screen value, but it is known that there is a population of consumers that eat abnormally large amounts of the fish; or if there is a population of consumers that has abnormal susceptibility to fish mercury, the Health Division may issue advisories for those unique conditions.

ODEQ FOOD WEB MODEL

(A Basin-Specific Aquatic Food Web Biomagnification Model for Estimation of Mercury Target Levels)

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SUMMARY

In Oregon's Willamette River Basin (WRB), health advisories currently limit consumption of fish that have accumulated methylmercury to levels posing a potential health risk for humans. Under the Clean Water Act, these advisories create the requirement for a Total Maximum Daily Load (TMDL) for mercury in the WRB. A TMDL is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards. Because methylmercury is known to biomagnify in aquatic food webs, a biomagnification factor can be used, given a protective fish tissue criterion, to estimate total mercury concentrations in surface waters required to lower advisory mercury concentrations currently in fish in the WRB. This paper presents a basin-specific aquatic food web biomagnification model that simulates inorganic (Hg[II]) and methylmercury accumulation in fish tissue and estimates WRB-specific biomagnification factors for resident fish species of concern to stakeholders. It was calibrated with WRB-specific fish tissue and surface water data. Probabilistic (Monte Carlo) techniques propagate stochastic variability and uncertainty throughout the model, providing decision makers with credible range information and increased flexibility in establishing a specific mercury target level. The model predicts the probability of tissue mercury concentrations in eight fish species within the range of concentrations actually measured in these species during 25+ years of water quality monitoring. Estimated mean biomagnification factor values range from 2.60×10^6 to 1.39×10^7 and are within the range of such values estimated by U.S. EPA on a national basis. Several WRB-specific mercury target levels are generated, which vary by their probability of affording human health protection relative to the U.S. EPA methylmercury tissue criterion of 0.30 mg/kg. Establishing a specific numeric target level is, however, a public policy decision, and one that will require further discussions among the various WRB stakeholders.

INTRODUCTION

A Total Maximum Daily Load (TMDL) is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards, and an allocation of that amount to the pollutant's sources. Water quality standards, which are set by states, territories, or tribes, identify the beneficial uses for each waterbody (e.g., drinking water supply, contact recreation (swimming), aquatic life support (fishing)) and the scientific criteria to support those uses. A TMDL is the sum of the allowable loads of a single pollutant from all contributing point and nonpoint sources, including natural background. The calculation must include a margin of safety to ensure that the waterbody can be used for its designated purposes. The Clean Water Act mandates the establishment of water quality standards and defines the requirements of the TMDL program [1].

The Willamette River Basin (WRB) occupies an area of approximately 32,000 km^2 in northwestern Oregon, USA. The Willamette River is the 13th largest river in the coterminous United States in terms of streamflow and produces more runoff per square mile than any of the larger rivers. Oregon's three largest urban areas, the cities of Portland, Salem, and Eugene, border the river. In the WRB, consumption of fish that have accumulated levels of mercury, particularly methylmercury (MeHg), is a significant mercury health risk for humans. A mercury advisory warning of health risks from consumption of fish has been in effect at Cottage Grove Reservoir (located on the Coast Fork Willamette River in the southern WRB) since 1979 [2,3]. In February 1997, the Oregon Department of Human Services issued a mercury advisory for consumption of largemouth bass, smallmouth bass, and northern pikeminnow for the entire mainstem Willamette River, including the Coast Fork to Cottage Grove Reservoir; a separate advisory was issued for Dorena Reservoir, also located on the Coast Fork [3]. The Oregon Department of Human Services issued a consolidated (all species) fish consumption advisory for the entire WRB in 2001. These advisories create, per Clean Water Act Section 303(d), the legal requirement for a mercury TMDL for the WRB.

Target Level

One of the goals within the overall WRB TMDL process is establishment of a target level for total mercury in surface water that is linked to the protection of specified beneficial uses (e.g., sport and subsistence fishing) [2,3]. Two pieces of information are needed to establish such a target level: (1) an acceptable methylmercury concentration in fish tissue (tissue criterion) and (2) a defined relationship between total mercury concentrations in surface water and total mercury concentrations in fish tissue. This target analysis uses the fish tissue MeHg criterion value of 0.30 mg/kg (wet weight) developed by the U.S. Environmental Protection Agency for protection of human health [4,5]. Although the Oregon Department of Human Services uses a level of 0.35 mg/kg to trigger fish consumption advisories, utilization of U.S. EPA's 0.30 mg/kg provides an additional margin of safety.

Aerobic surface waters without known sources of mercury contamination generally contain <5 ng/L of total mercury [7]. Approximately 7.8 percent of total dissolved mercury in the epilimnion (36 percent in the hypolimnion) is in the form of dissolved MeHg, the species predominantly accumulated by aquatic organisms [4,8]. MeHg concentrations in surface water may be better predictors of MeHg levels in fish than are MeHg levels in sediment [9]. Biomagnification of MeHg through diet, rather than gill uptake from water, is considered the dominant basis for elevated concentrations in fish [10,11,12,13,14]. Methylmercury accumulation via either surface water or food sources may be substantial, but the relative contribution of each pathway may vary with fish species [15,16,17,18,19]. The transfer efficiency of mercury through the food web is affected by the form of mercury. Although inorganic mercury is the dominant form in the environment and easily accumulated, it is also depurated quickly. The digestive wall is much more permeable for MeHg than for inorganic mercury, allowing MeHg to be readily transferred to other tissues [12]. Methylmercury accumulates quickly, is depurated very slowly, and therefore has a greater potential to biomagnify in higher-trophic-level species. The half-life of total mercury in fish is approximately 5 days to 5 months but 1 to >3 years for MeHg [4]. Due to its preferential uptake, ability to be transferred among tissues, and slow depuration, most (≈99%) of the mercury in fish muscle tissue is MeHg [4].

Estimating a target mercury water concentration requires a biomagnification factor (BMF) and a fish tissue criterion protective of human health. A target concentration in the ng/L range could be set simply through use of a default BMF of approximately 10^6 to 10^7 [4]. It is understood, however, that such factors are often influenced by local conditions and that default factors derived from nation-wide averages may be potentially unresponsive to, or inappropriate for, a given regional ecosystem. U.S. EPA suggests that, for a particular area of concern, BMFs derived from data collected within the area are preferred to default values [4]. They also suggest inclusion of site-specific considerations when calculating a surface water target level [5]. In addition, the WRB TMDL stakeholders expressed a desire for information on the behavior and levels of mercury in fish species of special interest to them. A default approach cannot adequately address this specific request. Thus, for the WRB, a food web biomagnification model, focusing on resident fish species of concern to stakeholders, and calibrated with basin-specific tissue and water data, was used to bring regional specificity to estimates of BMF values. A fundamental assumption of this approach, which is of particular importance to its use in the TMDL process, is that the BMF between MeHg in water and total mercury in fish will remain constant under new mercury loading regimes.

This model simulates mercury (as Hg[II] and MeHg) accumulation in fish through a basin-specific food web in response to chemical exposure, based upon chemical mass balances for aquatic biota. It equates rates of change in chemical concentration within a fish (and other aquatic organisms) to the sum of chemical fluxes into and out of the organism. These fluxes include direct uptake of the chemical from water, uptake through feeding, loss of the chemical due to elimination (desorption and excretion), and dilution due to growth. It addresses the potential for bioconcentration (concentration from water), bioaccumulation (concentration from diet as well as water), and biomagnification (systematic concentration as chemicals are passed to higher trophic levels) of Hg[II] and MeHg. To predict tissue levels in fish destined for human consumption, the model is repeatedly applied to organisms at each trophic level to simulate Hg[II] and MeHg transfer from primary and secondary producers, through a variety of intermediate invertebrate and fish species, to top predators (humans).

Due to their differing physicochemical properties, Hg(II) and MeHg are handled in separate sub-models, whose outputs are then combined to yield BMF and total mercury surface water concentration estimates that equate to the protective criterion. These estimates are provided for each fish species in the model. Probabilistic (Monte Carlo) techniques are used to propagate variability (due to both stochastic variability and incertitude (lack of knowledge) combined) throughout the model. This approach provides decision makers with information as to the credible range of target levels, as well as the probability of any given target level, to give them increased flexibility in establishing a specific mercury target level [4,20]. At present, there is only one food web model, with one human health endpoint, for the entire WRB. Because the WRB can be divided into four reaches on the basis of aquatic ecosystems and fish species assemblages, reach-specific sub-models may eventually be needed to better assess local conditions [21]. Food web models of this type have been developed for various hydrophobic organic chemicals [22] and metals [23], including mercury [24,25,26].

METHODS

Model Compartments

The model food web consists of 17 compartments selected to represent important components of the WRB aquatic ecosystem: 3 source media, 1 secondary carbon source (detritus), 3 primary producers, 6 primary consumers, 2 secondary consumers, 1 tertiary consumer, and 1 top (human) consumer (Figure 1). Primary (1°) producers are organisms that convert CO_2 to biomass. The term usually refers to photosynthesizers, but also includes chemosynthetic bacteria that use chemical instead of light energy for CO_2 fixation. Primary (1°) consumers are organisms that must eat other organisms for their energy metabolism, since they cannot produce new organic matter by photosynthesis or chemosynthesis (as can producers). Primary consumers, according to the ecological pyramid concept, are herbivorous grazers. Secondary (2°) consumers include herbivorous fish, whose diet is confined to plant items, as well as invertivorous and omnivorous fish whose diet can include both plant and animal items. As the invertebrate food source decreases in abundance and diversity due to habitat degradation (e.g., anthropogenic stressors), there is typically a shift from insectivorous to omnivorous fish species. Tertiary (3°) consumers include only larger piscivorous fish at the fourth trophic level. Although humans could be included at this level, they are kept separate to indicate their status as assessment endpoints for this target analysis.

To identify major fish species and their potential food items within the WRB, information was assembled from the general literature, previous regional studies, and data collected during water quality monitoring events. Biota compartments were defined based on organism anatomy and morphology, primary exposure medium, dietary (feeding) preferences, general life history, and local abundance. Aquatic species representative of each trophic level are listed in Table 1. Aquatic species selected for inclusion in this model, including eight of the eighteen fish species sampled during water quality monitoring events, and their food preferences, are listed in Table 2. Criteria for selecting the representative fish species were: (1) species consumed by humans, (2) abundant or common in their respective communities, (3) prominent species at each trophic level in regional food webs, (4) representative of a specific functional group, and (5) species for which mercury tissue data are currently available. Juvenile (young-of-year (YOY), ≤1 year in age) and adult fish are modeled separately because their feeding strategies often differ and juveniles are often prey items for adult omnivorous and piscivorous fish.

Compartments within the food web are linked by one or more discrete food chains or paths, each of which leads from surface water through varying intermediate biotic compartments, to the human (top level consumer) compartment. Pathways analysis is used to define feeding relationships represented in the model. This approach analyzes the flux of mercury along each of these individual paths, then combines individual path results to form an estimate of mercury concentrations in fish species available to, and consumed by, humans [27]. As summarized in Table 2, these paths are defined largely by the feeding preferences of representative species above the 1° producer level; feeding preferences are quantified with the dietary fraction variable.

Model Variables

With pathway analysis, mercury fluxes can be modeled with a limited number of variables. Some of these variables, such as bioconcentration factors, are readily obtainable for different species, whereas others, such as elimination rate constants and assimilation efficiencies, are less readily available and must be derived or estimated from data available for similar species. Each food web compartment is defined by eight variables:

Bioconcentration Factor (BCF, L/kg) For a given biotic compartment, the BCF represents simple partitioning between the compartment and MeHg and Hg[II] in surface water. BCFs for all aquatic invertebrate and fish compartments are relative to surface water concentrations.
Chemical Dietary Assimilation Efficiency (AE, μg chemical absorbed/μg chemical ingested)This is the fraction of ingested chemical that is absorbed across the gut lining of an organism [28].
Chemical Elimination Rate (k_2, d^{-1}) Chemicals that have been fully absorbed are assumed to deposit in storage sites determined by the selective preference of the chemical (proteins for mercury); depletion from these sites is a function of the chemical-specific elimination rate. Loss is assumed to be first-order for each model compartment and chemical.
Normalized Food Intake Rate (NIR, g intake/g body weight/d) The amount of food (wet weight) ingested by an organism per day, expressed as a percentage of its body weight.
Body weight (BW, g) This is used as an independent variable in the determination of food intake rates for several compartments.
Dietary Fraction (DF_{IJ}, unitless) For each predator (i) and prey (j) combination in the model, this term represents the fraction of predator (i) diet consisting of prey (j). For each predator, the sum of dietary fractions equals 1.
Predator-Prey Size Relationship Factor (Φ, unitless)The ratio of prey length to predator length for partially or exclusively piscivorous model compartments. This term is included to prevent implausible model behavior such as a predator consuming prey that is near its own size.
Water Temperature (T, °C) This is used as an independent variable in the determination of food intake rates for several compartments as well as in the calculation of compartment-specific MeHg elimination rates.

Model Algorithms

Bioaccumulation factors are calculated for each pathway (i.e., food chain) leading from surface water through intermediate compartments, to humans [27]. Given that each step along this pathway represents a trophic level in the food chain, then:

Level 1 $BCF_1 = C_B / C_W$ {1}

Level 2 $BAF_2 = BCF_2 + f_2 BCF_1$ {2}

Level 3 $BAF_3 = BCF_3 + f_3 BCF_2 + f_3 f_2 BCF_1$ {3}

Level 4 $BAF_4 = BCF_4 + f_4 BCF_3 + f_4 f_3 BCF_2 + f_4 f_3 f_2 BCF_1$ {4}

where:

- C_B Concentration of chemical in biota (mg/kg)
- C_W Concentration of chemical in surface water (mg/L)
- BCF_K Bioconcentration factor for the kth trophic level (L/kg)
- BAF_K Bioaccumulation factor for the kth trophic level (unitless)
- f_K Food term for the kth trophic level (unitless)

The food term (f_K) is dependent on the trophic level in question and has been adapted to describe bioaccumulation in an entire food web, as opposed to a single food chain, by use of a dietary fraction variable [27]. To avoid the DF_{IJ} sum among all prey for a given predator from exceeding 1 during model simulations, individual DF_{IJ} values are normalized relative to their sum to result in a total of 1. The food term and normalized DF were calculated as,

$$f_K = \left(\frac{AE \cdot NIR \cdot NDF_{IJ}}{k_2} \right) \quad \{5\}$$

$$NDF_{IJ} = \left(\frac{DF_{IJ} \cdot S}{\sum (DF_{IJ} \cdot S)} \right) \quad \{6\}$$

where:

- f_K Food term for the kth trophic level (unitless)
- AE Toxicant assimilation efficiency (μg toxicant absorbed/μg toxicant ingested)
- NIR Weight-normalized food intake rate (intake (g)/body weight (g)/d)
- DF_{IJ} Dietary fraction of jth prey item in ith predator diet (unitless)
- NDF_{IJ} Dietary fraction normalized over all preferred food items (unitless)
- k_2 Toxicant elimination rate (d^{-1}); Equation {16} or {17}
- S Size switch (unitless); Equation {19}

Organisms at Level 1 are assumed to be autotrophic, such that all mercury accumulation results from uptake from surface water per Equation {1}. Small aquatic organisms with varied feeding habits (microinvertebrates, macroinvertebrates, zooplankton) are also included at Level 1, on the assumption that uptake from water (or surface adsorption) would outweigh uptake from diet to the point where uptake from diet was insignificant [27].

Total residue accumulation from all pathways to a given compartment at level 2 or higher is termed the biomagnification factor (BMF) to indicate that residue accumulation in the entire food web to that compartment is being addressed. For food chains of aquatic organisms, BAF values are not directly additive at Level 2 and higher because their bioconcentration would then be counted more than once [27]. To sum residue accumulation in multiple food chains containing several trophic levels of aquatic organisms, variations of the following equations are used:

Level 2 $BMF_2 = \left(BCF_2 + \sum f_2 BCF_1\right) \cdot f_E$ {7}

Level 3 $BMF_3 = \left(BCF_3 + \sum f_3 BMF_2\right) \cdot f_E$ {8}

Level 4 $BMF_4 = \left(BCF_4 + \sum f_4 BMF_3\right) \cdot f_E$ {9}

$f_E = 1 - \exp\left(-k_2 \cdot (t \cdot 365)\right)$ {10}

where:

$BMF_{1\text{-}4}$ Biomagnification factor at trophic levels 1 through 4 (L/kg)
$BCF_{1\text{-}4}$ Bioconcentration factor at trophic levels 1 through 4 (L/kg)
$f_{1\text{-}4}$ Food term at trophic levels 1 through 4 (unitless)
f_E Fraction of equilibrium attained at time of consumption (unitless)
k_2 Elimination rate (d^{-1}); Equation {17} or {18}
t Average age at time of consumption (years); Equation {15}

These equations are used to calculate the BMF for aquatic organisms at Level 2 and higher because they account for total residue accumulation in all pathways in lower trophic levels. The fraction of contaminant equilibrium attained (f_E) is dependent on an organism's age (c.f., Equation {15}) at time of consumption; it applies only to the invertebrate and fish compartments.

Given estimates of inorganic mercury and MeHg BMF values, the total mercury concentration in fish tissue is estimated as,

$$C_{Tn} = \left[\frac{\left(C_{IN} \cdot BMF_{IN}\right) + \left(C_{MEn} \cdot BMF_{MEn}\right)}{CF}\right] \quad \{11\}$$

and the target level for total mercury in surface water as,

$$TL_n = \left[\frac{TC}{BMF_{MEn} \cdot \Omega}\right] \cdot CF \quad \{12\}$$

where:

C_{Tn} Total mercury concentration in the n^{th} fish species (mg/kg)
C_{IN} Inorganic mercury concentration in surface water (ng/L)
C_{ME} Methylmercury concentration in surface water (ng/L)
BMF_{INn} Inorganic mercury biomagnification factor for the n^{th} fish species (L/kg)
BMF_{MEn} MeHg biomagnification factor for the n^{th} fish species (L/kg)
TL_n Total mercury target level for the n^{th} fish species (ng/L)
TC U.S. EPA fish tissue criterion for MeHg (0.30 mg/kg)
Ω Ratio of dissolved MeHg to total mercury in surface water (unitless)
CF Conversion factor (1×10^6 ng/mg)

Model Input Variables

As in most probabilistic modeling analyses, selection of values and definition of distributions is based in part on site-specific data, in part on literature values, and in part on best professional judgment (i.e., informed assumptions). Although their use can obscure significant physiological and ecological differences between fish species, several generalized relationships (e.g., Equations {17}, {18}, {19}) are used to address a lack of species-specific information. The procedures used to derive distributions for the probabilistic analysis generally follow those of MacIntosh et al. [25,26]. All input variables, any distributions defining them, parameter values for these distributions, and references to information which formed the basis for selecting these parameters are summarized in Table 3. Selected variables are discussed further below.

To maintain understood relationships between length, age, and weight, and because substantial length data were available for all eight fish species, body length was used to derive values for both body weight and age. A continuous distribution was fit to measured length data for each species; separate distributions were formed for adult and juvenile fish. Adult fish were assumed to be those 1 year or older. The adult length distribution for a given species was truncated low at a length equivalent to age 1 and truncated high at the mean asymptotic length (length at an infinitely high age, L_∞). Adult length at age 1 was determined by the von Bertalanffy growth function,

$$L_t = L_\infty\left(1 - \exp\left(-K \cdot \left(t - t_0\right)\right)\right) \qquad \{13\}$$

where:

L_t	Predicted length of fish at age *t* (cm)
L_∞	Asymptotic length [length at an infinitely high age] (cm)
K	Time factor (year^{-1})
t	Age (years)
t_0	Theoretical age at length 0 (years)

Values for L_∞ and K were obtained from the literature [29]. For consistency, a default t_0 value for each species was estimated from L_∞ and K with the empirical relationship [29],

$$\log\left(-t_0\right) = -0.3922 - 0.2752 \cdot \log\left(L_\infty\right) - 1.038 \cdot \log\left(K\right) \qquad \{14\}$$

Growth parameter values are summarized in Table 4. All juvenile length distributions were assumed to be uniform, with a lower bound of 1 cm and an upper bound equal to length at age 1, estimated with the von Bertalanffy growth function (Equation {13}) [29]. Parameters for these distributions are given in Table 3. Comparisons of measured length data and resulting fitted distributions for adults are provided in Appendix A.

The average age at time of consumption of individuals comprising the invertebrate and fish compartments was used only to determine the fraction of contaminant equilibrium attained (f_E; Equation {10}) in those compartments. Lifespan in all other compartments is assumed to be great enough for practical equilibrium (≈90% of theoretical) to be reached. For juvenile fish, age was estimated simply as the ratio of a value drawn from a uniform juvenile length distribution to a point estimate of length at end of year 1. For adult fish, age was estimated from length data through back-calculation of the von Bertalanffy growth function [29],

$$t = t_0 - \ln\left(1 - L/L_\infty\right) / K \qquad \{15\}$$

where:

t	Age (years)
L_t	Length of fish at age *t* (cm)
L_∞	Asymptotic length [length at an infinitely high age] (cm)
K	Time factor (year^{-1})
t_0	Theoretical age at length 0 (years)

For all fish species, body weight was estimated from length as,

$$BW = a \cdot L^b \qquad \{16\}$$

where:

BW Fish body weight (g)
a Species-specific coefficient (unitless)
b Species-specific coefficient (unitless)

Initial estimates of “a” and “b” values were obtained from the literature [29], then adjusted using length and weight measurements of fish collected in the WRB. Adjusted values for “a” and “b” are given in Table 3. Comparisons of modeled and measured length-weight relationships are provided in Appendix B. For invertebrates at trophic level 1, body weight and age were assigned a positive 1:1 correlation.

The methylmercury elimination rate in all fish species was estimated as a function of fish body weight and water temperature [30],

$$\ln k_{2(ME)} = c \cdot T - d \cdot \ln BW + e - f \quad \{17\}$$

where:

$k_{2(ME)}$ MeHg elimination rate (d^{-1})
c Temperature coefficient (unitless); literature value 0.066 (0.019, standard error (SE)); model values in Table 3
d Body weight coefficient (unitless); literature value 0.20 (0.06 SE); model values in Table 3
e Acute / chronic exposure value (unitless); literature value 0.73 (0.24 SE) for chronic, 0 for acute; model values in Table 3
f Constant (unitless); literature value 6.56 (0.45 SE); model values in Table 3
BW Body weight of fish (g)
T Surface water temperature (°C)

The elimination rate for Hg[II] in all fish species was estimated as a function of fish weight [25]:

$$k_2 = 0.111 \cdot BW^{0.46} \quad \{18\}$$

where:

k_2 Hg(II) elimination rate (d^{-1})
BW Body weight of fish (g)

Food assimilation efficiency has been shown to be directly related to temperature and inversely to fish body size for grass carp [31], and similar relationships may exist for the assimilation efficiency of dietary MeHg. However, because no published information was available to support derivation of such a relationship specifically for MeHg, its assimilation was treated as independent of metabolic rate. Reported point estimates for assimilation efficiency of dietary MeHg range from <0.20 to >0.80, with 0.80 a typical default value [16,30]. However, MeHg bioavailability estimates obtained for channel catfish (*Ictalurus punctatus*) with pharmacological methods were lower (non-compartmental average 0.33, range 0.14 - 0.55; compartmental average 0.29, range 0.12 - 0.42) than those obtained with mass balance methods, suggesting that mass balance methods overestimate the bioavailability of toxicants in fish [32]. The initial, pre-calibration distribution of dietary MeHg assimilation efficiency values for all fish species spanned <0.20 to >0.80, with an assumed median value of 0.50, so that AE_{MeHg} ~ Triangular(0.05, 0.50, 0.95). This distribution was subsequently customized for each species during model calibration.

The daily ingestion rate for all fish was estimated as a function of water temperature and fish body weight using a bioenergetics-based model [22],

$$IR = \left(0.022 \cdot BW^{0.85}\right)\left(\exp\left(0.06 \cdot T\right)\right) \qquad \{19\}$$

where:

IR Ingestion rate (kg food / day)
BW Body weight of fish (kg)
T Water temperature (°C)

Food preferences of invertebrates and fish are summarized in Table 2; a matrix of predator-prey interactions included in the model is shown in Table 5 [25,29]. Precise quantification of the dietary fraction (DF_{IJ}) for each predator-prey interaction was not attempted. For non-preferred food items, DF_{IJ} = 0. For a preferred food item, variability in its actual consumption was expressed by defining DF_{IJ} as a uniform distribution, with a minimum of 0.001 and a maximum of 1.0 (c.f., Table 5). Dietary fractions were normalized to 1 with respect to all preferred food items (NDF_{IJ}) before being used for food term (f_K, Equation {5}) estimation.

Prey size was a factor only for the fish compartments. A predator-prey size relationship factor (Φ) expresses prey size as a function of predator length. For largemouth bass a mean value for Φ of 0.34, with a standard deviation of 0.028, has been reported [33]. The ratio of predator-prey sizes is approximately 4:1 (geometric mean ratio ≈3.5:1) among fishes of different species, when sizes are expressed as body lengths [29]. Distributions for Φ for each species are given in Table 3. The size switch (S) was computed as:

$$S = \begin{cases} 0 & \text{if } L_{PREY} > \left(L_{PRED} \times \Phi\right) \\ 1 & \text{if } L_{PREY} \le \left(L_{PRED} \times \Phi\right) \end{cases} \qquad \{20\}$$

where:

S	Size switch (unitless)
Φ	Predator-prey size ratio (unitless)
L_{PREY}	Length of prey (cm)
L_{PRED}	Length of predator (cm)

Model Operation

In a quantitative probabilistic exposure model, variability in the result may be due to stochastic variability (heterogeneity), incertitude (lack of knowledge), or some combination of the two. If both stochastic variability and incertitude are negligible, the outcome is purely deterministic - a rare occurrence. When incertitude is negligible, variation in the result is described by a single cumulative density function (CDF) representing the expected statistical variation in, for example, tissue concentration or target level. If neither incertitude or stochastic variability are negligible, there are multiple CDFs representing variability because, due to lack of knowledge, the exact position of the one CDF that correctly represents variability cannot be known [34]. When assessing the confidence in a model estimate, considerable judgment is involved in distinguishing which input variables should be modeled as only stochastic, which as only imperfectly known (due to lack of knowledge), and which as influenced by both sources of variation [35]. For the one-dimensional (1-D) Monte Carlo (MC) analyses, all variables were considered to be influenced by stochastic variability and incertitude combined; no effort was made to distinguish between these two sources of uncertainty. No variables were treated as second-order random variables [36].

The model was constructed in an MS Excel® (Microsoft Corporation, Redmond, Washington) spreadsheet environment. Circular cell references must be permitted to allow for simulation of food web feedback loops (e.g., adult-juvenile predation within the same species). Probabilistic analyses were performed with an MS Excel® compatible software capable of performing 1-D MC analyses (Crystal Ball®, Decisioneering, Inc., Denver, Colorado), using Latin hypercube sampling, with a fixed random number seed. One-dimensional MC results are based on 10,000 model iterations.

RESULTS AND DISCUSSION

Model Calibration

Prior to model calibration, empirical density functions (EDFs) were formed from measured tissue concentrations of dissolved total mercury and MeHg water column concentration distributions were estimated from measured data. Cumulative density functions (CDFs) of estimated tissue concentrations were then generated using literature values for all variables, with the exception of the empirically-derived surface water concentrations, and 1-D MC techniques. Pre-calibration results for tissue concentration are shown in Figures 4 to 11 and for tissue-body length relationships in Appendix C. A strong positive correlation between fish length and mercury tissue concentration has been reported for large (>120 mm) fish in Oregon state-wide [37]. Measured data from the WRB show a negligible to moderate positive relationship between tissue concentration and body length depending on species (c.f., Appendix C). Calibrating the model to WRB conditions involved minimizing the differences, particularly at the median, between model-generated CDFs and measured EDFs of mercury tissue concentration and replicating, to the extent practicable, observed mercury tissue concentration - body length relationships. During calibration the number of variables adjusted was kept to a minimum and all adjustments were maintained within limits imposed by measured and literature data. Following calibration, estimated tissue concentration CDFs were generated with 1-D MC techniques.

The Weibull plotting position {rank/(n+1)} method was used to generate EDFs for each fish species, using data collected between 1969 and 1997 for basin-wide water quality monitoring (Figure 2). These EDFs indicate the probability of observing a specific tissue concentration for a given species on a basin-wide, long-term average basis. Measured tissue total mercury concentrations are highest in adult piscivorous northern pikeminnow (median ≈0.57 mg/kg, wet weight) and lowest in adult, largely invertivorous, cutthroat trout (median ≈0.11 mg/kg, wet weight) (Figure 2). Similarly, the probability of a northern pikeminnow exceeding the U.S. EPA tissue criterion is ≈80%. Mercury concentrations obtained through water quality monitoring are higher than those for large (>120 mm) invertivores and piscivores probability sampled throughout western Oregon (c.f., Table 7) [37]. But average mercury concentrations for western Oregon are higher than the national average of 0.10 mg/kg [7]. In certain WRB reservoirs, elevated tissue mercury concentrations (>1 mg/kg, wet weight) are thought to be associated with mercury releases from legacy mining activities [38]. This suggests that some monitoring events occurred, intentionally or unintentionally, at locations with anthropogenically elevated mercury levels.

Model estimation of tissue mercury concentrations requires knowledge of dissolved total (inorganic and MeHg concentrations combined) and MeHg concentrations in surface water. Such data are sparse for the WRB, as are synoptic surface water-fish tissue data, owing largely to the lack, until very recently, of adequately sensitive analytical techniques for differentiating inorganic mercury and MeHg in surface water. Early (pre-1995) studies have reported inorganic mercury concentrations in surface water possibly influenced by anthropogenic mercury sources (e.g., legacy mining activities) [40,41]. Samples collected in 1995 from the Row River and Coast Fork Willamette River (southern WRB) had total mercury concentrations of 2.60 and 5.00 ng/L (unfiltered), respectively and 1.47 and 2.70 ng/L (filtered), respectively. MeHg concentrations in unfiltered samples were 0.1 and 0.3 ng/L, respectively, while those in filtered samples were 0.05 and 0.2, respectively [42]. Samples collected in June 1998 near Cottage Grove Reservoir (southern WRB) showed dissolved MeHg concentrations ranging from 0.022 to 0.255 ng/L and total MeHg concentrations ranging from 0.022 to 0.142 ng/L [42]. Samples collected in 2001 in the Willamette River (including Portland Harbor) showed total mercury concentrations (unfiltered) from <0.05 ng/L (detection limit, EPA Method 1631) to 4.95 ng/L (highest maximum) [43]. Total mercury values in unfiltered samples from the Tualatin River, a tributary of the Willamette, ranged from <1.0 ng/L to 1.9 ng/L [43]. Total mercury concentrations in filtered samples ranged from <0.05 ng/L to 1.65 ng/L (highest maximum) in the Willamette River (including Portland Harbor) [43]. A two-year study to gather mercury data specifically in support of the WRB TMDL was initiated by the Oregon Department of Environmental Quality in 2002. Water and sediment samples were collected throughout the WRB in 2002 and analyzed for both total mercury and MeHg (using EPA Method 1631E) [44]. Distributions for dissolved (filtered) total mercury and MeHg concentrations given in Table 3 are derived from these data, as they have met strict quality control / quality assurance criteria and are assumed to best reflect basin-wide concentrations and are consistent with previous post-1995 results for specific locations in the WRB.

Sensitivity analysis shows (Table 6) that contributions to variance in tissue estimates come primarily from variables associated with the dietary exposure pathway: MeHg elimination rate coefficients, MeHg assimilation efficiency, adult body length, and, for some species, MeHg bioconcentration factors for their food items. Pre-calibration tissue concentration distributions were within an order of magnitude (Figures 3 to 10) and tissue concentration-length relationships generally within the measured 90 percent confidence interval (Appendix C). The pre-calibration model could have been used, although with greater uncertainty, to estimate target levels. Calibration served to reduce uncertainty in the model and make it clearly WRB-specific. Calibration thus focused on changing (1) MeHg assimilation rate distributions for four species (CAR, LSS, CTT, SMB), (2) the MeHg elimination rate body weight coefficient ("d" in Equation {17}) for four species (NPM, LMB, LSS, CAR), and (3) the MeHg bioconcentration factor for BLU. The MeHg elimination rate acute/chronic variable ("e" in Equation {17}) was set at zero for all species. Although the MeHg elimination rate temperature coefficient ("c" in Equation {17}) did not require adjustment, its contribution to variance (Table 6) suggests that multiple sub-basin models may be needed to more accurately represent the water temperature differences across the WRB system. Changes necessary for calibration indicate the challenges posed when generic uptake or loss relationships are applied to a given species in a given environment, as well as the need to better understand MeHg uptake and loss kinetics in all fish species, but particularly trophic level 2 fish species such as carp and largescale sucker.

Fish Tissue Concentrations

Measured values for total and MeHg mercury concentrations, Equation {11}, and 1-D MC methods (variability and incertitude combined) were used to generate tissue total mercury concentrations CDFs for comparison with EDFs of measured tissue concentrations. Measured tissue concentration EDFs (☐) and modeled tissue concentration CDFs (×) are in general agreement and estimated and measured median and mean values are within one standard deviation (Figures 3 to 10 and Table 7). The northern pikeminnow, for example, has measured and estimated mean mercury tissue concentrations of 0.60 and 1.02 mg/kg, respectively, and measured and estimated median values of 0.57 and 0.55 mg/kg, respectively (Table 7). .

Biomagnification Factors

Model estimates of biomagnification factors for each of the eight species are summarized in Table 8. Modeled BMF values are highest for trophic level 4 piscivorous species (northern pikeminnow, large and smallmouth bass), somewhat lower for trophic level 3 omnivorous species, and within range of "direct estimate" mercury BMF values reported by U.S. EPA for trophic level 3 and 4 fish species [4]. This model does not, therefore, represent a sharp departure from prior mercury BMF estimates derived with other methods. Nationally, U.S. EPA's tissue criterion of 0.30 mg/kg (wet weight) has been equated to an average MeHg water concentration of 0.058 ng/L for an age-3 largemouth bass [9]. For modeled largemouth bass BMF values in Table 8, equivalent MeHg water concentrations range from 0.01 ng/L to 0.25 ng/L, overlapping the national estimate. Using U.S. EPA's direct estimated BMF values, this range is 0.02 ng/L to 0.92 ng/L. This suggests that applying a national default BMF, rather than the model-derived BMF, to fish species in the WRB could result in a mercury target level less than that necessary for protection of human health.

Surface Water Mercury Target Level

A fish tissue criterion of 0.30 mg/kg, a distribution for the fraction of total mercury that is dissolved MeHg (Ω), a model estimated value for BMF_{ME}, and Equation {12} were used to estimate total mercury surface water target levels for each fish species. Water quality-based pollution control activities traditionally rely on the total concentration of the inorganic metal form, not the dissolved organic form, making Ω the ratio of dissolved MeHg to total mercury. For the WRB, the mean value of Ω for dissolved MeHg to total mercury is 0.05 (range 0.001 to 0.182, n = 64) (Figure 11) [44]. Target level calculation results are summarized in Table 9. For the northern pikeminnow, for example, when the total mercury water concentration exceeds 10.03 ng/L (1-D MC estimate), there is a 95 percent probability that the tissue concentration in an individual fish will exceed the criterion. This probability falls to 50 percent when the water concentration is 0.92 ng/L, and to 5 percent at 0.07 ng/L.

Selection of an actual mercury TMDL target level for the WRB is a matter of public policy, will require further discussions among the Agency and WRB stakeholders, and will likely not depend on this model alone. The model does, however, provide decision makers with several choices, with differing degrees of uncertainty, for a total mercury surface water target level. For example, a conservative choice would be the upper 95th percentile for the northern pikeminnow or ≅0.07 ng/L (Table 9). At this level, it is expected that 95 percent of the northern pikeminnow population in the WRB would achieve U.S. EPA's tissue criterion. The Oregon Department of Human Services initiates a fish consumption advisory when the average tissue concentration exceeds its tissue criterion of 0.35 mg/kg. Thus the median, 0.92 ng/L (1-D MC) could be chosen (Table 9), with the expectation that U.S. EPA's tissue criterion would not be exceeded for an individual northern pikeminnow 50% of the time. A much less conservative choice would be the lower 5th percentile for the northern pikeminnow, or 10.03 ng/L. At this level, it is expected that only 5 percent of the northern pikeminnow population in the WRB would achieve the protective tissue criterion. The California Regional Water Quality Control Board has proposed a human health mercury target of 0.1 ng/L for the San Francisco Bay estuary, based on the Food and Drug Administration action level of 1 mg/kg MeHg in fish tissue and a default bioaccumulation factor of 10^7. In the southeastern U.S., U.S. EPA Region 6 has proposed MeHg targets ranging from 0.2 to 0.4 ng/L for the Ouachita River Basin and Bayou Bartholomew in Arkansas and Louisiana, using a BAF of 6.8×10^6 L/kg and an MeHg:total Hg ratio of 0.2 [45].

When selecting any TMDL target level it should be noted that detection limits for cold vapor atomic absorption (CVAA) are approximately 40 to 500 ng/L and for U.S. EPA Method 1631 (low level, clean sampling) approximately 0.05 to 2 ng/L. For any target level $\leq$2.0 ng/L, the more logistically demanding and costly Method 1631E will be required for compliance verification, even though false negatives would still occur. These increased demands and costs may have an impact on the nature and extent of water quality and compliance monitoring activities. In addition, U.S. EPA's fish tissue criterion for mercury simply reflects a level of mercury that could be consumed by humans without inducing adverse health effects. It was developed without reference to specific conditions in regions to which it might be applied. In some regions, natural levels (i.e., those not associated with anthropogenic sources of mercury contamination), that may be difficult, if not impossible, to mitigate or eliminate, may be sufficient to generate tissue concentrations equal to or greater than this criterion. Such ambient levels should be a factor when selecting a target level.

Conclusion

At its current level of development, this model appears able to reasonably approximate the behavior of Hg(II) and MeHg in WRB aquatic food webs. For selected species in the WRB, it is capable of (a) estimating the probability of a specific fish tissue mercury concentration within the range of such probabilities actually measured in these species and (b) closely approximating observed fish tissue concentration-body length relationships. It can thus be used to estimate a surface water mercury concentration linked to acceptable tissue levels in WRB fish populations. Confidence range widths suggest that further quantification of up to eleven variables categorized as uncertain (but measurable) would enhance the WRB-specificity of the model and its usefulness for establishing a target level. Developing and manipulating this model has been a useful exercise. Aside from supporting target level selection, it has highlighted both data gaps and the assumptions made to bridge them, suggested where such gaps and assumptions could be filled or tested with further research and data collection, and provided a guide for asking more informed questions about MeHg behavior in aquatic systems, and in the WRB in particular.

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DATA TABLES AND FIGURES

Table 1. Compartments and representative species for differing trophic levels in the Willamette River food web model

COMPARTMENT	TROPHIC LEVEL	REPRESENTATIVE SPECIES
Surface water	Level 0 [source media]	Open water overlying sediment.
Detritus	Level 1 [2° carbon source]	Dead or decaying algae and weeds; technically called organic detritus to distinguish it from the mineral detritus classified by geologists. Serves as a secondary organic carbon source
Aquatic macrophytes	Level 1 [1° producer]	Higher aquatic plants; in the sense of "higher" evolutionarily than algae and having roots and differentiated tissues; may be emergent (cattails, bulrushes, reeds, wild rice), submergent (water milfoil, bladderwort) or floating (duckweed, lily pads).
Phytoplankton	Level 1 [1° producer]	Microscopic floating plants, mainly algae, that live suspended in water and that drift about because they cannot move by themselves or because they are too small or too weak to swim effectively against a current. A basic food source in many aquatic ecosystems.
Periphyton	Level 1 [1° producer]	A complex matrix of algae and heterotrophic microbes attached to submerged substrata in almost all aquatic ecosystems. An important food source for invertebrates and some fish.
Zooplankton	Level 2 [1° consumer]	Animal portion of the living particles in water that freely float in open water, eat bacteria, algae, detritus and sometimes other zooplankton and are in turn eaten by planktivorous fish. May include planktonic caldocerans, copepods, ostracods, mites
Aquatic insect larvae	Level 2 [1° consumer]	Primarily benthic, including chironomid, trichopteran, ephemeropteran, and dipteran larvae
Aquatic crustaceans	Level 2 [1° consumer]	Crayfish
Aquatic insects	Level 2 [1° consumer]	Primarily pelagic, including a variety of diving insects and those that skim the water surface such as water boatmen, pond skimmers, etc.
Aquatic mollusks	Level 2 [1° consumer]	Mussels, snails, clams, etc.
Aquatic worms	Level 2 [1° consumer]	Oligochaetes
Omnivorous fish	Level 3 [2° consumer]	Northern pikeminnow (juvenile) Largemouth bass (juvenile) Largescale sucker (juvenile, adult) Common carp (juvenile, adult) Rainbow trout (juvenile, adult) Cutthroat trout (juvenile, adult) Smallmouth bass (juvenile) Bluegill (juvenile, adult)
Piscivorous fish	Level 4 [3° consumer]	Northern pikeminnow (adult) Largemouth bass (adult) Smallmouth bass (adult)
Top piscivorous predator	Level 5	Humans

Table 2. Food item preferences of representative species for different trophic levels in the Willamette River food web model

REPRESENTATIVE SPECIES	FOOD PREFERENCE	
	JUVENILE	ADULT
Zooplankton		Phytoplankton Detritus
Aquatic insect larvae	Periphyton Aquatic macrophytes Detritus Zooplankton	
Aquatic crustaceans		Aquatic macrophytes Detritus
Aquatic insects		Aquatic insect larvae Aquatic macrophytes Aquatic worms Zooplankton
Aquatic mollusks		Phytoplankton Zooplankton
Aquatic worms		{Sediment} * Detritus Periphyton
Northern pikeminnow [46,47] Ptychocheilus oregonensis piscivore, edible	Fork Length (FL) < 30cm Zooplankton Aquatic insect larvae Aquatic insects	Fish (salmonids) Aquatic crustaceans Aquatic insects Aquatic mollusks
Largemouth bass [46] Micropterus salmoides piscivore, edible	Zooplankton Aquatic insect larvae Aquatic crustaceans Aquatic worms Small fish (FL < 2-5 cm)	Aquatic insect larvae Aquatic crustaceans Aquatic worms Fish (fishminnows, juvenile carp)
Smallmouth bass [47,48] Micropterus dolomieui piscivore, edible	Zooplankton Aquatic insect larvae Aquatic insects + small fish bulk of diet at FL > 4 cm	Aquatic crustaceans Small fish
Largescale sucker [46,48] Catostomus macrocheilus benthivorous omnivore, edible	Detritus Zooplankton Aquatic insect larvae	Phytoplankton Periphyton Aquatic insects Aquatic mollusks
Common carp [49] Cyprinus carpio benthivorous omnivore, edible	Phytoplankton Periphyton Zooplankton Aquatic insect larvae	Aquatic macrophytes Periphyton Aquatic crustaceans Aquatic insects Aquatic worms Aquatic mollusks
Rainbow trout [50] Oncorhynchus mykiss pelagic invertivore, edible	Zooplankton	Aquatic insect larvae Aquatic crustaceans Aquatic insects Aquatic mollusks Small fish
Cutthroat trout [51] Oncorhynchus clarkii pelagic invertivore, edible	Zooplankton	Aquatic insect larvae Aquatic crustaceans Aquatic insects Small fish
Bluegill [46] Lepomis macrochirus pelagic omnivore, edible	Aquatic macrophytes Detritus Phytoplankton Zooplankton Aquatic crustaceans Aquatic insect larvae Aquatic worms	{Sediment} * Aquatic macrophytes Phytoplankton Zooplankton Aquatic insects larvae Aquatic crustaceans Small fish

* Incidental ingestion of sediment was not included as an exposure pathway.

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
ENVIRONMENTAL VARIABLES				
Total dissolved mercury concentration in surface water	ng/L	Lognormal	1.32, 1.45	Best-fit to field data, *n* = 64. Based on four quarterly measurements of total dissolved mercury levels in WRB surface water [44].
Dissolved MeHg concentration in surface water	ng/L	Lognormal	0.06, 0.03	Best-fit to field data, *n* = 64. Based on four quarterly measurements of dissolved MeHg levels in WRB surface water [44].
Dissolved MeHg to total mercury ratio (Ω)	unitless	Lognormal	0.056, 0.082, upper bound = 1	Best fit to field data, n = 64. Based on four quarterly measurements of total to MeHg ratios in WRB surface water [44].
Water temperature	°C	Triangular	6.0, 12.5, 22.0	Between 1969 and 1992, median temperatures in the Willamette River temperatures at Portland ranged from a low of 5.6 °C to a high of 21.8 °C, with a most likely value of ≈ 12.5 °C [41]. This range was assumed to encompass all temperature regimes within the WRB.
MeHg BIOCONCENTRATION FACTOR				
Detritus (DET)	L/kg	Logtriangular	2.50, 3.00, 3.50	Assumed to be the same as that for Hg[II] (see below).
Aquatic macrophytes (AQP)	L/kg	Logtriangular	0.80, 2.15, 3.50	Values for submergent and emergent portions of six species of aquatic vascular plants from 34 to 3500 and 6 to 32, respectively [52]. Values for duckweed (*Lemna minor*) (480, 2950); reed grass (*Phragmites communis*) (850, 25, 530, 74, 139); bulrush (*Scirpus lucustris*) (90, 790, 8, 1250, 39, 190); yellow iris (*Iris pseudacorus*) (20, 40, 18, 34, 31, 90) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
Phytoplankton (PHY)	L/kg	Triangular	3.50, 4.50, 5.50	Values for *Scedesmus obliquus* and *Microcystis incerta* from 761 to 2100 and from 461 to 990, respectively [25,54]. Values of 1200 and 2610 for filamentous algae *Oedogonium* sp. [53]. Values of 3400, 38400, 107000, and 133000 have been calculated for phytoplankton [4]. Distribution spans these calculated values.
Periphyton (PER)	L/kg	Triangular	3.50, 4.50, 5.50	Assumed same as PHY compartment

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
Zooplankton (ZOO)	L/kg	Logtriangular	2.45, 3.90, 5.40	Value for *Gammarus* sp. of approximately 8000 [50]. A value of 249000 for the marine copepod *Acartia clausi* [55]. Values of 3570 and 286 for water fleas (*Daphnia* sp.) and caldocerans (*Eurycerus*), respectively [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
Aquatic insect larvae (AQL)	L/kg	Logtriangular	2.80, 3.40, 4.10	Values for *Chironomus riparius* from 3000 to 5000. Values for bloodworms (Chironomidae) (988, 3070, 12700); mayfly (Ephemeridae) naiads (900, 3290, 690); caddisfly (*Tricoptera* sp.) larve (710), dragonfly (*Odonata* sp.) nymphs (1296), damselfly (*Odonata* sp.) nymphs (1186), cranefly (*Tipula* sp.) larvae (625), alderfly (*Sialis lutaria*) larvae (1270), great diving beetle (*Dytiscus marginalis*) larvae and imago (3134, 800) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
Aquatic crustaceans (AQC)	L/kg	Loguniform	2.45, 5.40	Specific BCF data not available for this compartment. Uncertainty bounds span to those for AQL and ZOO compartments.
Aquatic insects (AQI)	L/kg	Logtriangular	2.80, 3.15, 3.50	Values for adult lesser water boatman (*Corixa* sp.) (4200, 8470, 740), water boatman (*Notonecta glaaca*) (2460, 674), pond skater (*Gerris najas*) (754), aquatic saw bug (*Asellus aquaticus*) (954), and water spiders (Hydraacnidae) (624) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
Aquatic mollusks (AQM)	L/kg	Logtriangular	3.00, 4.20, 5.40	Values for pond snails (*Planorbis* sp.) (1280, 3570, 1970), giant pond snails (*Lymnaea stagnalis*) (1800, 3480, 1178), and the snail *Physa fontinalis* (4266) [53]. Value of 249000 calculated from uptake and depuration data for marine bivalve *Crassostrea virginica* exposed to $(CH_3COO)_2$ for 45 days [56]. Distribution defined by minimum, geometric mean, and maximum of these data.
Aquatic worms (AQW)	L/kg	Logtriangular	2.00, 2.65, 3.30	Values for annelids *Haemopis sanguisuga* (2030, 450, 1148) and *Glossosiphonia complanata* (110, 640), as well as Oligochaeta (1780, 690) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
NPM, LMB, LSS, CAR, RBT, CTT, SMB, BCF	L/kg	Logtriangular	3.00, 4.50, 6.00	Values for brook trout (10000, 12000, 23000) and one for rainbow trout (11000) [54]. Values for juvenile rainbow trout (*Salmo gairdneri*) (4525, 6628, 8033), bluegill sunfish (*Lepomis macrochirus*) (1138, 2454), and pike (*Esox lucius*) organs (7673, 7230, 2002, 2198) [57,58]. Values for brook trout exposed to varying concentrations of MeHg for 28 to 38 weeks, were 127000 [59] and 69000 to 630000 [60]. Distribution spans these data.
BLU †	L/kg	Logtriangular	3.00, 6.50, 7.00	Calibration adjustment.
MeHg ASSIMILATION EFFICIENCY				
ZOO	unitless	Triangular	0.20, 0.50, 0.80	[25]
AQL	unitless	Triangular	0.50, 0.73, 0.95	[25]
AQC	unitless	Uniform	0.50, 0.95	Efficiency of 72% and 76% reported for blue crabs and pink shrimp, respectively [61]. Mode is mean of these values, minimum and maximum are ±30% of this mean.
AQI	unitless	Uniform	0.50, 0.95	Based on [25]; but a high minimum is conservatively assumed.
AQM	unitless	Triangular	0.50, 0.75, 0.95	Efficiency of 72% reported for marine bivalve, *Mytilus edulis*, exposed to MeHg for 80 days [62]. Distribution bounds reflect high uncertainty owing to lack of freshwater mollusk data.
AQW	unitless	Uniform	0.50, 0.95	Specific assimilation efficiency data were not available for this compartment. Maximum approaches maximum possible; a high minimum is conservatively assumed.
BLU	unitless	Triangular	0.45, 0.60, 0.95	Distribution based on assimilation efficiencies of 0.94, 0.815, and 0.15 for yellow perch, mosquito fish, predacious fish, respectively [16,25,63].
RBT †	unitless	Triangular	0.35, 0.50, 0.95	Distribution established during calibration.
NPM †	unitless	Triangular	0.40, 0.45, 0.50	Distribution established during calibration.
LMB †	unitless	Triangular	0.50, 0.55, 0.60	Distribution established during calibration.
CAR †	unitless	Triangular	0.10, 0.10, 0.30	Distribution established during calibration.
LSS †	unitless	Triangular	0.15, 0.25, 0.30	Distribution established during calibration.
CTT †	unitless	Triangular	0.20, 0.30, 0.50	Distribution established during calibration.
SMB †	unitless	Triangular	0.05, 0.10, 0.95	Distribution established during calibration.
MeHg ELIMINATION RATE				

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
ZOO	day^{-1}	Logtriangular	-1.17, -0.69, -0.22	[25]
AQL	day^{-1}	Logtriangular	-1.48, -1.00, -0.52	[25]
AQC	day^{-1}	Logtriangular	-1.37, -1.06, -0.76	[25]
AQI	day^{-1}	Loguniform	-1.48, -1.00, -0.52	Assumed same as AQL compartment.
AQM	day^{-1}	Loguniform	-3.00, -0.22	Elimination rates for two marine bivalves, *Mytilus edulis* and *Crassostrea virginica*, are 0.0003 and 0.001, respectively [24,64]. Minimum established during calibration; maximum is highest invertebrate value (that for ZOO [25]).
AQW	day^{-1}	Loguniform	-2.00, -0.22	Minimum established during calibration; maximum is highest invertebrate value (that for ZOO [25]).
CTT, RBT	day^{-1}	Normal	c(0.066, 0.019); d(0.20, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Coefficient values as given in the literature [30].
BLU †	day^{-1}	Normal	c(0.066, 0.019); d(0.22, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Calibration resulted in body weight coefficient (d) higher than literature value [30].
SMB †	day^{-1}	Normal	c(0.066, 0.019); d(0.30, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Calibration resulted in body weight coefficient (d) higher than literature value [30].
NPM †	day^{-1}	Normal	c(0.066, 0.019); d(0.28, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Calibration resulted in body weight coefficient (d) higher than literature value [30].
LMB †	day^{-1}	Normal	c(0.066, 0.019); d(0.18, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Calibration resulted in body weight coefficient (d) within 1 SE of literature value [30].
LSS †	day^{-1}	Normal	c(0.066, 0.019); d(0.54, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Calibration resulted in body weight coefficient (d) higher than literature value [30].
CAR †	day^{-1}	Normal	c(0.066, 0.019); d(0.55, 0.06); e(0) f(6.56, 0.45)	Estimated on basis of body weight and temperature with Equation {17}. Calibration resulted in body weight coefficient (d) higher than literature value [30].

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
Hg[II] BIOCONCENTRATION FACTOR				
DET	L/kg	Logtriangular	2.50, 3.00, 3.50	Value is approximately 1100 [65]. Distribution as given in [25].
AQP	L/kg	Logtriangular	0.50, 1.65, 2.80	Values for six species of aquatic vascular plants reported 3 to 77 and 4 to 264, respectively [52]. Values for duckweed (*Lemna minor*) (70); reed grass (*Phragmites communis*) (56, 149); bulrush (*Scirpus lucustris*) (77, 70); yellow iris (*Iris pseudacorus*) (18, 23) [53], as well as water hyacinth (*Eichhornia crassipes*) (580) [66]. Distribution defined by minimum, geometric mean, and maximum of these data.
PHY	L/kg	Logtriangular	2.90, 3.45, 4.00	Values for four algae types reported from 853 to 10920 [25,54]. Values of 8537 and 871 reported for *Croomonas salina* and *Oedogonium* sp., respectively [53,67]. Distribution defined by minimum, geometric mean, and maximum of these data.
PER	L/kg	Logtriangular	2.90, 3.45, 4.00	Assumed same as PHY compartment.
ZOO	L/kg	Logtriangular	3.40, 3.65, 3.90	Value for *Gammarus* sp. of 2500. Value of 7600 for the copepod *Acartia clausi* [54,55]. Distribution defined by minimum, geometric mean, and maximum of these data.
AQL	L/kg	Logtriangular	2.10, 3.20, 4.30	Values for caddisfly (*Tricoptera* sp.) larve (513), damselfly (*Odonata* sp.) larvae (655), cranefly (*Tipula* sp.) larvae (840), and great diving beetle (*Dytiscus marginalis*) larvae and imago (603, 862) [53]. Values for larva and pupa life stages of *Chironomus riparius* of 19600 and 15600, respectively [68]. Value of 138 for mayfly (Ephemeridae) larvae [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
AQC	L/kg	Logtriangular	2.00, 2.25, 2.50	Three values reported for crayfish (*Procambarus clarkii*:) 121, 158, 216 [69]. Value of 333 grass shrimp (*Palaemonetes pugio*) [70]. Distribution defined by minimum, geometric mean, and maximum of these data.
AQI	L/kg	Logtriangular	2.60, 3.25, 3.90	Value of 7500 for the adult life stage of *Chironomus riparius* [68]; 414 and 483 for adult lesser water boatman (*Corixa* sp.), water boatman (*Notonecta glaaca*), and pond skater (*Gerris najas*) (431) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
AQM	L/kg	Logtriangular	2.30, 2.60, 2.90	Values for mussels (Mytilus edulis) (664, 236), short-necked clams (*Venerupis philiooinarum*) (190), pond snails (*Planorbis* sp.) (795), giant pond snail (*Lymnaea stagnalis*) (297), and the snail *Physa fontinalis* (637) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
AQW	L/kg	Logtriangular	2.30, 2.78, 3.25	Values reported for annelid *Haemopis sanguisuga* (670) and Oligochaeta (517) [53]. Distribution defined by minimum, geometric mean, and maximum of these data.
NPM, SMB, LMB, LSS, CAR, RBT, CTT, BLU	L/kg	Logtriangular	0.70, 2.20, 3.70	1800 and 4994 for rainbow trout and fathead minnow, respectively [25]. 97 and 2560 for *Serranus cabrilla* (marine species) and *Gambusia affinis*, respectively [60,71]. Juvenile rainbow trout (*Salmo gairdneri*) values of 5, 12, 26 [72]. Distribution defined by minimum, geometric mean, maximum of these data.
Hg[II] ASSIMILATION EFFICIENCY				
ZOO	unitless	Triangular	0.50, 0.60, 0.90	[25]
AQL	unitless	Triangular	0.50, 0.60, 0.90	[25]
AQC	unitless	Triangular	0.50, 0.60, 0.90	[25]
AQI	unitless	Triangular	0.50, 0.60, 0.90	[25]
AQM	unitless	Triangular	0.01, 0.04, 0.12	An efficiency of 4% was reported for the marine bivalve, *Mytilus edulis*, exposed to Hg[II] for 80 days [62]. Distribution bounds are ± 3× this value.
AQW	unitless	Triangular	0.50, 0.60, 0.90	[25]
NPM, SMB, LMB, LSS, CAR, RBT, CTT, BLU	unitless	Triangular	0.112, 0.172, 0.264	[25]
Hg[II] ELIMINATION RATE				
All invertebrate compartments	day^{-1}	Logtriangular	-1.89, -0.89, 0.10	[25]
NPM, SMB, LMB, LSS, CAR, RBT, CTT, BLU	day^{-1}	---	---	Estimated on basis of body weight with Equation {18}.
BODY WEIGHT				

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
ZOO	g	Triangular	1.4×10^{-5}, 3.3×10^{-5}, 7.6×10^{-5}	[25]
AQL	g	Triangular	4×10^{-4}, 6.25×10^{-4}, 9.8×10^{-4}	[25]
AQC	g	Loguniform	-1.00, 0.60	[25]
AQI	g	Triangular	4×10^{-4}, 6.25×10^{-4}, 9.8×10^{-4}	Assumed same as AQL compartment.
AQM	g	---	n/a	Estimate of mollusk body weight not required, as an estimated body-weight normalized food intake rate value was available (see below)
AQW	g	Loguniform	0.0023, 0.019	Range is based on reported fresh weights for *Tubifex tuibifex* [73]
BLU	g	---	$0.05\ L^{2.8702}$	Best-fit to field data, Spearman rank correlation (r_s) = 0.736, p <0.001.
NPM	g	---	$0.006\ L^{3.1079}$	Initial values from [74], then best-fit to field data, r_s = 0.962, p <0.001.
LMB	g	---	$0.0185\ L^{2.9920}$	Initial values from [29], then best-fit to field data, r_s = 0.979, p <0.001.
LSS	g	---	$0.0175\ L^{2.8687}$	Initial values from [75], then best-fit to field data, r_s = 0.964, p <0.001.
CAR	g	---	$0.028\ L^{2.8289}$	Best-fit to field data, r_s = 0.933, p <0.001.
RBT	g	---	$0.0146\ L^{2.9748}$	Best-fit to field data, r_s = 0.964, p <0.001.
CTT	g	---	$0.009\ L^{3.0044}$	Initial values from [75,76], then best-fit to field data, r_s = 0.848, p <0.001.
SMB	g	---	$0.012\ L^{3.0570}$	Best-fit to field data, r_s = 0.729, p <0.001.
FOOD INTAKE RATE				
ZOO	g/day	Logtriangular	-1.04, -0.56, -0.09	[25,77]
AQL	g/day	Loguniform	-1.00, -0.39	[25]
AQC	g/day	Loguniform	-1.00, -0.39	Assumed same as AQL compartment.
AQI	g/day	Loguniform	-1.00, -0.39	Assumed same as AQL compartment.
AQM	g/day	Logtriangular	-1.65, -1.525, -1.40	Intake rate of 0.025 g(dry)/g(dry)/d estimated for marine bivalve *Mytilus edulis* on basis of bivalve respiration, growth rate, and food assimilation efficiency [59]. Distribution bounds are ± 3× this estimated value.
AQW	g/day	Loguniform	-1.00, -0.39	Assumed same as AQL compartment.
All juvenile and adult fish	g/day	---	---	Estimated on basis of body weight and water temperture using Equation {19}.
FISH LENGTH				
BLU (juv)	cm	Uniform	1.0, 10.3	Length range equivalent to age ≤ 1 year; assumes juvenile populations dominated by younger, smaller individuals.
NPM (juv)	cm	Uniform	1.0, 12.0	See BLU.
LMB (juv)	cm	Uniform	1.0, 17.2	See BLU.
LSS (juv)	cm	Uniform	1.0, 22.3	See BLU.

Table 3. Input variables and parameter values used in the Monte Carlo simulations of total mercury concentrations in fish tissue from the Willamette River Basin.

VARIABLE	UNITS	DISTRIBUTION	PARAMETERS	COMMENTS / REFERENCES
CAR (juv)	cm	Uniform	1.0, 18.8	See BLU.
RBT (juv)	cm	Uniform	1.0, 21.5	See BLU.
CTT (juv)	cm	Uniform	1.0, 21.5	See BLU.
SMB (juv)	cm	Uniform	1.0, 16.2	See BLU.
BLU (adult)	cm	Weibull	Location = 90.93, Scale = 76.80, Shape = 1.5869	Best-fit to field data. n = 25. Kolmogorov-Smirnov (K-S) p = 0.098. Lower and upper bounds provided in Table 4.
NPM (adult)	cm	Logistic	Mean = 383.00, Scale = 38.00	Best-fit to field data. n = 62. K-S p = 0.077. Lower and upper bounds provided in Table 4.
LMB (adult)	cm	Beta	α = 6.50, β = 6.50, Scale = 678.60	Best-fit to field data. n = 192. K-S p = 0.066. Lower and upper bounds provided in Table 4.
LSS (adult)	cm	Logistic	Mean = 458.04, Scale = 30.10	Best-fit to field data. n = 90. K-S p = 0.094. Lower and upper bounds provided in Table 4.
CAR (adult)	cm	Logistic	Mean = 554.41, Scale = 45.20	Best-fit to field data. n = 43. K-S p = 0.061. Lower and upper bounds provided in Table 4.
RBT (adult)	cm	Pareto	Location = 213.94, Shape = 5.61	Best-fit to field data. n = 36. K-S p = 0.083. Lower and upper bounds provided in Table 4.
CTT (adult)	cm	Beta	α = 16.26, β = 4.65, Scale = 356.40	Best-fit to field data. n = 25. K-S p = 0.069. Lower and upper bounds provided in Table 4.
SMB (adult) †	cm	Uniform	Minimum = 190.00, Maximum = 410.00	Best-fit to field data. n = 10. K-S p = 0.129. Lower and upper bounds from field data.
PREDATOR - PREY SIZE RATIO				
NPM, SMB, LSS, CAR, RBT, CTT, BLU	unitless	Triangular	0.225, 0.25, 0.275	Generic species value of 0.25 [from 29] ± 10%.
LMB	unitless	Normal	0.340, 0.028	Value for largemouth bass from [33].
LIFESPAN				
ZOO	days	Uniform	10, 20	[25]
AQL	days	Uniform	30, 360	[25]
AQC	days	Uniform	30, 360	[25]
AQI	days	Uniform	30, 360	[25]
AQM	days	Uniform	30, 360	[25]
AQW	days	Uniform	30, 360	[25]

† Initial, literature-based, value altered during model calibration.

Table 4. Parameters for the von Bertalanffy growth function (Equation {12}) used to estimate age of adult fish from measured length data.

Species	L_∞ [a]	K [b]	t_0 [c]	L_0 [d]	L_1 [e]	L_{max} [f]	R-L_{max} [g]	Ref
LMB	65.1	0.170	-0.808	1.0	17.2	97	58	[29,79]
BLU	31.4	0.231	-0.748	1.0	10.3	41	27	[29]
SMB	54.5	0.210	-0.681	1.0	19.0 [h]	69	39	[29,79]
CAR	74.8	0.157	-0.845	1.0	18.8	120	72	[29]
LSS	61.0	0.300	-0.456	1.0	21.5	61	59	[29,80]
NPM	54.9	0.100	-1.469	1.0	12.0	63	54	[29,78]
CTT	51.8	0.397	-0.356	1.0	21.5	99	33	[29]
RBT	51.8	0.397	-0.356	1.0	21.5	120	38	[29]

a) Asymptotic length [length at an infinitely high age] (cm). Upper bound of adult length distribution.

b) Time factor (year^{-1})
c) Theoretical age at length 0 (years). Estimated with Equation {14}.
d) Assumed length (cm) at age 0. Lower bound of juvenile length distribution.
e) Length (cm) at age 1 from Equation {13}. Upper bound of juvenile length distribution; Lower bound of adult length distribution.
f) Maximum length (cm) reported in the literature [29].
g) Maximum length (cm) measured in fish collected from the Willamette River Basin.

Table 5. Matrix of predator-prey interactions included in the model.

pred →												NPM		LMB		SMB		LSS		CAR		RBT		CTT		BLU	
prey ↓		DET	AQP	PHY	PER	ZOO	AQL	AQC	AQI	AQM	AQW	J	A	J	A	J	A	J	A	J	A	J	A	J	A	J	A
DET						●	●	●	●		●							●	●		●					●	●
AQP							●	●	●									●	●		●					●	●
PHY						●				●								●	●	●	●				●	●	●
PER							●	●			●							●	●	●	●					●	●
ZOO							●	●	●	●		●		●		●		●	●	●	●	●		●	●	●	●
AQL									●			●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
AQC													●	●	●		●		●		●		●			●	●
AQI												●	●	●	●	●	●		●		●	●	●	●	●	●	●
AQM									●										●		●					●	●
AQW														●		●			●		●		●		●	●	●
NPM	J												●	●	●	●	●						●		●		●
	A														●		●										
LMB	J											●	●		●	●	●						●		●		●
	A												●				●										
SMB	J											●	●	●	●		●						●		●		●
	A												●		●												
LSS	J											●	●	●	●	●	●						●		●		●
	A												●		●		●										
CAR	J											●	●	●	●	●	●						●		●		●
	A												●		●		●										
RBT	J											●	●	●	●	●	●						●		●		●
	A												●		●		●										
CTT	J											●	●	●	●	●	●						●		●		●
	A												●		●		●										
BLU	J											●	●	●	●	●	●						●		●		●
	A												●		●		●										

●: DF_{IJ} ~ Uniform (0.001, 1.00); otherwise DF_{IJ} = 0.

Table 6. Results of a 1-D MC sensitivity analysis of the WRB food web model. Sensitivity is expressed as percentage contribution to variance of the tissue concentration estimate. Only values ≥ ±1.5% are shown. [Numbers in parentheses indicate a negative contribution to variance.]

Variable	% Contribution to Variance							
	NPM	SMB	LMB	BLU	CAR	LSS	CTT	RBT
Water (filtered) concentration, Hg[II]	8.0	3.7	8.5	6.1	5.7	5.3	6.6	4.4
Water (filtered) concentration, MeHg	8.1	3.8	8.6	6.1	5.8	5.3	6.6	4.4
Water temperature	2.7	1.6	3.8				4.2	4.6
MeHg elimination rate (body weight coefficient)	5.0	4.5	7.5	1.6	13.0	8.3	5.1	5.0
MeHg elimination rate (temperature coefficient)	(6.7)	(2.6)	(4.8)		(2.0)	(2.2)		(1.5)
MeHg elimination rate (constant)	1.8	6.3			8.7	5.7	5.7	3.1
MeHg assimilation efficiency	1.5	29.1		6.3	11.4	6.9	16.7	15.2
Adult body length	9.1	8.8	7.6	4.7	5.1	6.1	2.6	5.8
Dietary fraction, BLU juveniles in diet	2.9	1.8	2.9					1.6
Ingestion rate, AQI	1.5							
Juvenile body length, BLU		2.7		(2.2)			(4.9)	(4.1)
Juvenile body length, CAR					(5.8)			
Juvenile body length, CTT							(2.4)	
Juvenile body length, LSS						(15.0)		
Juvenile body length, RBT								(4.1)
MeHg bioconcentration factor, AQC						2.0		
MeHg bioconcentration factor, BLU	12.3	4.9	11.3	32.1			3.9	3.6
MeHg bioconcentration factor, PER	8.5	4.7	8.3	3.6	9.8	10.5	9.6	10.4
MeHg bioconcentration factor, PHY	3.9		2.6		5.9	6.4		
MeHg bioconcentration factor, ZOO	4.2	2.7	4.2		2.9	2.9	1.5	2.5
MeHg elimination rate, AQW	(2.8)		2.3		(2.6)	(2.1)	(3.5)	(3.5)

Table 7. Comparison of measured and model estimated (post-calibration) tissue mercury concentrations for eight species of adult fish in the Willamette River Basin.

	Model Estimate (mg/kg) [a]			
Trophic level 4 species				
Fish Species	5^{th}-%tile	50^{th}-%tile	Mean [c]	95^{th}-%tile
Northern pikeminnow	0.10 [0.13] [b]	0.55 [0.57]	1.02 $\pm$ 1.76 {0.64 $\pm$ 0.31, n = 61}	3.43 [1.33]
Largemouth bass	0.07 [0.12]	0.41 [0.43]	0.83 $\pm$ 1.37 {0.52 $\pm$ 0.32, n = 192}	2.90 [1.14]
Smallmouth bass	0.02 [0.09]	0.20 [0.24]	0.49 $\pm$ 1.10 {0.30 $\pm$ 0.20, n = 9}	1.78 [0.70]
Large piscivores	---	---	0.225 [d] (0.161 - 0.315)	---
Trophic level 3 species				
Rainbow trout	0.02 [0.02]	0.12 [0.17]	0.24 $\pm$ 0.43 {0.23 $\pm$ 0.26, n = 33}	0.85 [0.60]
Cutthroat trout	0.02 [0.02]	0.08 [0.06]	0.15 $\pm$ 0.22 {0.13 $\pm$ 0.14, n = 25}	0.54 [0.46]
Carp	0.04 [0.10]	0.22 [0.24]	0.41 $\pm$ 0.67 {0.28 $\pm$ 0.19, n = 42}	1.37 [0.50]
Largescale sucker	0.03 [0.05]	0.19 [0.18]	0.36 $\pm$ 0.56 {0.22 $\pm$ 0.16, n = 90}	1.23 [0.62]
Bluegill	0.03 [0.01]	0.14 [0.25]	0.23 $\pm$ 0.30 {0.36 $\pm$ 0.32, n = 24}	0.74 [1.00]
Large invertivores	---	---	0.042 [d] (0.035 - 0.049)	---

a) Calculated using Equation {11} and 1-D MC analysis (stochastic variability and incertitude combined).

b) Values in [brackets] are from empirical distribution functions formed from measured tissue concentration data for adult fish.

c) Model estimated arithmetic mean tissue concentration $\pm$ one standard deviation. Values in {braces} are the mean and standard deviation of the measured tissue concentrations (adult fish only) for all sampling locations within the WRB combined (n = number of tissue samples for a given species).

d) Least-squares mean (with 95% confidence interval) mercury concentration in large (>120 mm) fish sampled in the Western aggregate ecoregion of Oregon, as reported in [37].

Table 8. Comparison of model estimated biomagnification factors for eight species of Willamette River fish and U.S. EPA national bioaccumulation factors for mercury.

Fish Species	Model Estimates (L/kg) [a]			
	5th-%tile	50th-%tile	Mean	95th-%tile
TROPHIC LEVEL 4 SPECIES				
Northern pikeminnow	2.20×10^6	1.02×10^7	1.67×10^7	4.83×10^7
Largemouth bass	1.60×10^6	7.70×10^6	1.39×10^7	4.34×10^7
Smallmouth bass	4.36×10^5	3.67×10^6	8.10×10^6	3.03×10^7
U.S. EPA direct estimate bioaccumulation factor for trophic level 4 species [4, Tables D-8 and -19]	3.26×10^5	6.81×10^6	1.11×10^7	1.42×10^7
TROPHIC LEVEL 3 SPECIES				
Rainbow trout	4.15×10^5	2.20×10^6	4.03×10^6	1.32×10^7
Carp	8.56×10^5	4.09×10^6	6.92×10^6	2.19×10^7
Largescale sucker	7.23×10^5	3.46×10^6	6.04×10^6	1.95×10^7
Bluegill	5.41×10^5	2.61×10^6	3.87×10^6	1.14×10^7
Cutthroat trout	3.39×10^5	1.54×10^5	2.60×10^6	7.92×10^6
U.S. EPA direct estimate bioaccumulation factor for trophic level 3 species [4, Tables D-7 and -18]	4.61×10^5	1.58×10^6	2.09×10^6	5.41×10^6

a) Biomagnification factor estimates based on a 1-D MC (stochastic variability and incertitude combined) analysis.

Table 9. Potential species-specific surface water target levels for total mercury in the Willamette River Basin, based on a post-calibration model.

	Model Estimate (ng/L) [a]					
Fish Species	5th-%tile [b]	50th-%tile [c]		95th-%tile [d]		
Northern pikeminnow	10.03	0.92		0.07		
Largemouth bass	15.16	1.27		0.11		
Smallmouth bass	38.42	2.82		0.20		
Rainbow trout	54.72	4.78		0.31		
Bluegill	37.56	3.65		0.40		
Largescale sucker	28.97	2.75		0.22		
Carp	34.96	3.25		0.21		
Cutthroat trout	73.40	6.02		0.50		

a) Calculated using Equation {12} and 1-D MC methods, with biomagnification factor and Ω as distributions.
b) Total mercury concentration that would achieve the U.S. EPA tissue criterion in 5 percent of individuals.
c) Total mercury concentration that would achieve the U.S. EPA tissue criterion in 50 percent of individuals.
d) Total mercury concentration that would achieve the U.S. EPA tissue criterion in 95 percent of individuals.

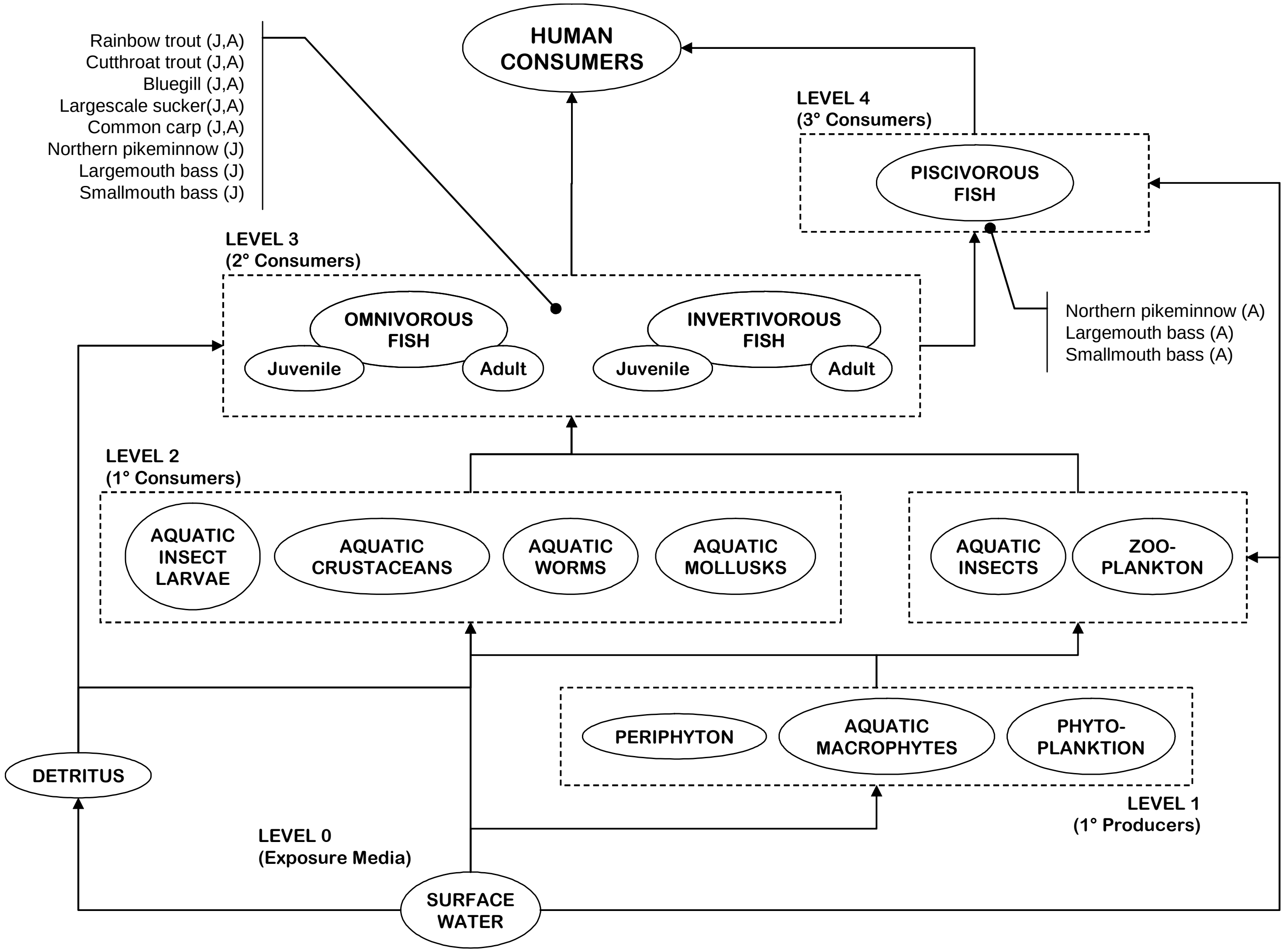

Figure 1. Overview of representative aquatic species and feeding relationships included in the Willamette River Basin food web model. (J = juvenile fish; A = adult fish),

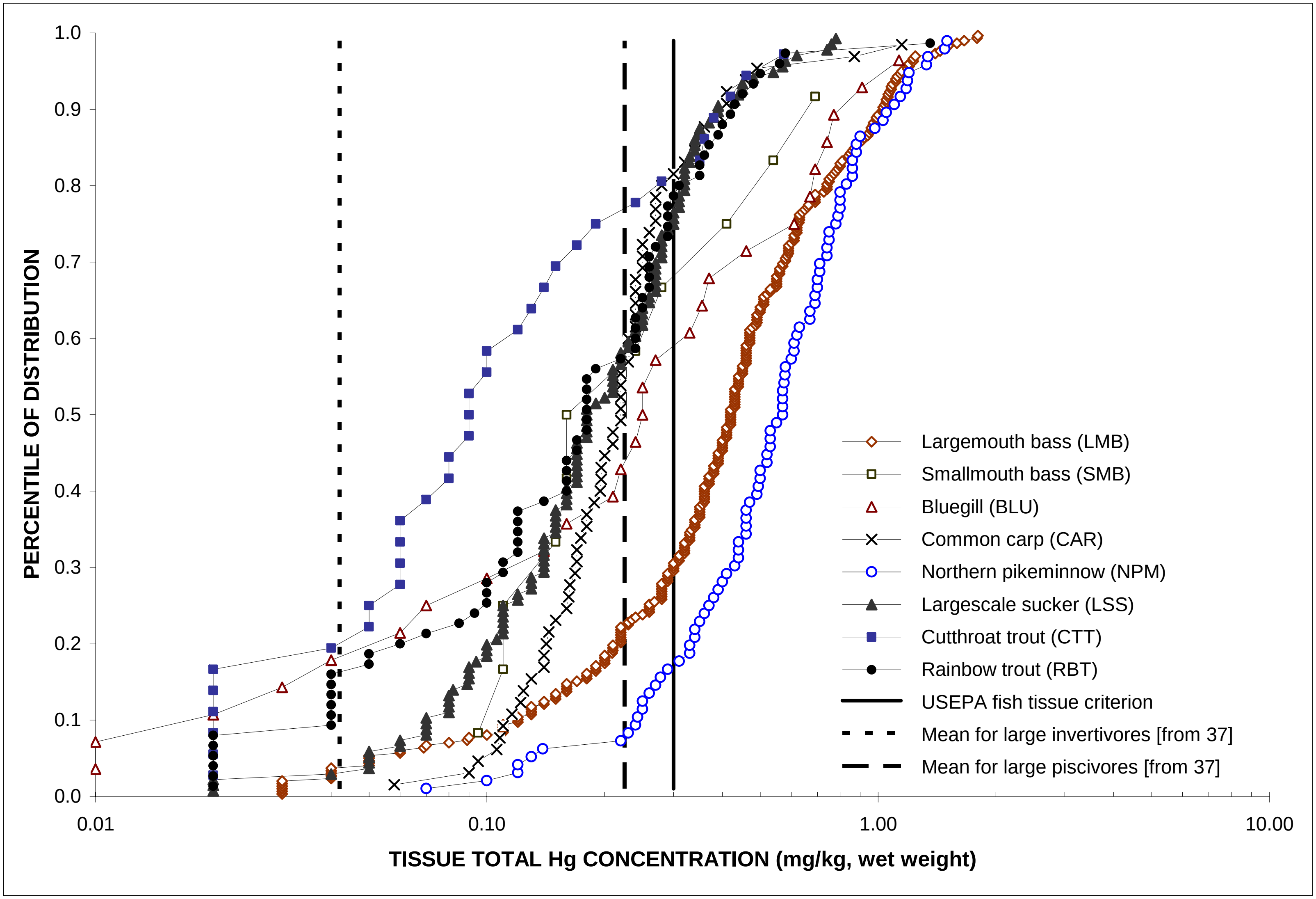

Figure 2. Empirical density functions of tissue total mercury concentrations in eight species of Willamette River Basin fish. U.S. EPA human health fish tissue criterion (0.3 mg/kg) and results of recent survey of mercury in Oregon fish [37] provided for comparison.

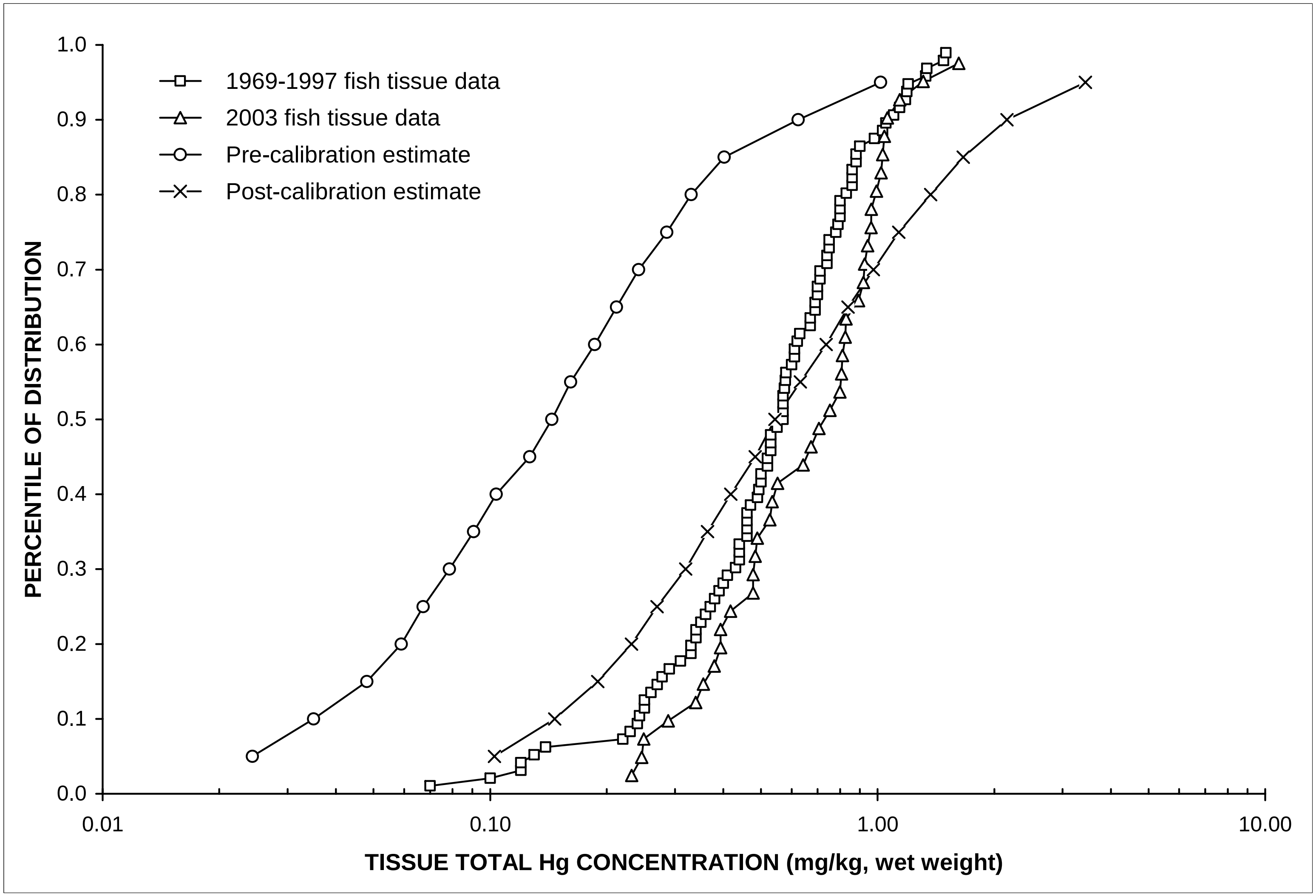

Figure 3. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in northern pikeminnow (NPM).

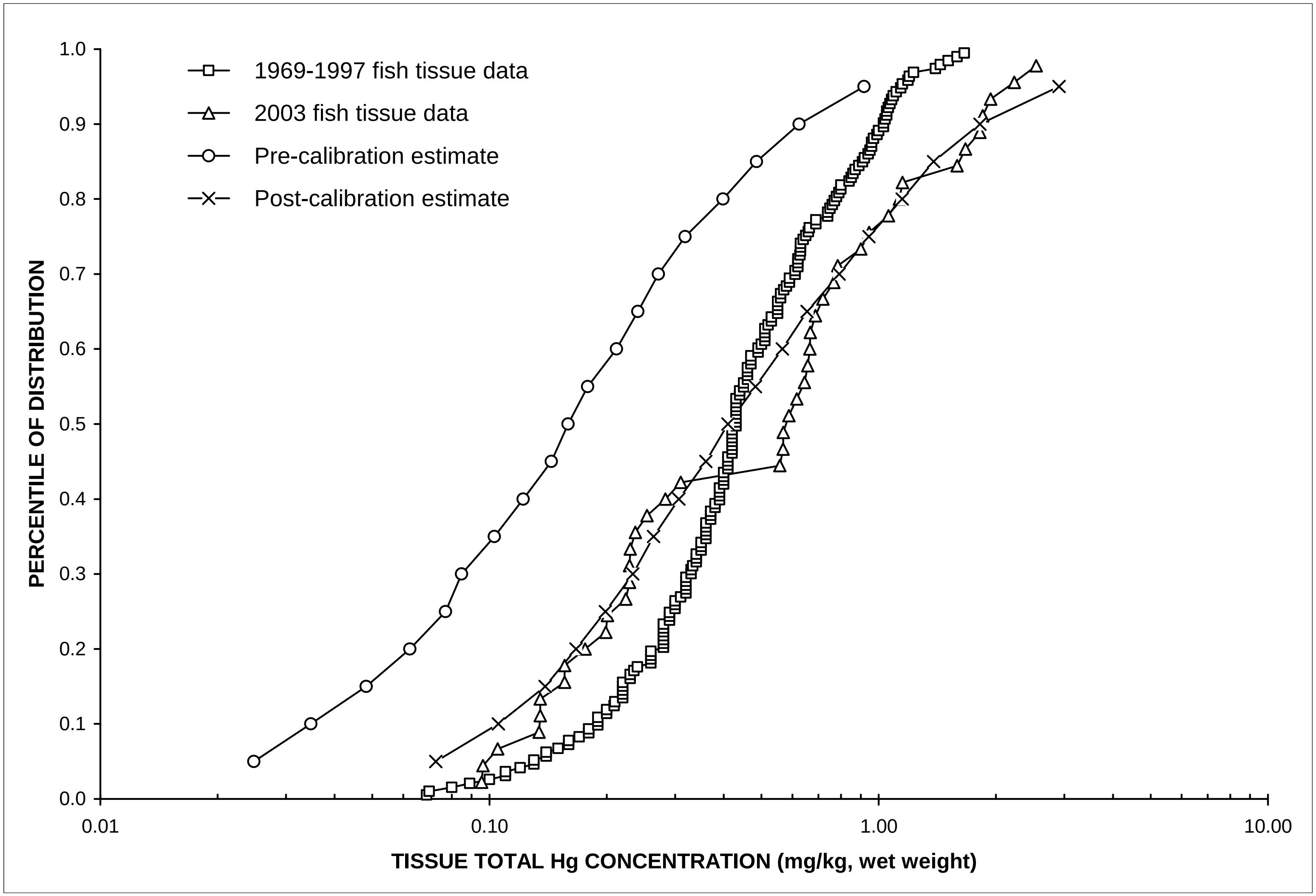

Figure 4. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in largemouth bass (LMB).

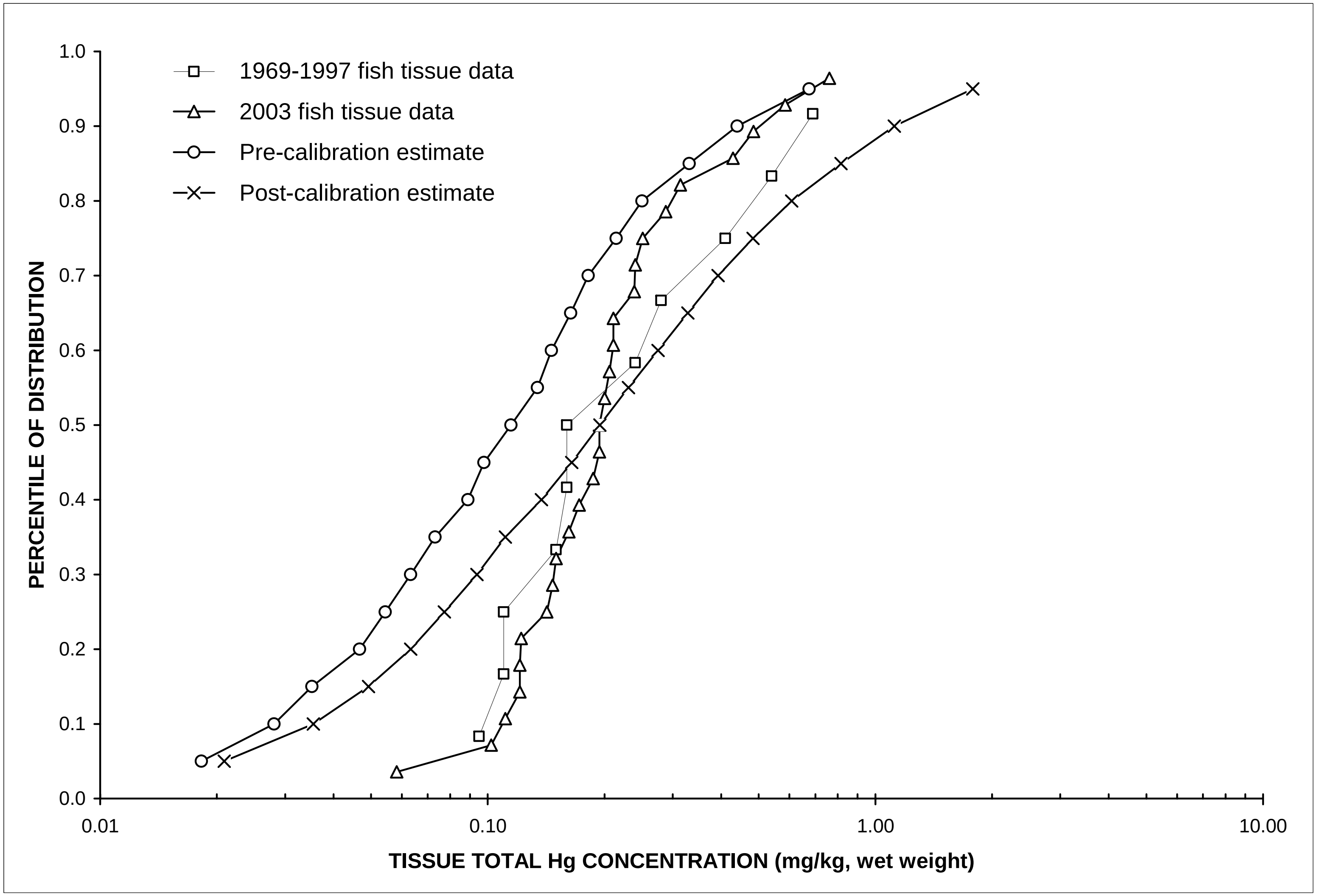

Figure 5. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in smallmouth bass (SMB).

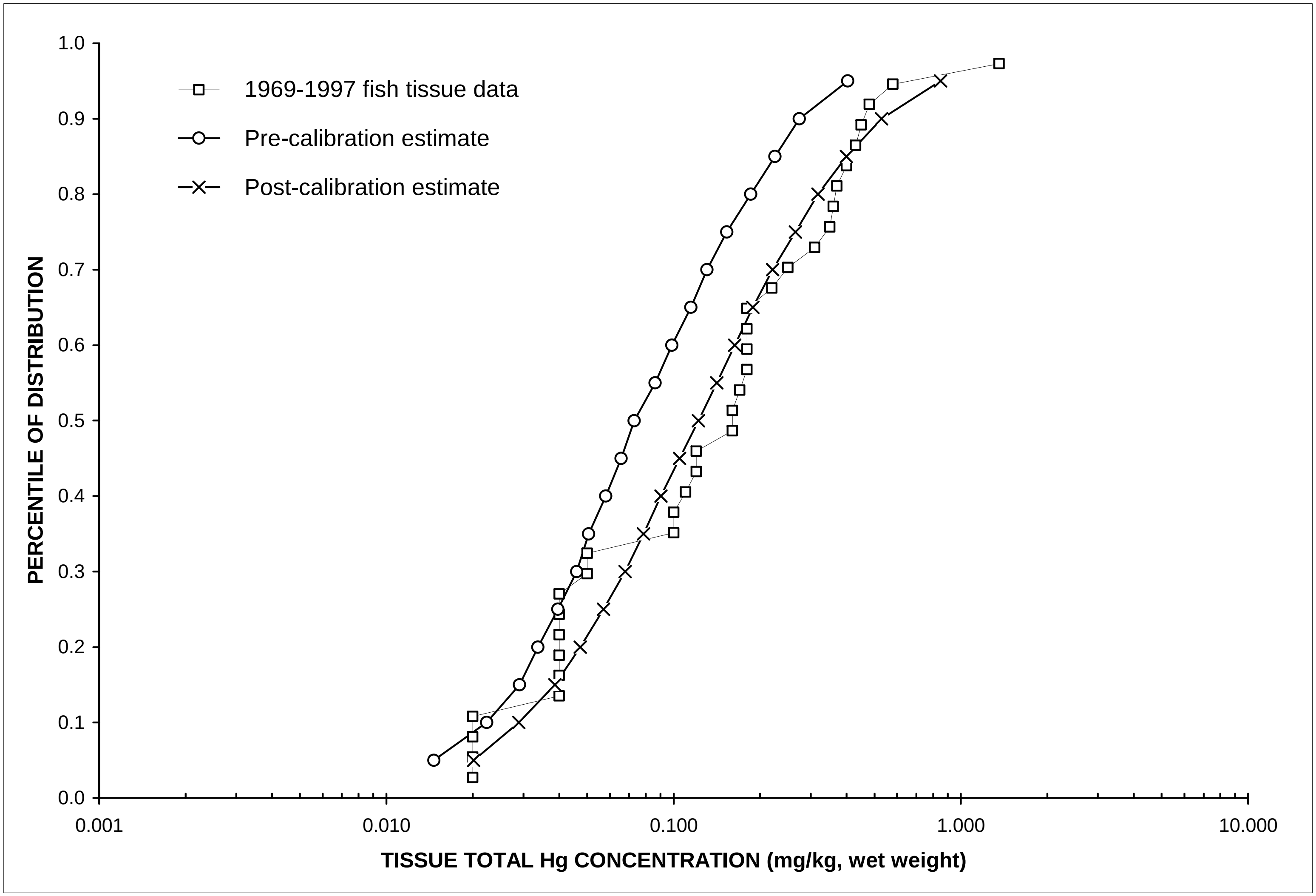

Figure 6. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in rainbow trout (RBT).

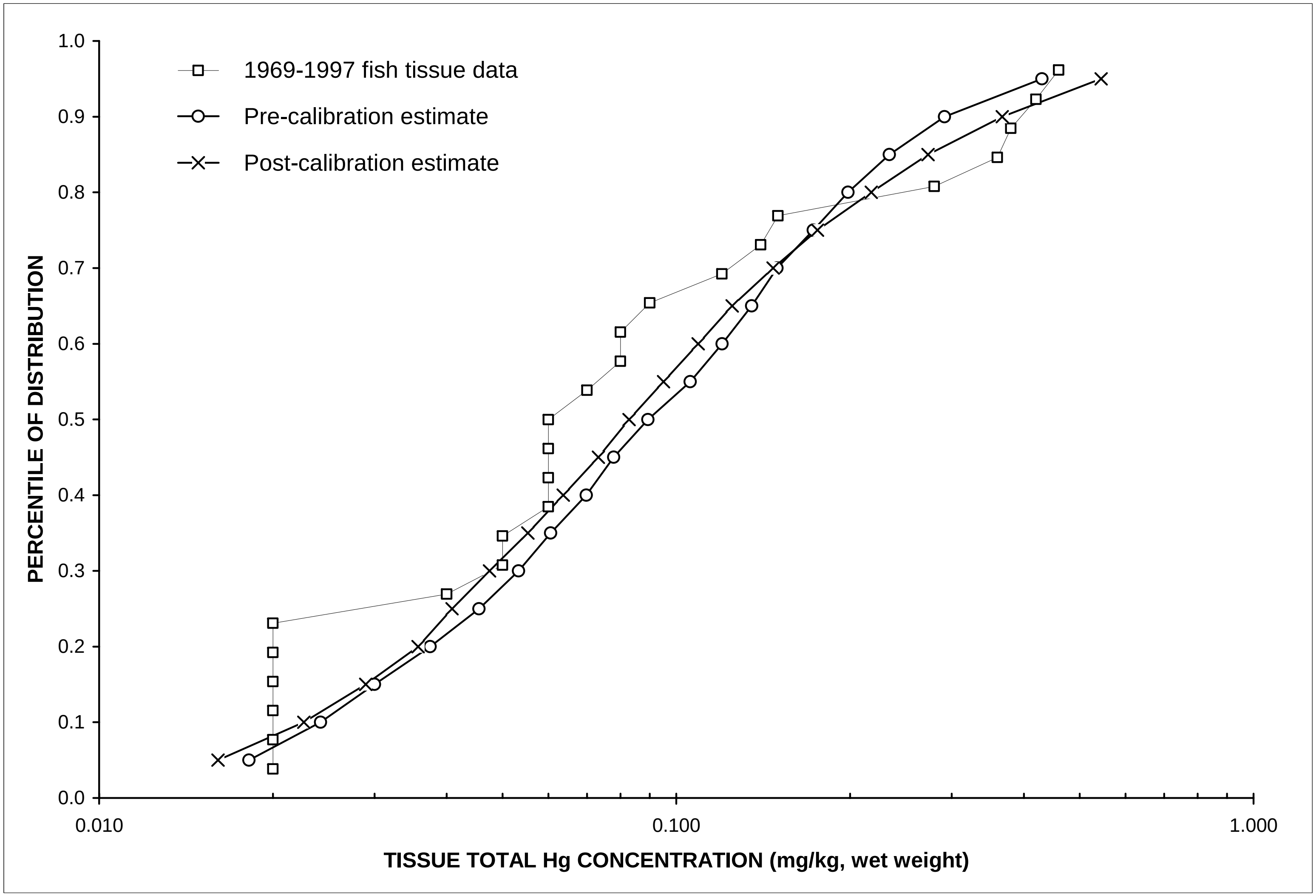

Figure 7. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in cutthroat trout (CTT).

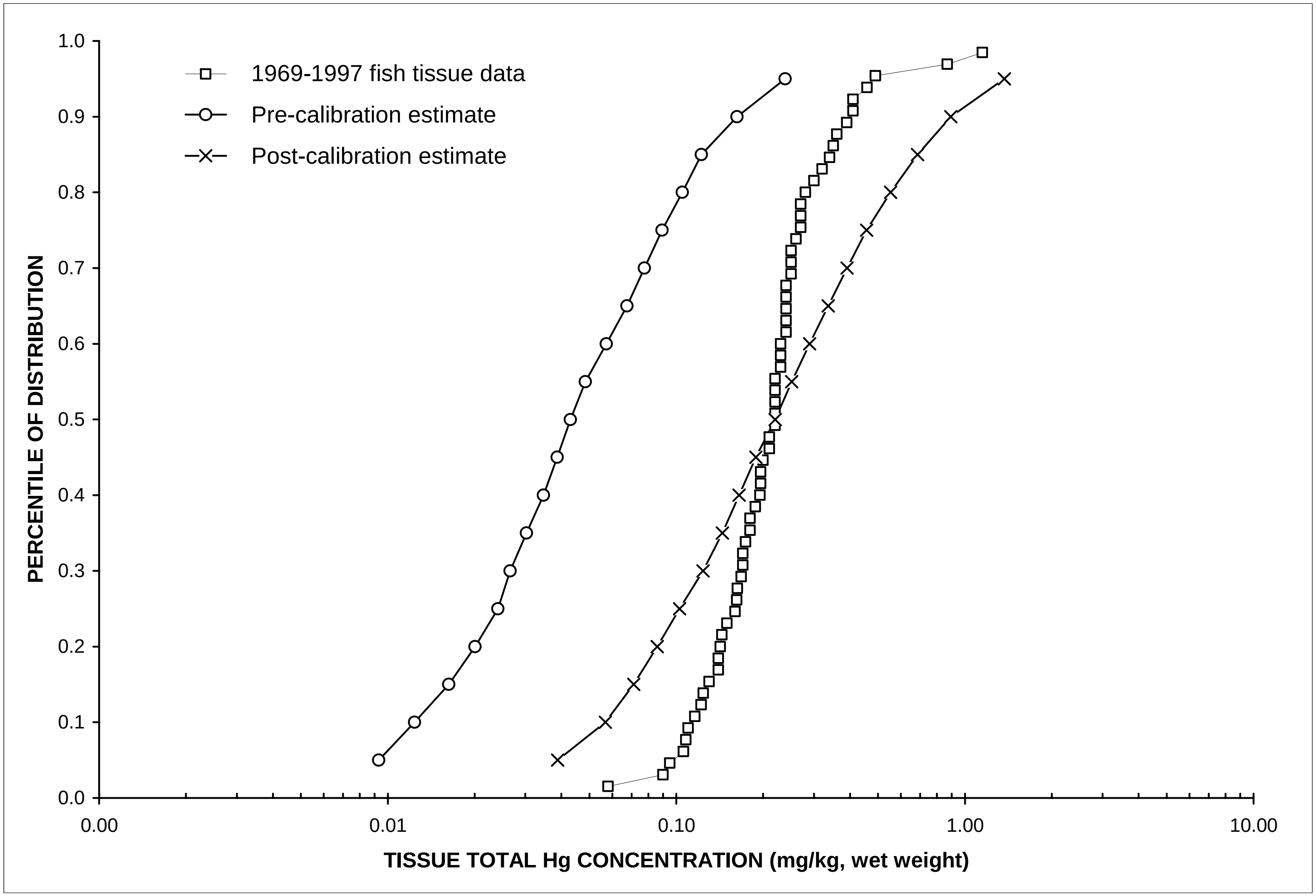

Figure 8. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in common carp (CAR).

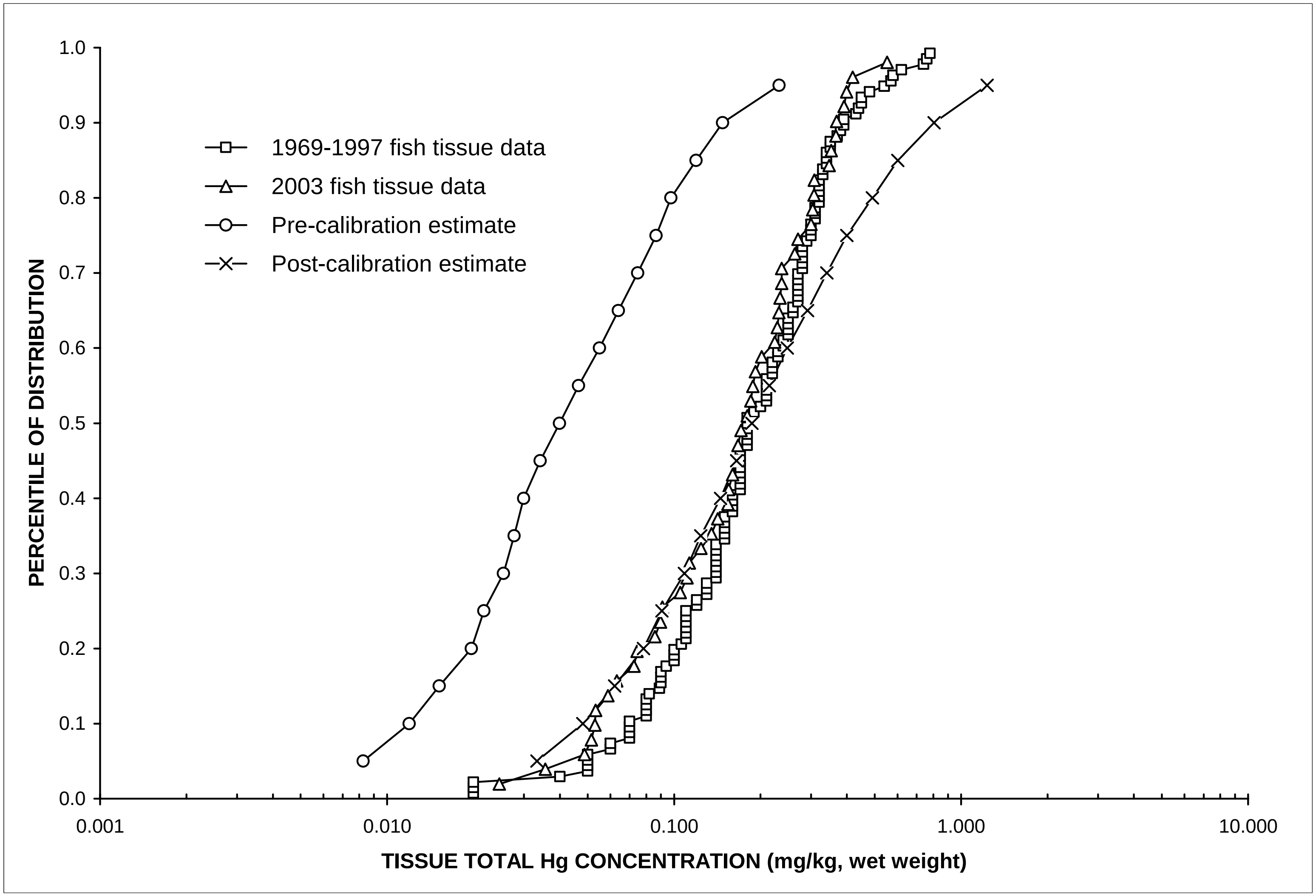

Figure 9. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in largescale sucker (LSS).

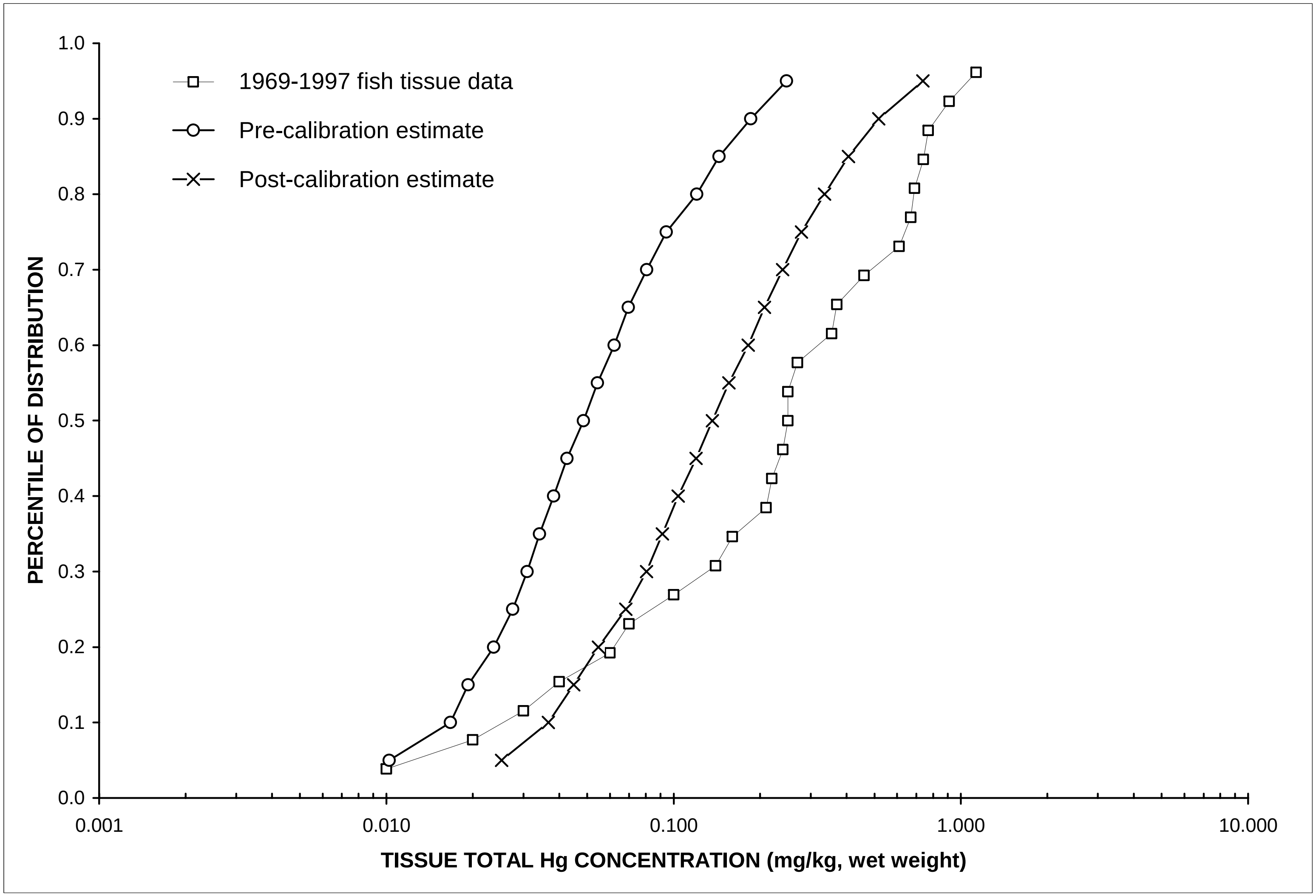

Figure 10. Comparison of measured and pre- and post-calibration model estimates of total mercury concentrations in bluegill (BLU).

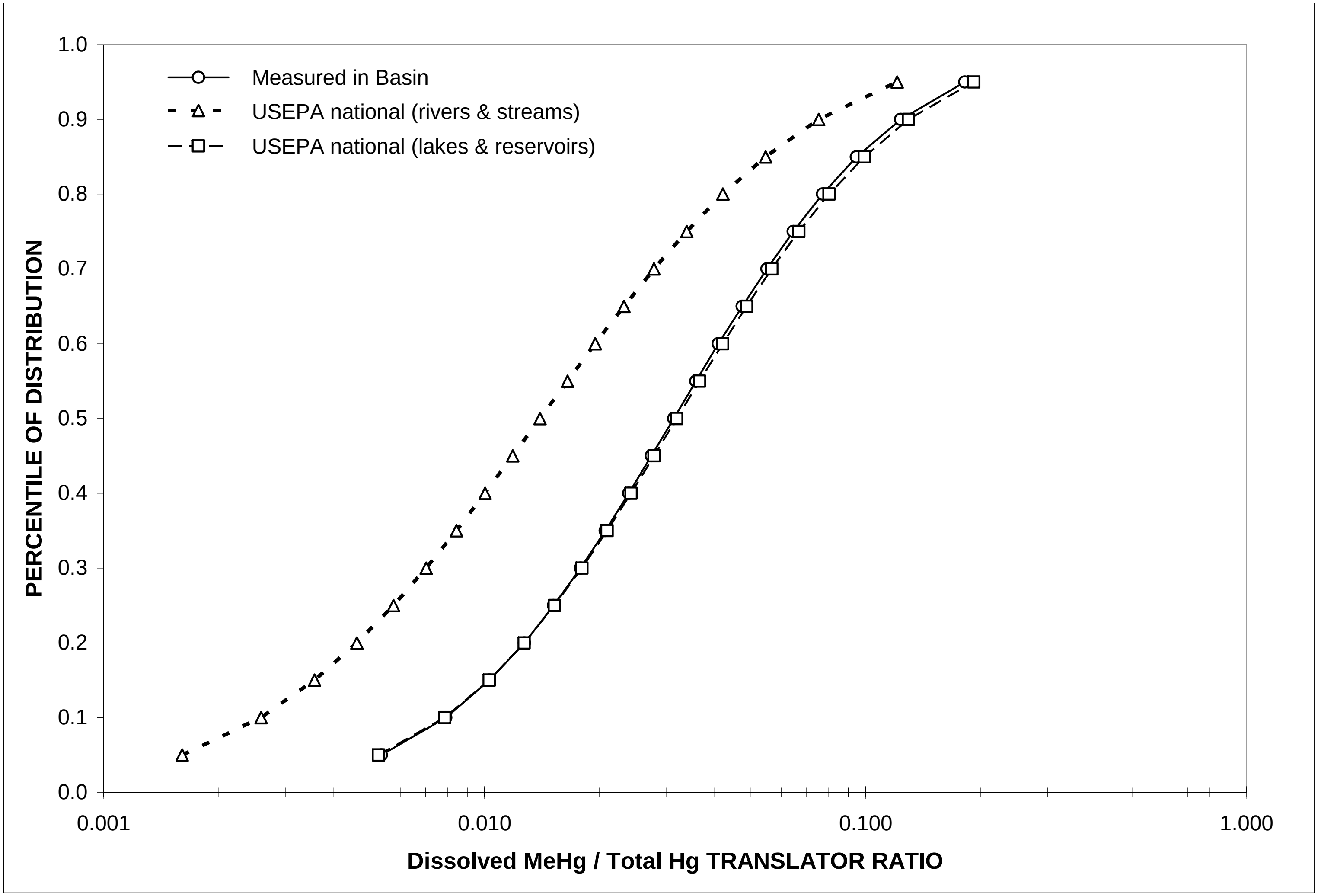

Figure 11. Comparison of MeHg - THg translator ratios measured in the Willamette River Basin [44] to ratios estimated by U.S. EPA for rivers, lakes, reservoirs, and streams [4].

APPENDIX A: COMPARISON OF MODELED AND MEASURED FISH LENGTH DISTRIBUTIONS

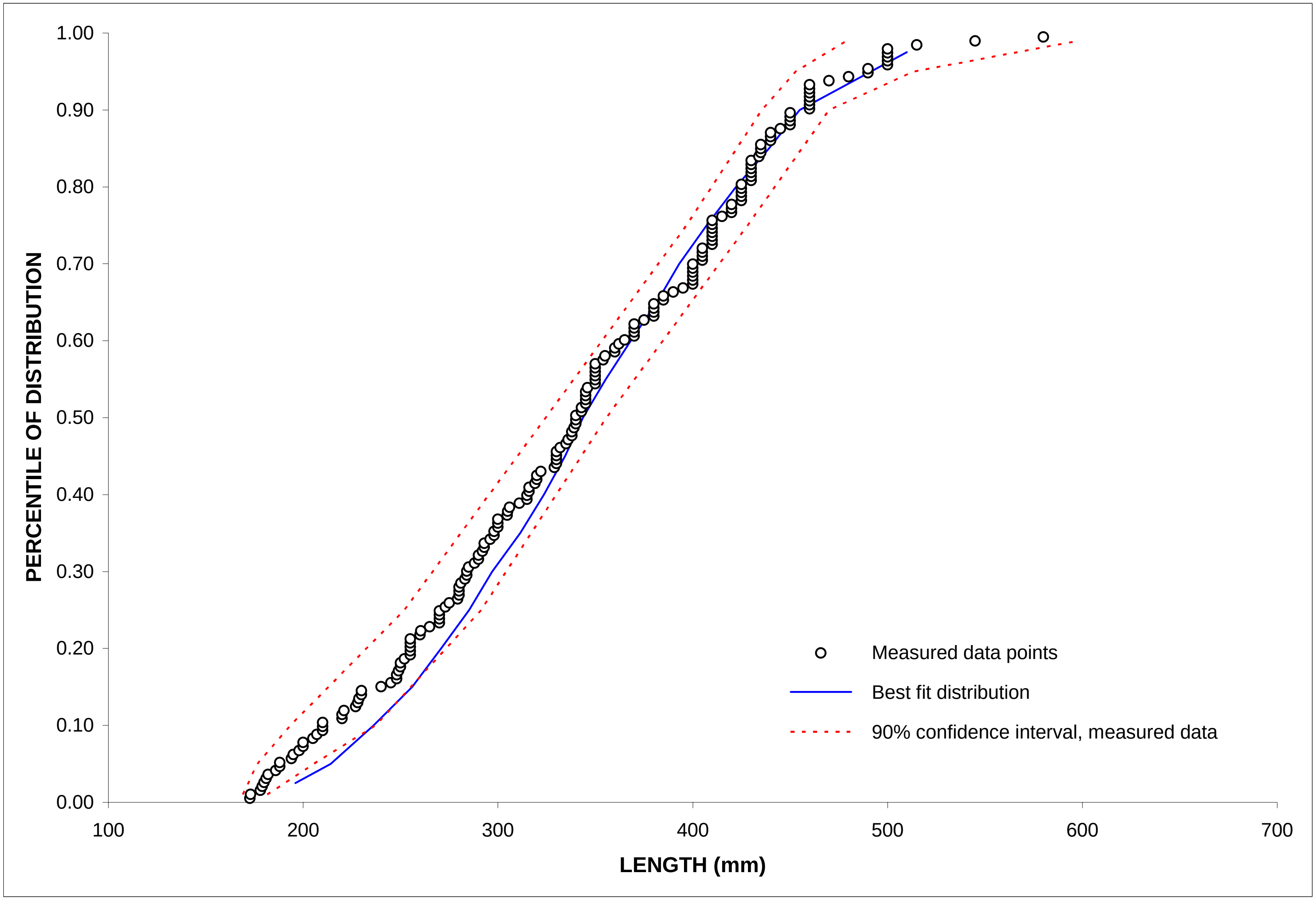

Figure A-1. Comparison of the measured adult fish body length empirical density function (O) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for largemouth bass (LMB).

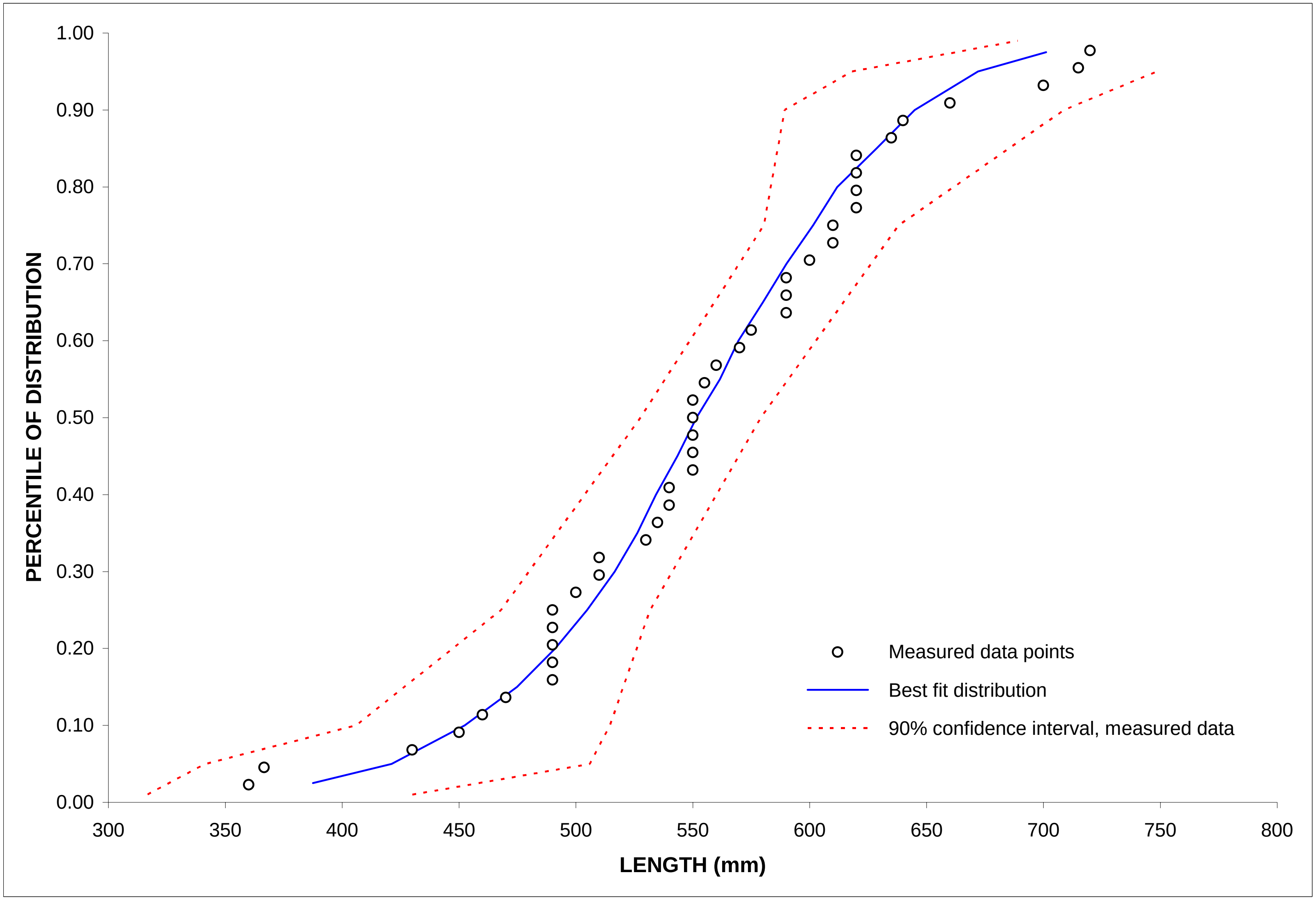

Figure A-2. Comparison of the measured adult fish body length empirical density function (O) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for common carp (CAR).

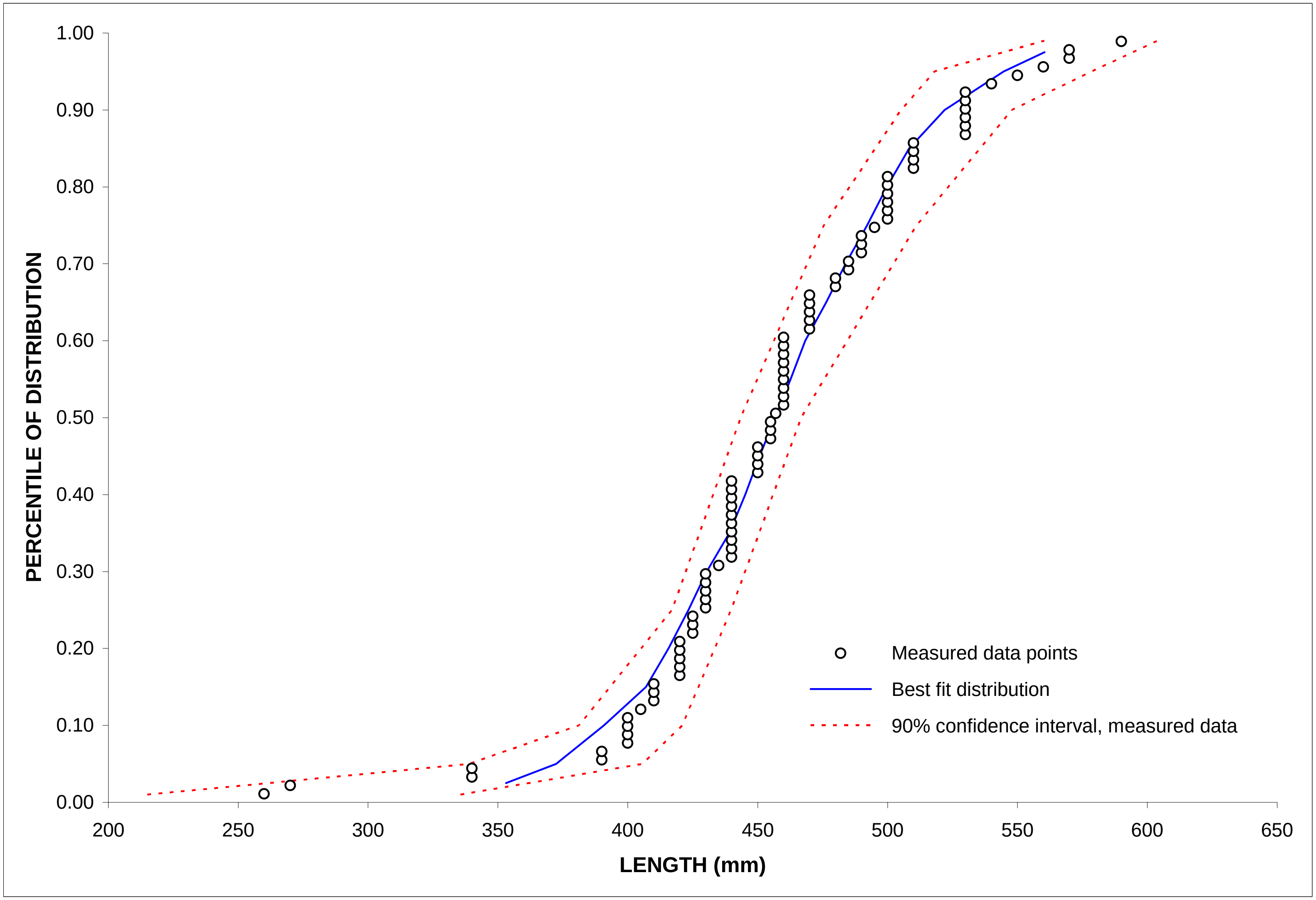

Figure A-3. Comparison of the measured adult fish body length empirical density function (○) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for largescale sucker (LSS).

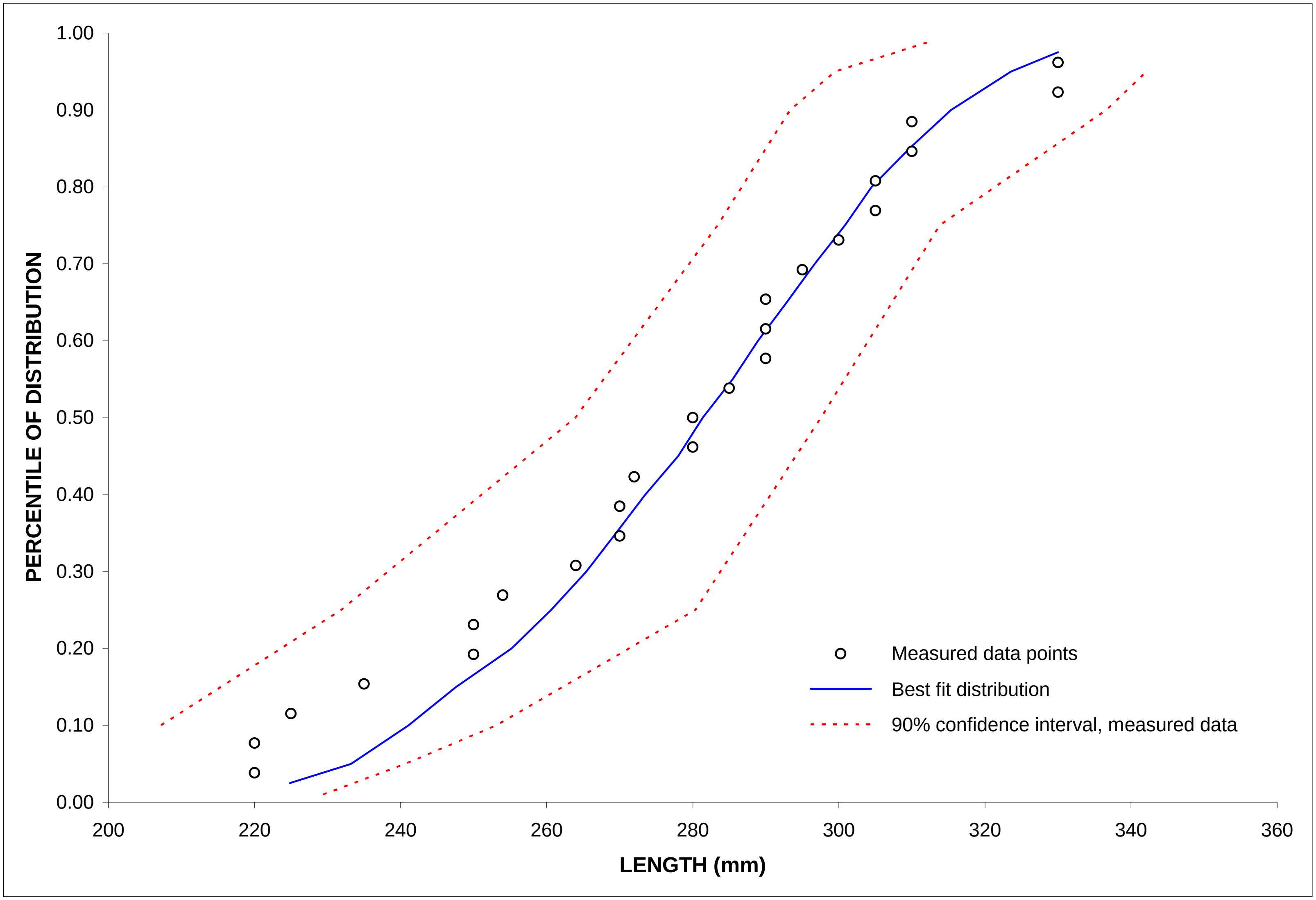

Figure A-4. Comparison of the measured adult fish body length empirical density function (○) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for cutthroat trout (CTT).

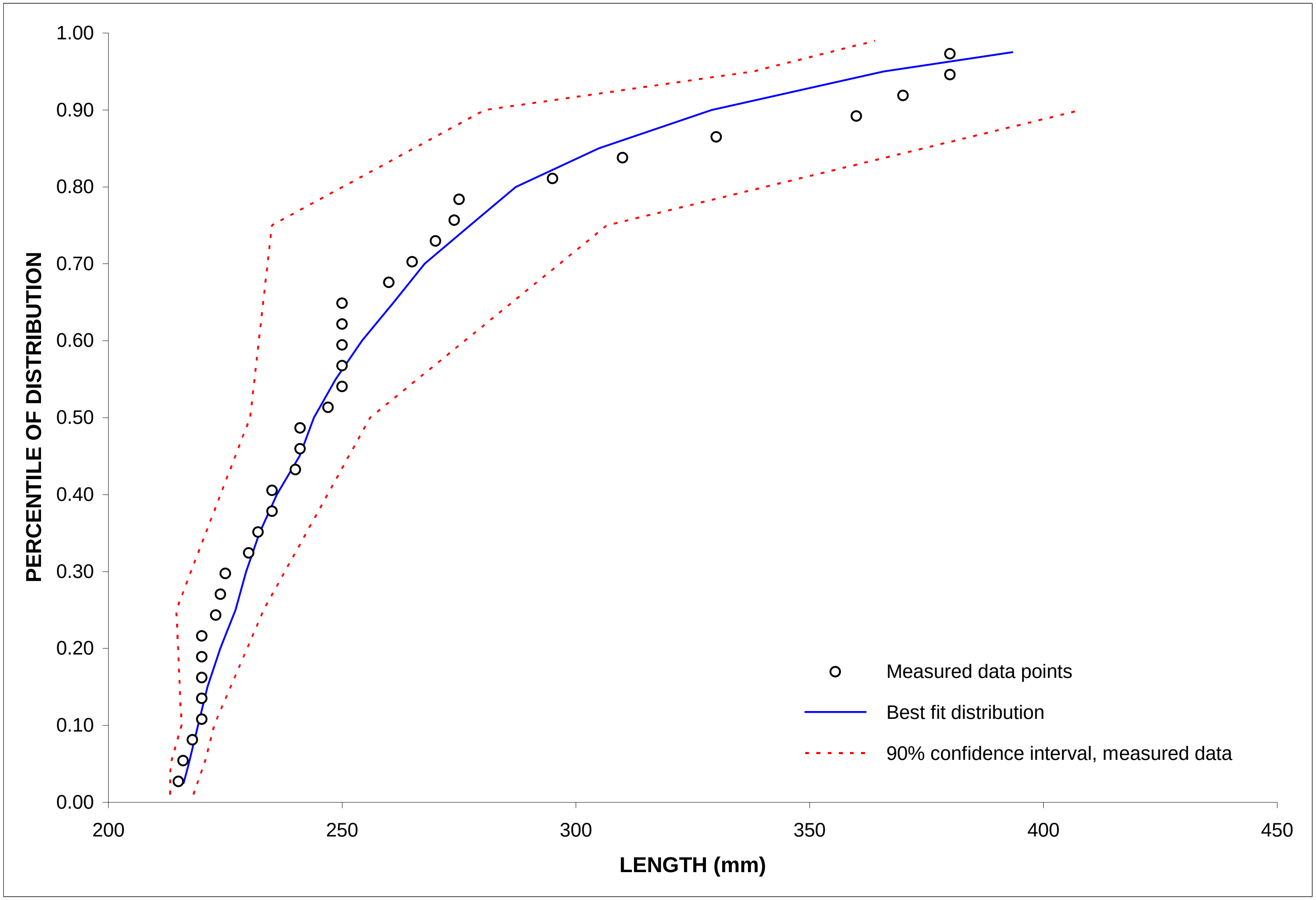

Figure A-5. Comparison of the measured adult fish body length empirical density function (O) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for rainbow trout (RBT).

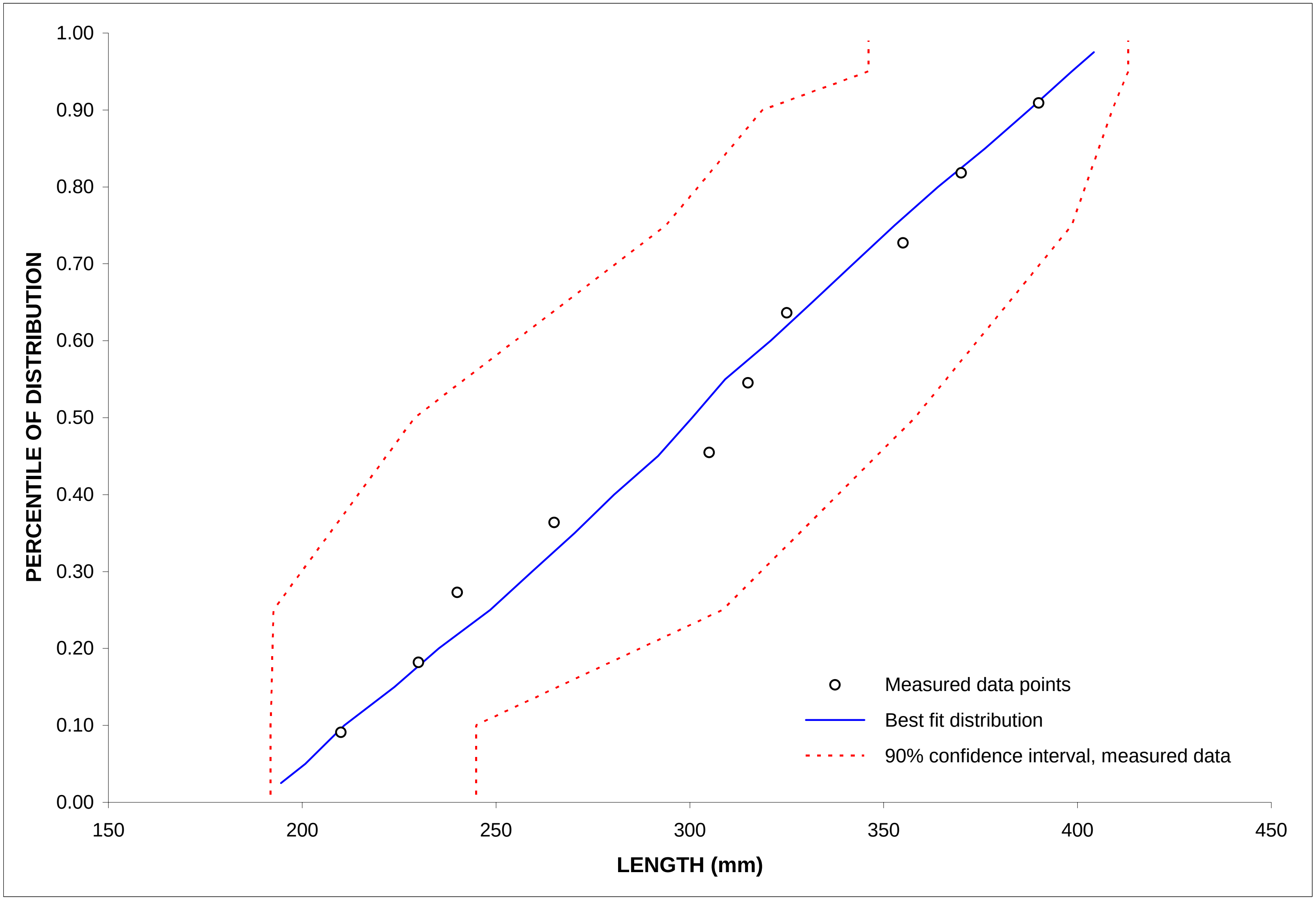

Figure A-6. Comparison of the measured adult fish body length empirical density function (O) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for smallmouth bass (SMB).

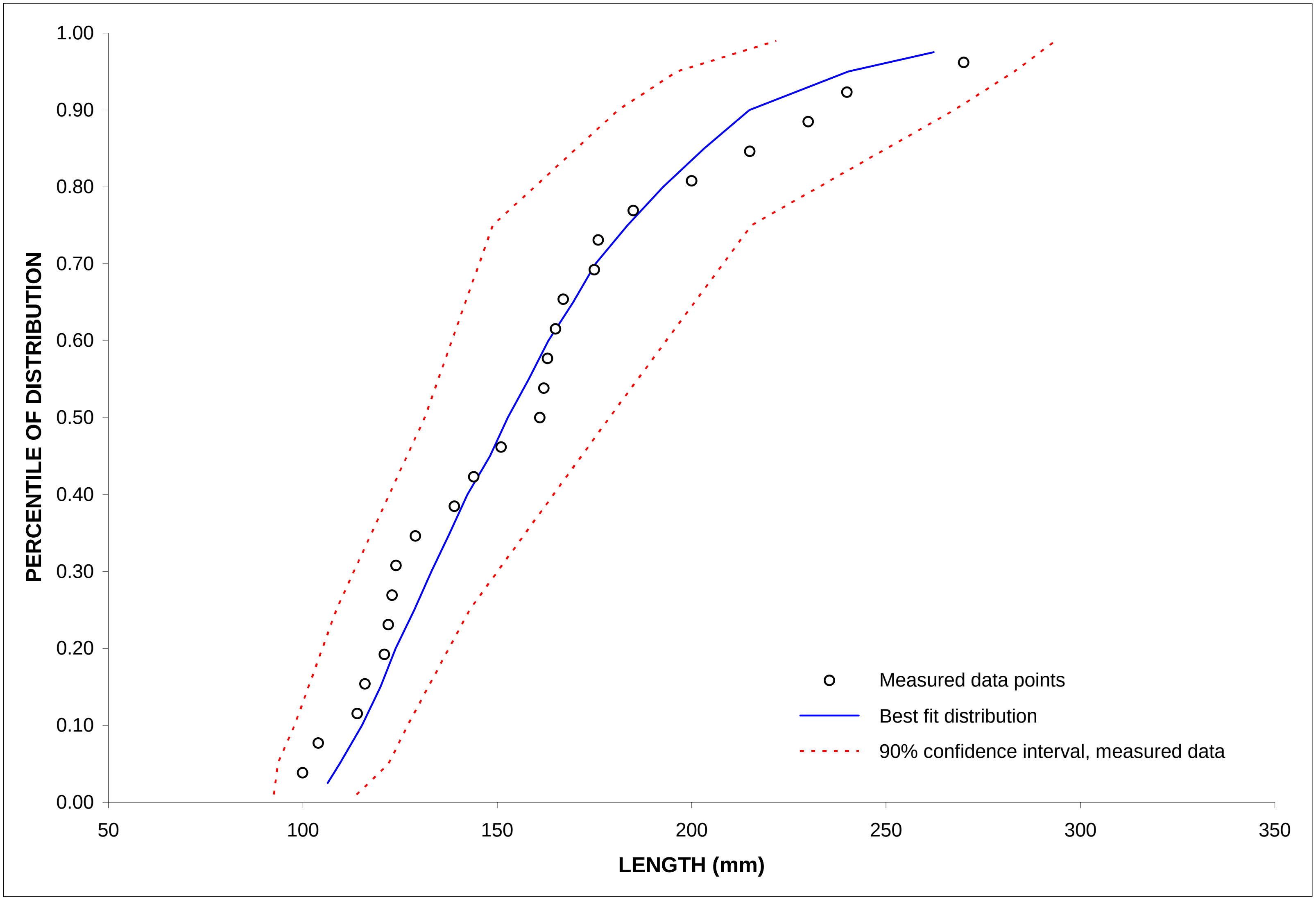

Figure A-7. Comparison of the measured adult fish body length empirical density function (○) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for bluegill (BLU).

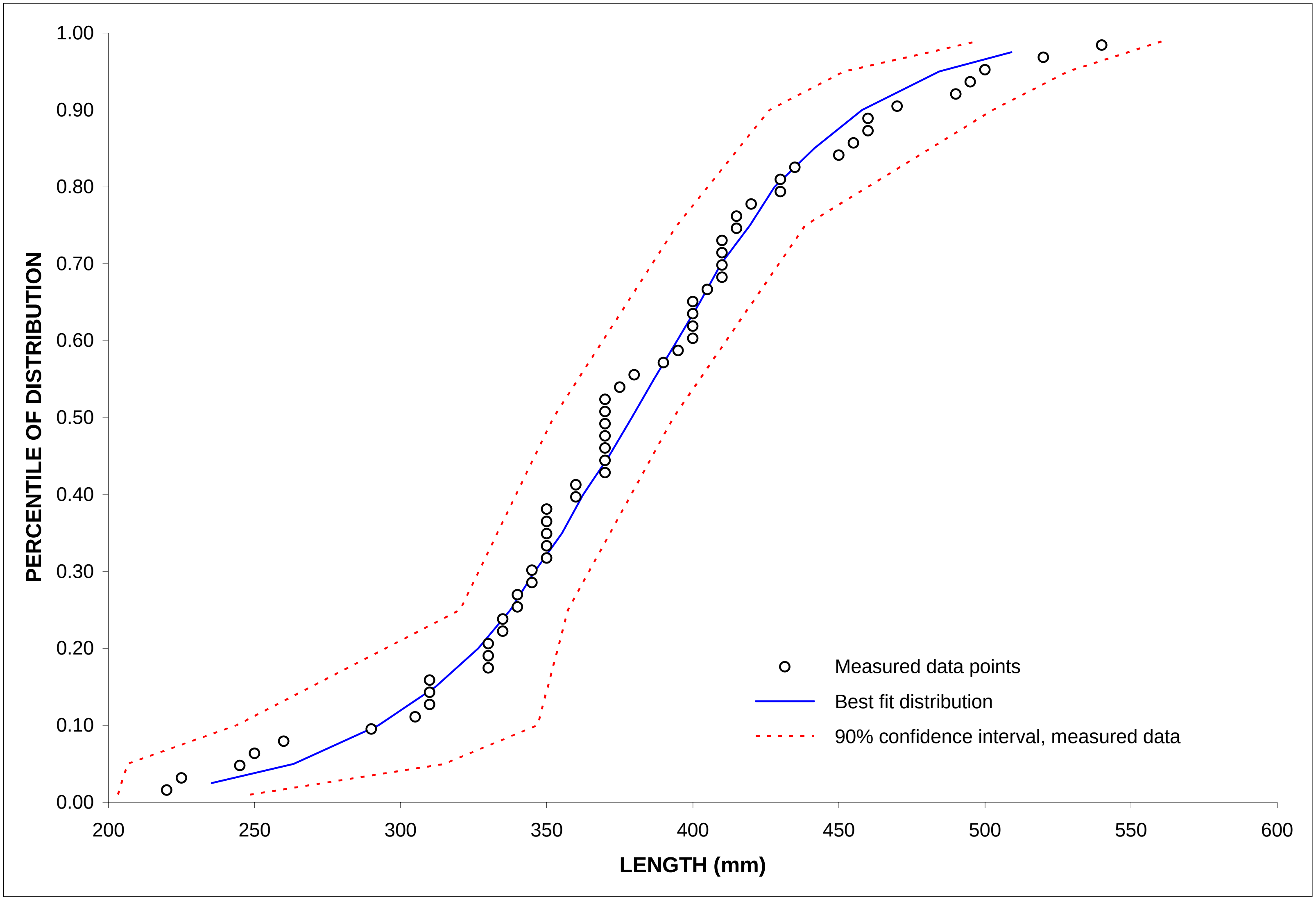

Figure A-8. Comparison of the measured adult fish body length empirical density function (O) (with 90 percent confidence interval (----)) and the best fit cumulative density function (—) for northern pikeminnow (NPM).

APPENDIX B: COMPARISON OF MODELED AND MEASURED FISH LENGTH-WEIGHT RELATIONSHIPS

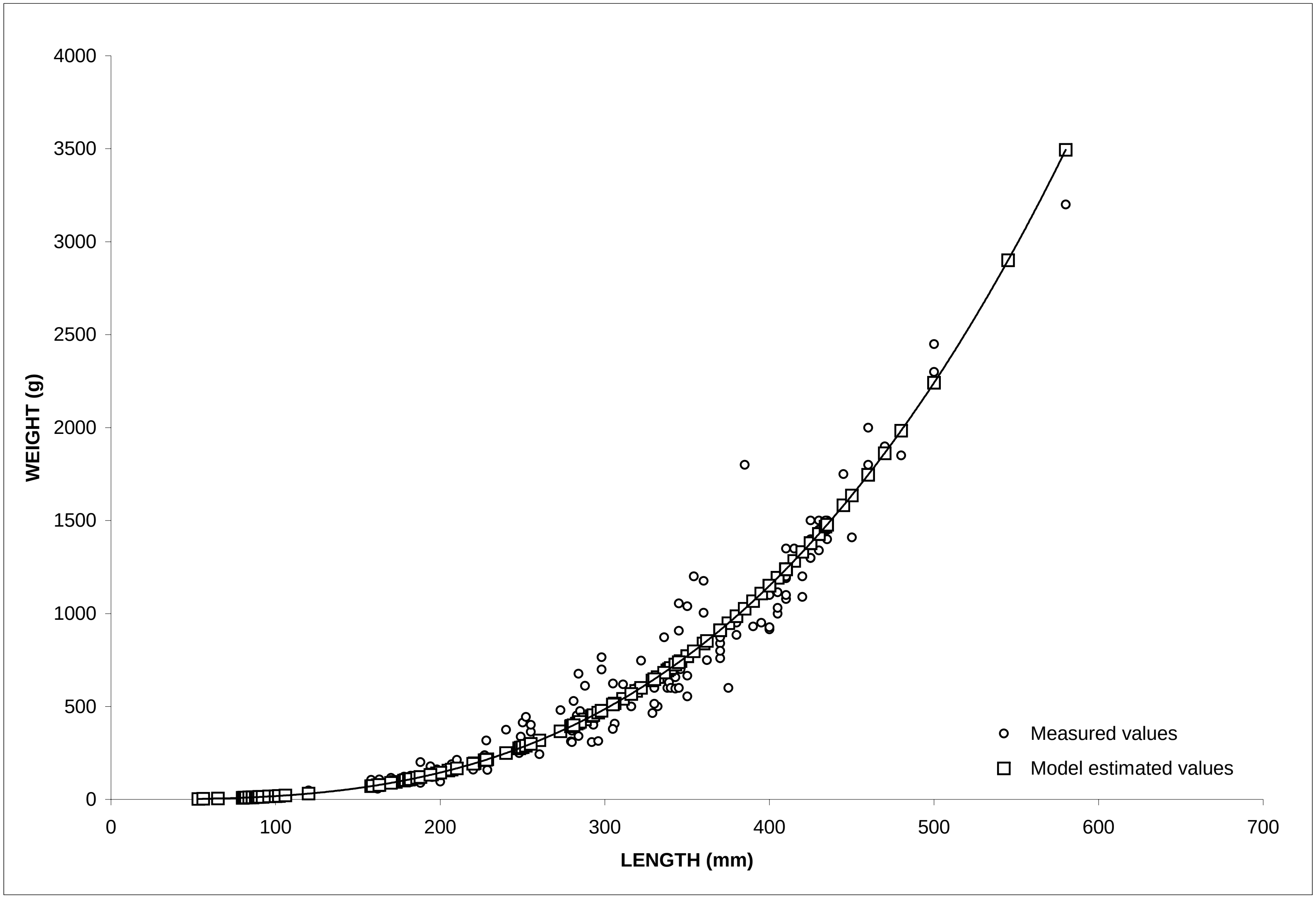

Figure B-1. Comparison of measured (○) and modeled (□) length-weight relationships for largemouth bass (LMB) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.979, *p* <0.001.

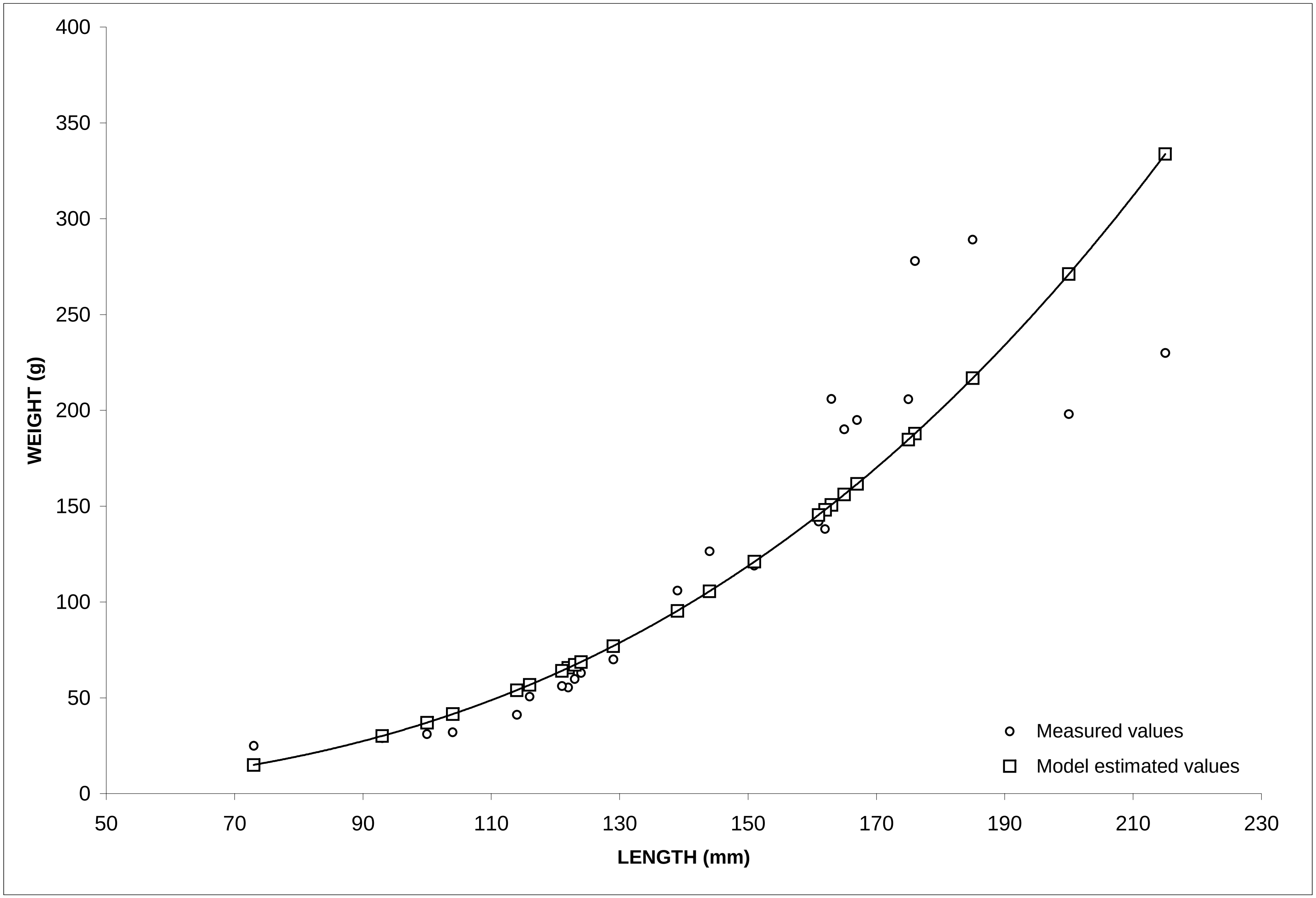

Figure B-2. Comparison of measured (○) and modeled (⊟) length-weight relationships for bluegill (BLU) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.736, p <0.001

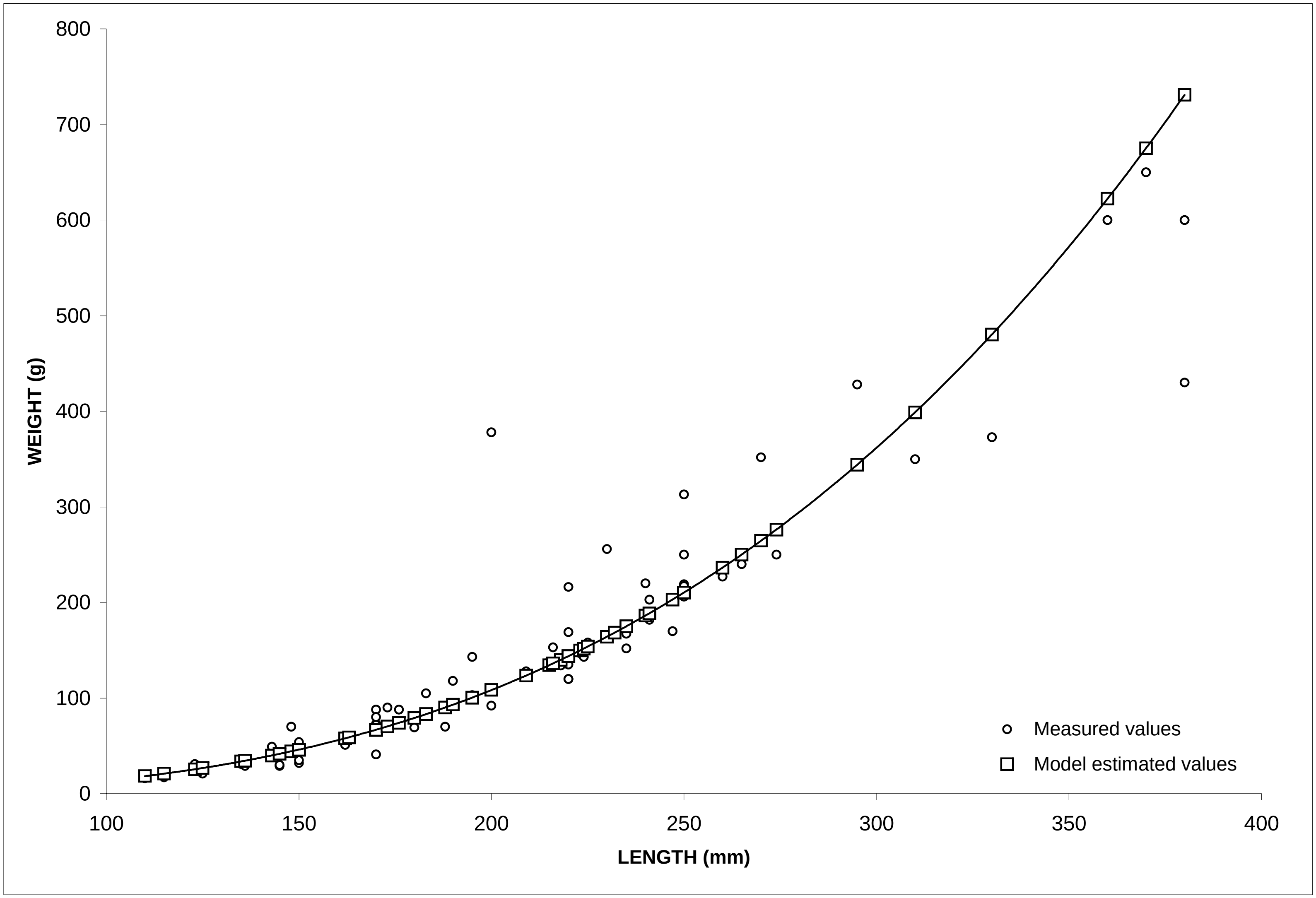

Figure B-3. Comparison of measured (○) and modeled (⊟) length-weight relationships for rainbow trout (RBT) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.964, p <0.001.

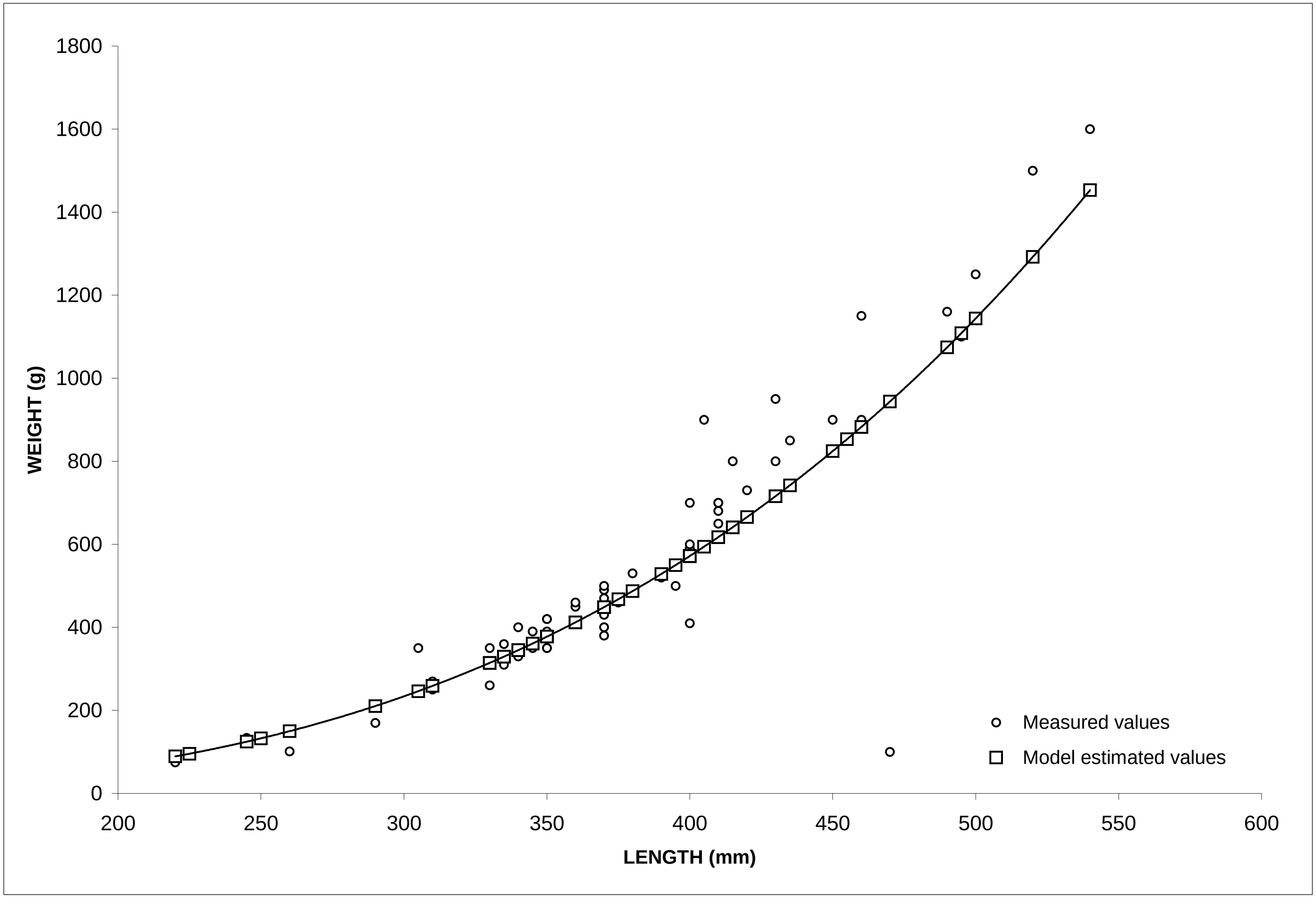

Figure B-4. Comparison of measured (○) and modeled (⊟) length-weight relationships for northern pikeminnow (NPM) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.962, p <0.001.

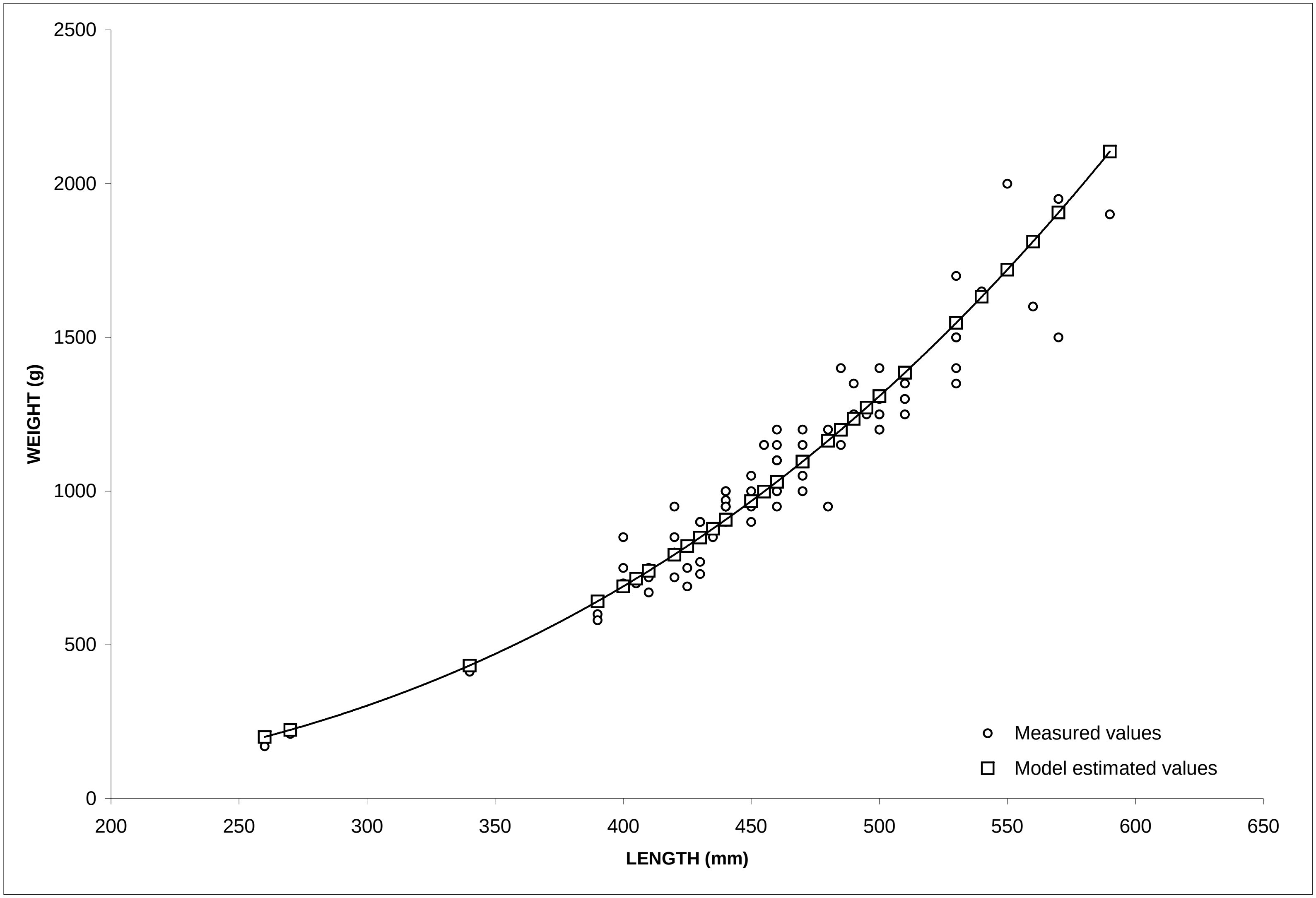

Figure B-5. Comparison of measured (○) and modeled (⊟) length-weight relationships for largescale sucker (LSS) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.964, p <0.001.

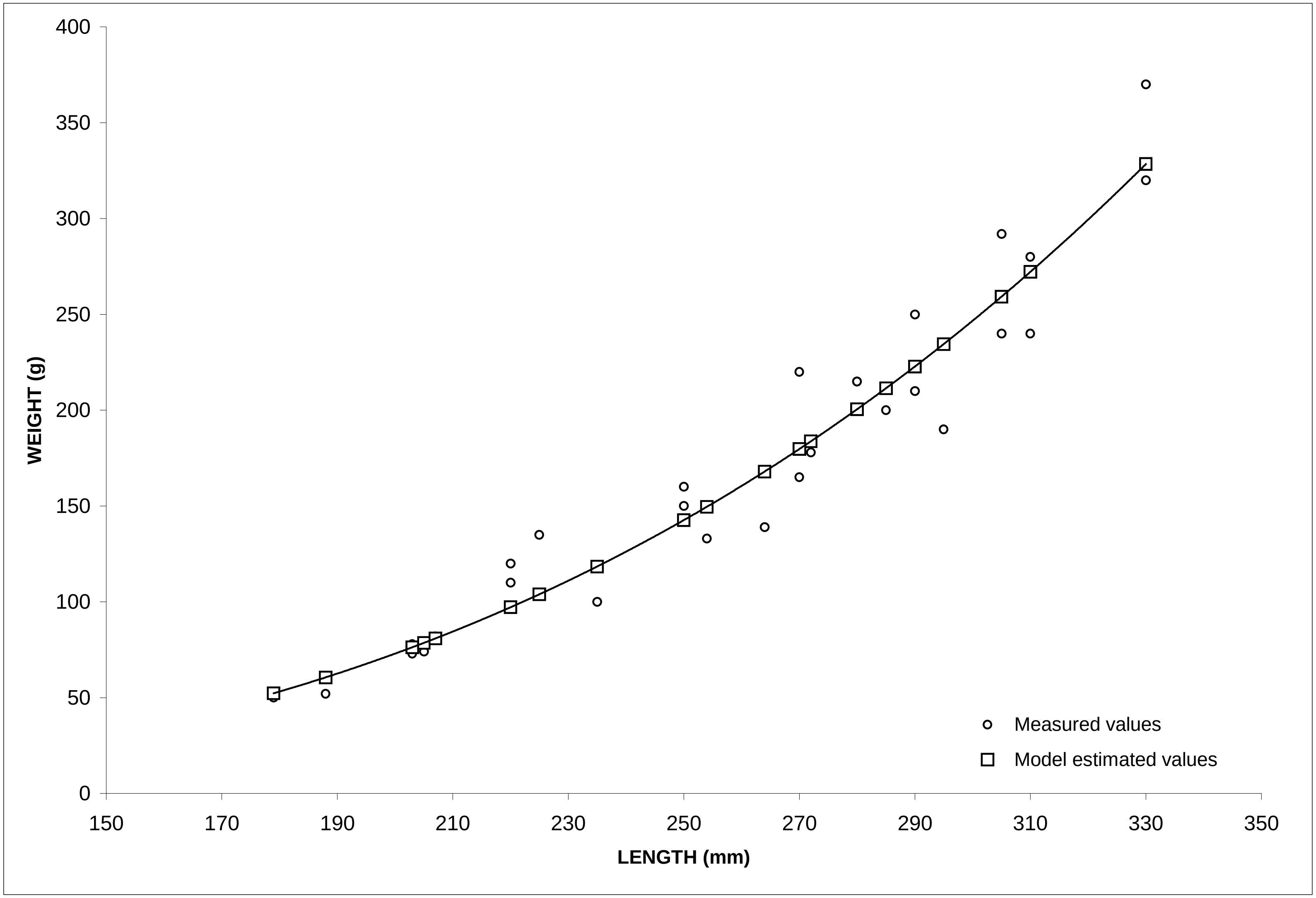

Figure B-6. Comparison of measured (○) and modeled (⊟) length-weight relationships for cutthroat trout (CTT) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.848, p <0.001.

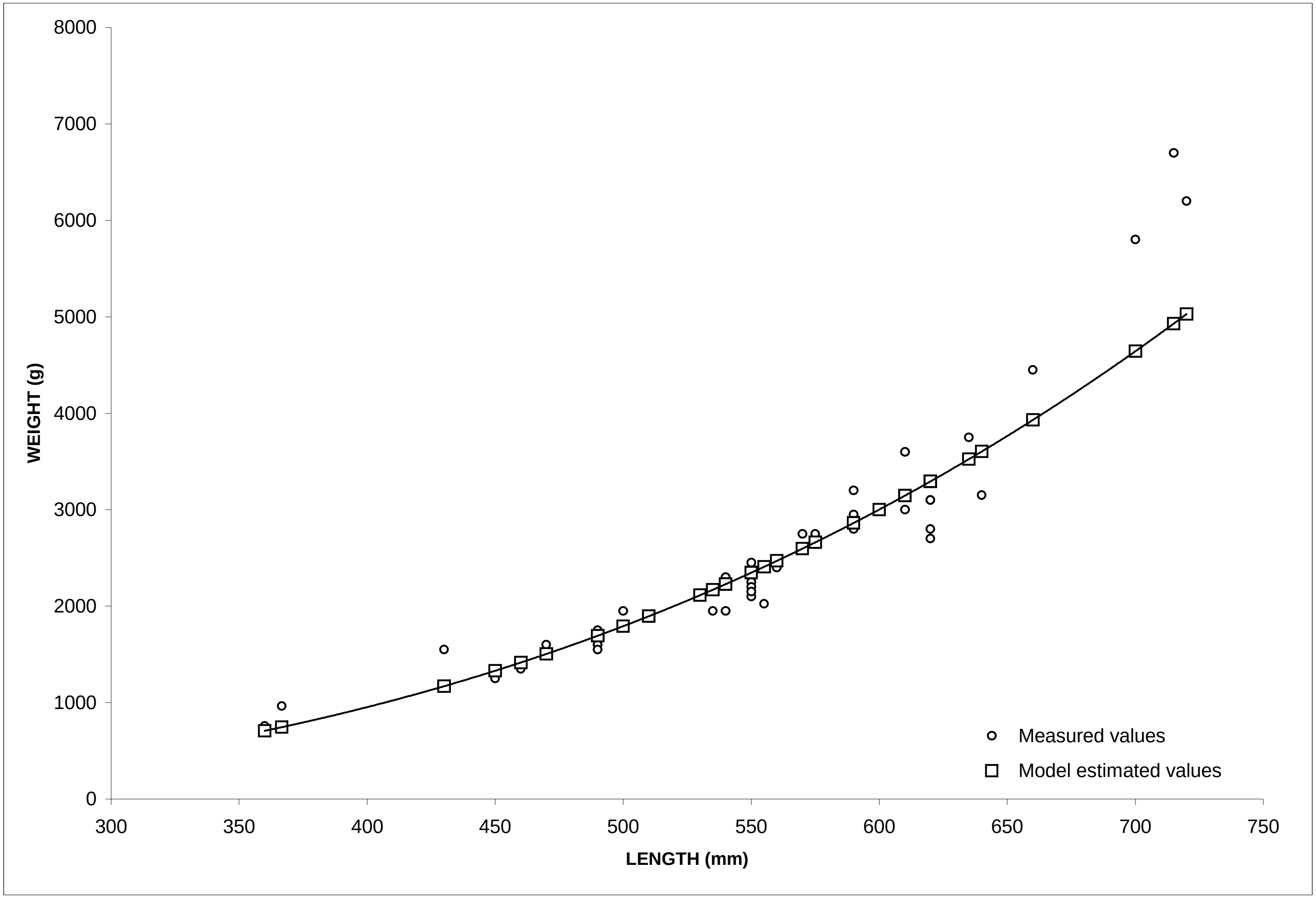

Figure B-7. Comparison of measured (○) and modeled (⊟) length-weight relationships for common carp (CAR) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.933, p <0.001.

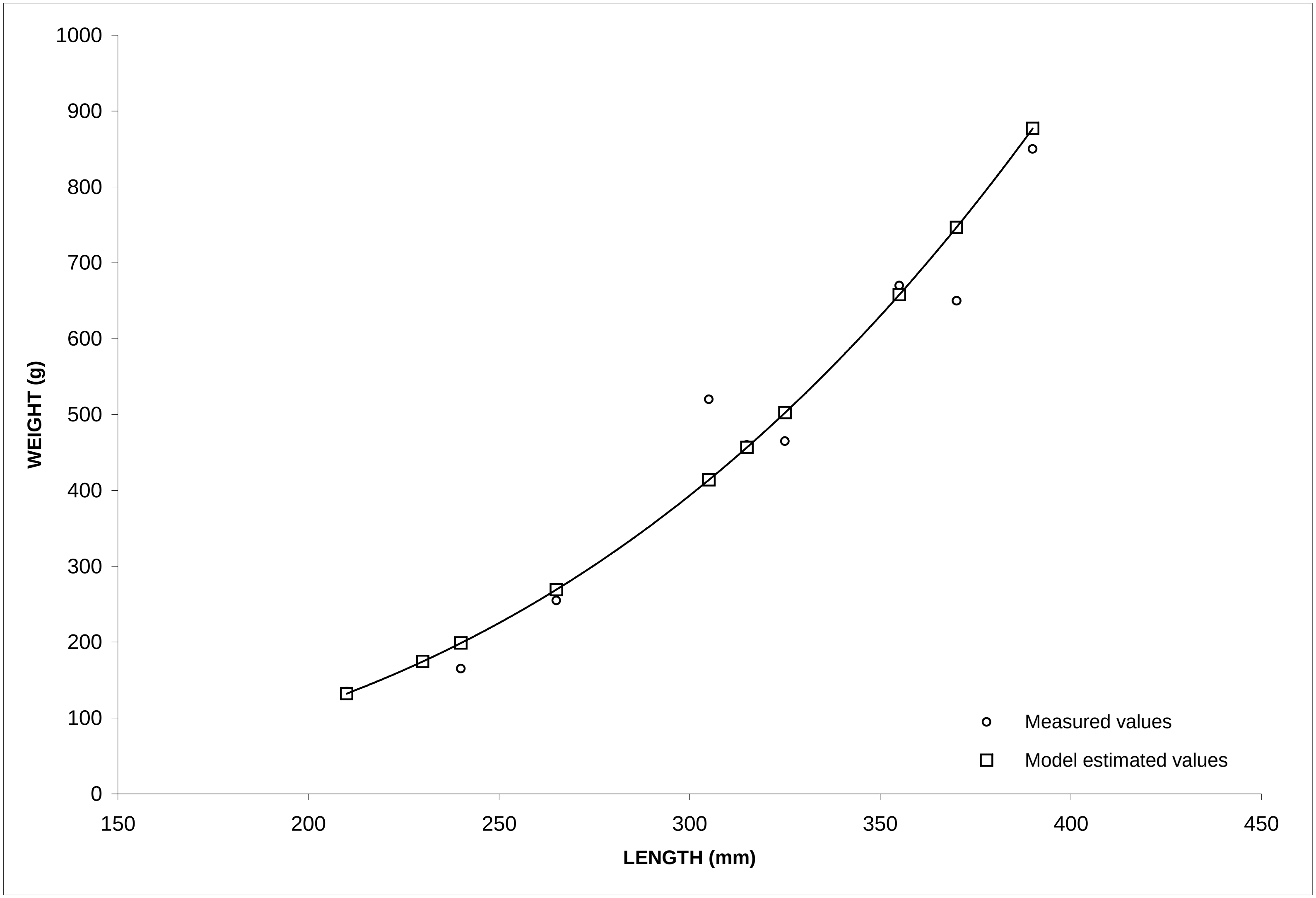

Figure B-8. Comparison of measured (○) and modeled (⊟) length-weight relationships for smallmouth bass (SMB) in the Willamette River Basin. Spearman rank correlation (r_s) = 0.729, p <0.001.

APPENDIX C: COMPARISON OF FISH TISSUE CONCENTRATION - BODY LENGTH RELATIONSHIPS

Table C-1. Summary of regression statistics for measured and model estimated tissue concentration - body length relationships.

	slope	intercept	Spearman (r_s)	Spearman p
MEASURED				
BLU	0.0002	-0.73	-0.02	0.92
NPM	0.0020	-1.00	0.50	<0.001
LMB	0.0008	-0.64	0.23	<0.001
LSS	0.0039	-2.54	0.58	<0.001
CAR	0.0018	-1.60	0.45	0.003
RBT	0.0034	-1.78	0.29	0.09
CTT	0.0042	-2.28	0.38	0.06
SMB	0.0041	-1.86	0.84	0.005
POST - CALIBRATION MODEL ESTIMATE				
BLU	0.0033	-1.39	0.21	<0.001
NPM	0.0015	-0.84	0.26	<0.001
LMB	0.0017	-0.98	0.37	<0.001
LSS	0.0019	-1.66	0.17	<0.001
CAR	0.0012	-1.37	0.22	<0.001
RBT	0.0021	-1.41	0.26	<0.001
CTT	0.0028	-1.90	0.22	<0.001
SMB	0.0023	-1.42	0.34	<0.001

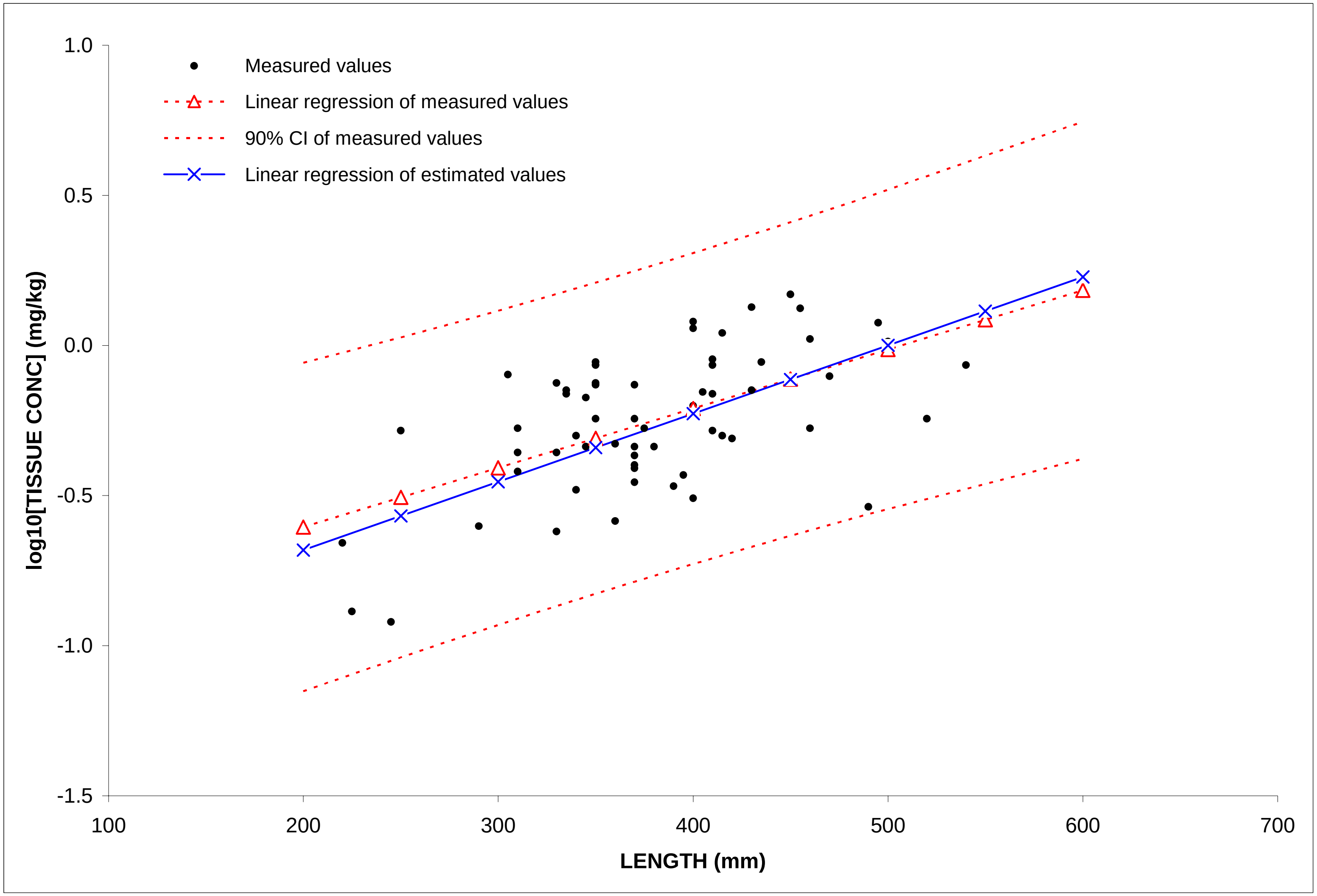

Figure C-1. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for northern pikeminnow (NPM).

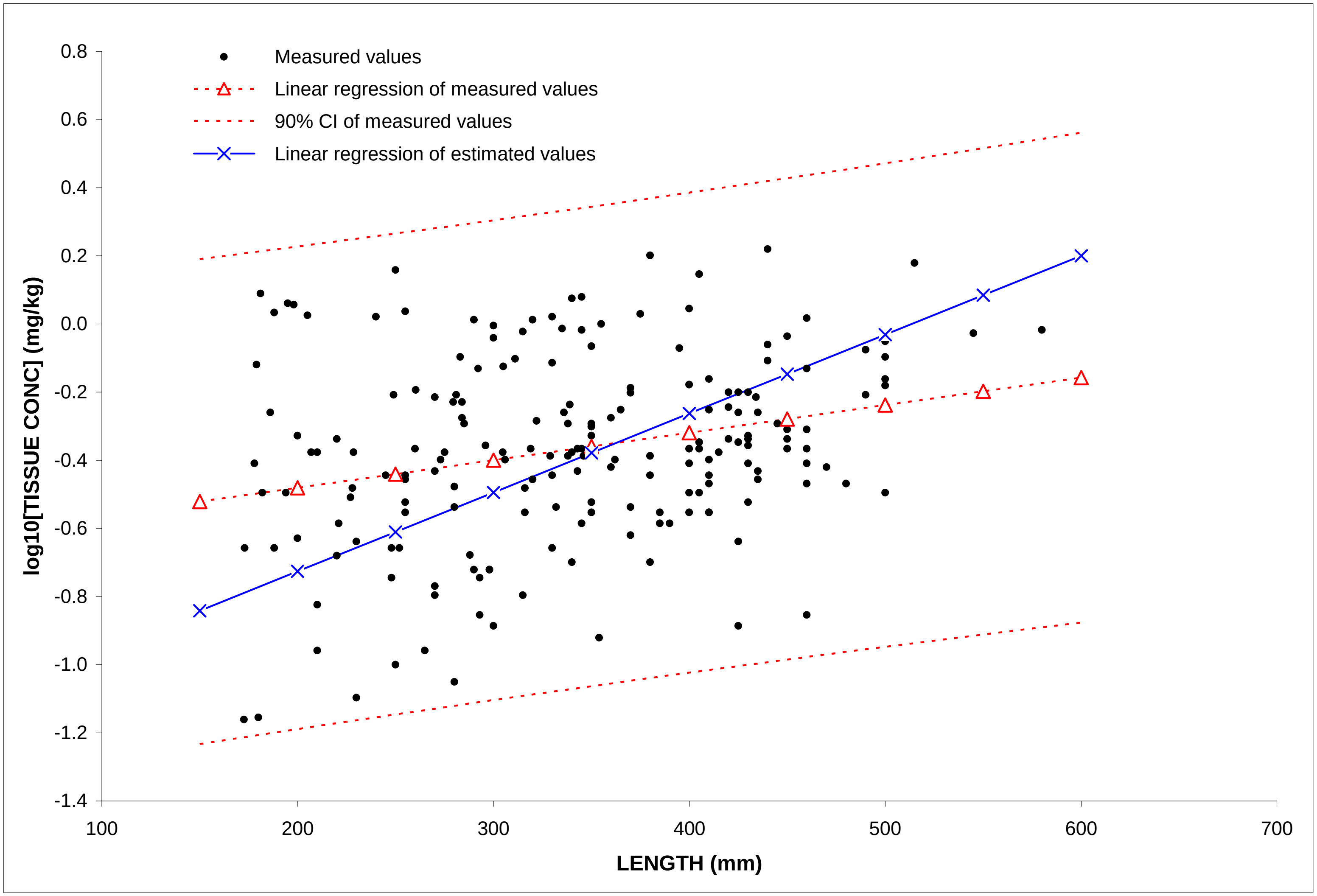

Figure C-2. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for largemouth bass (LMB).

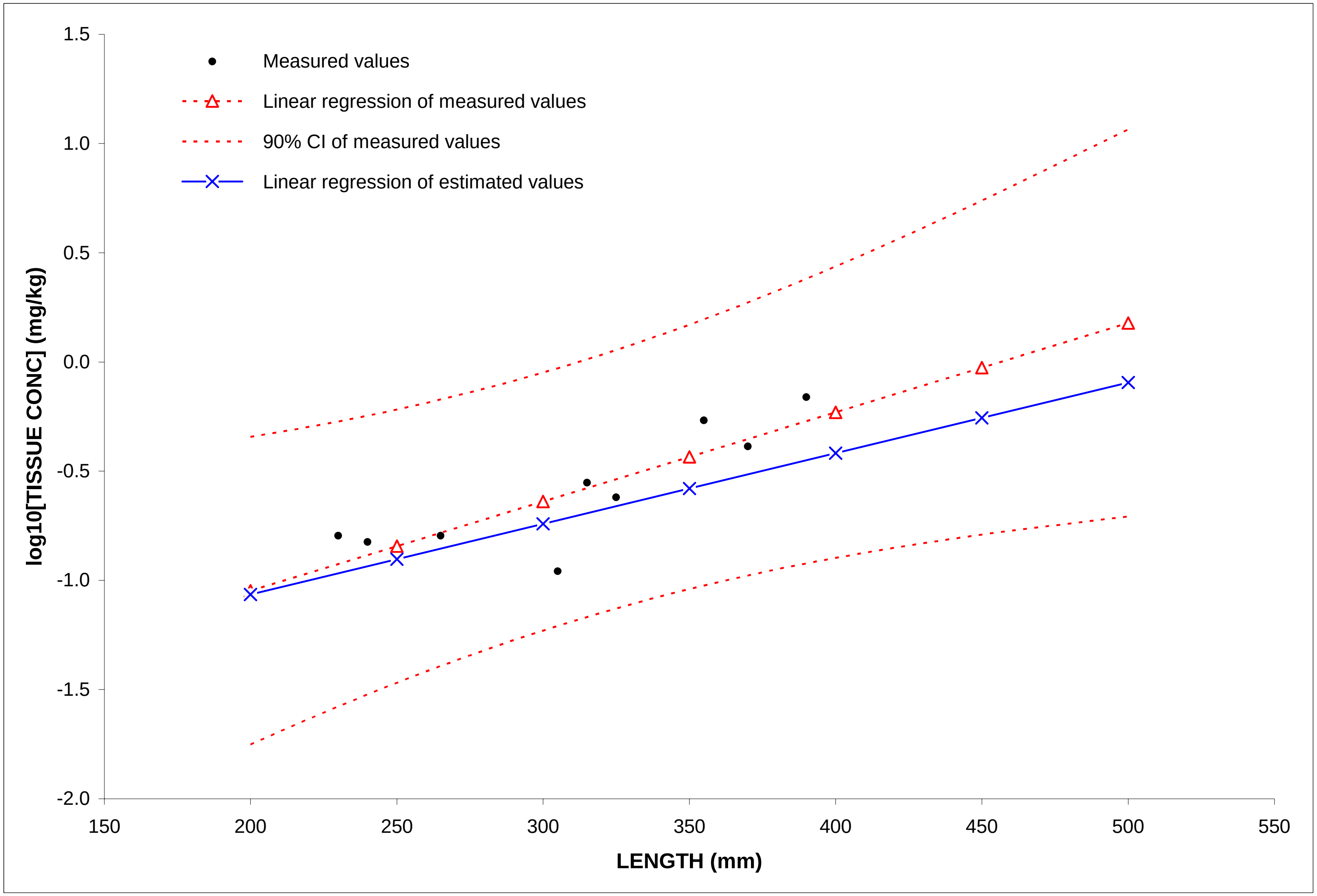

Figure C-3. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for smallmouth bass (SMB).

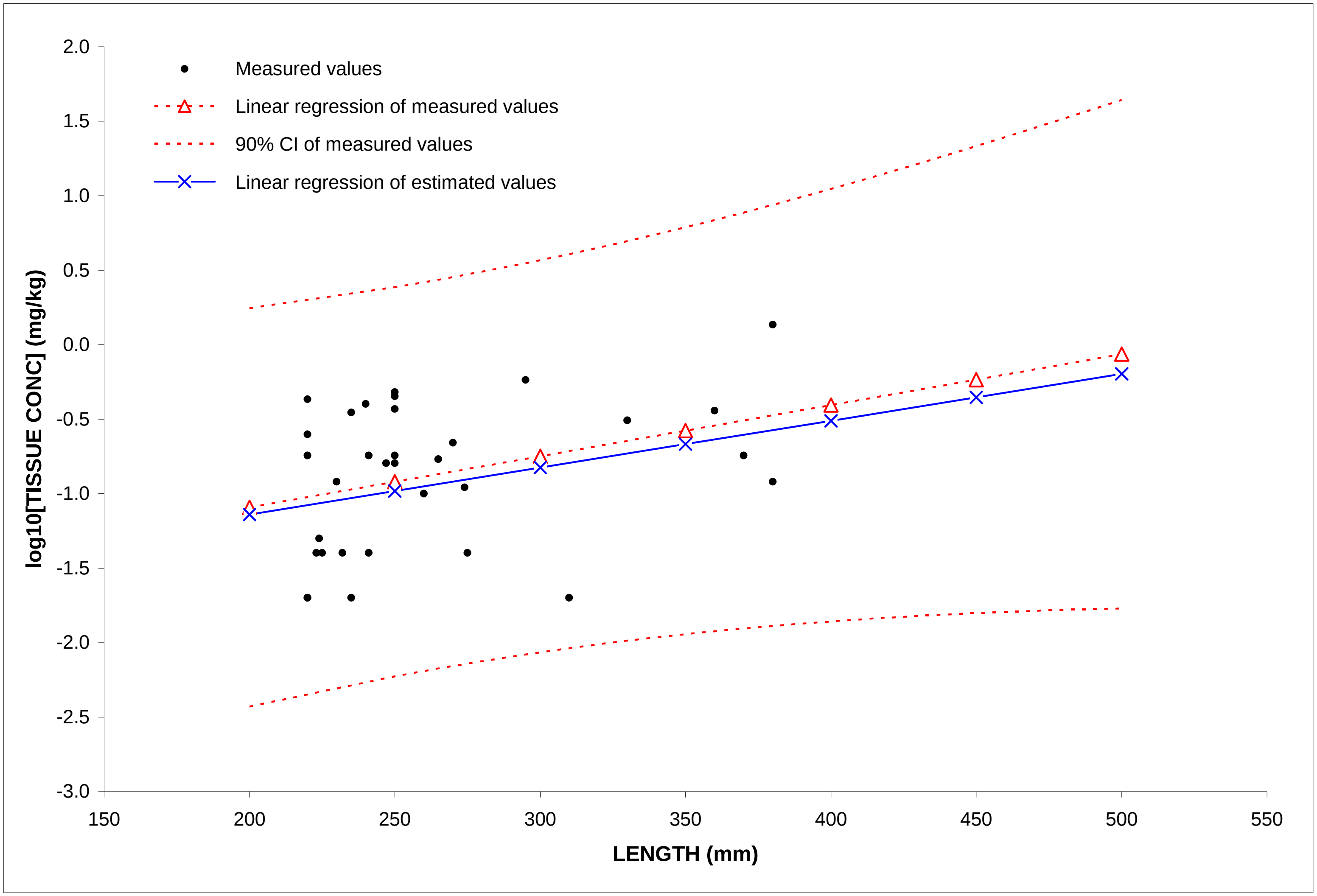

Figure C-4. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for rainbow trout (RBT).

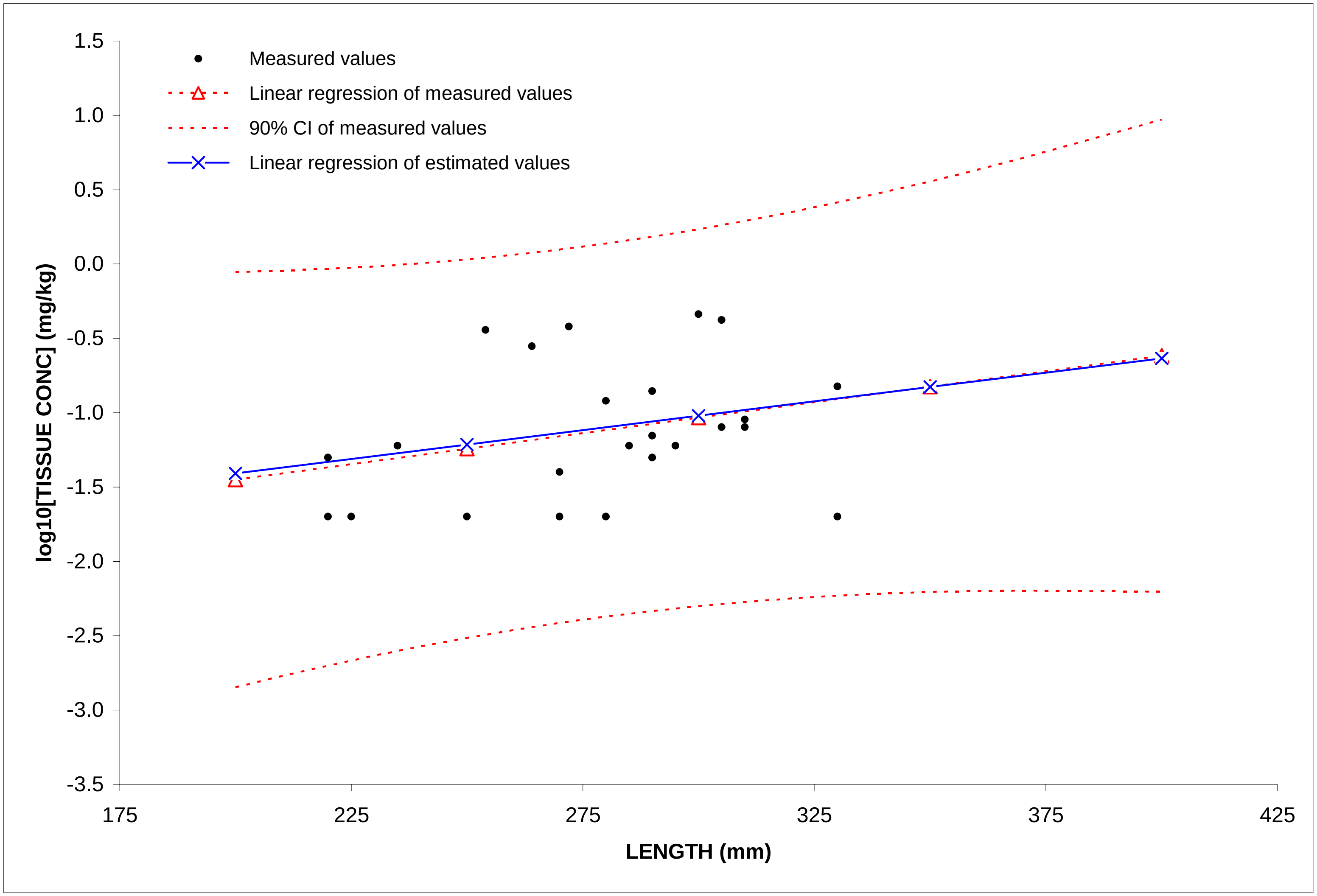

Figure C-5. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for cutthroat trout (CTT).

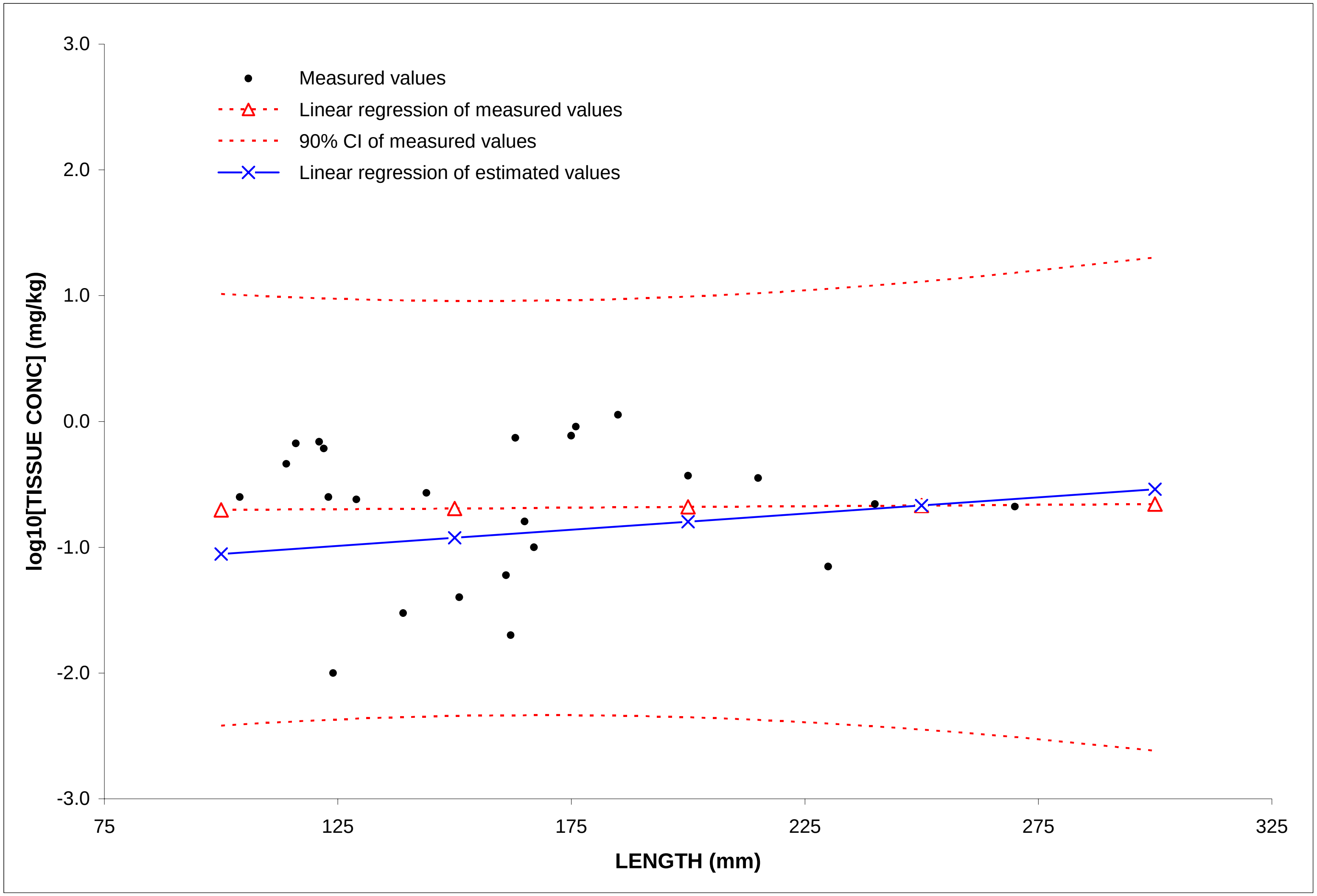

Figure C-6. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for bluegill (BLU).

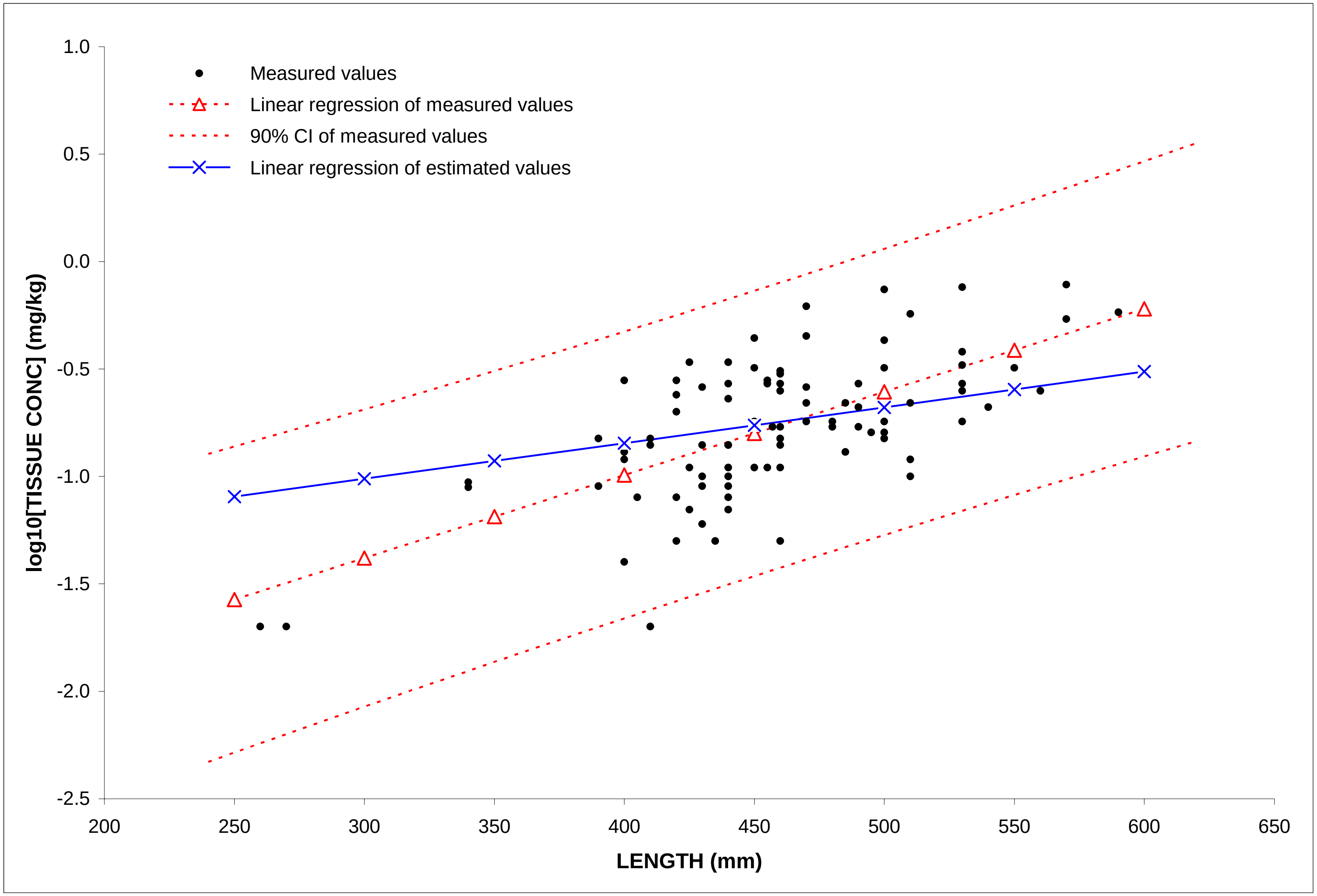

Figure C-7. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for largescale sucker (LSS).

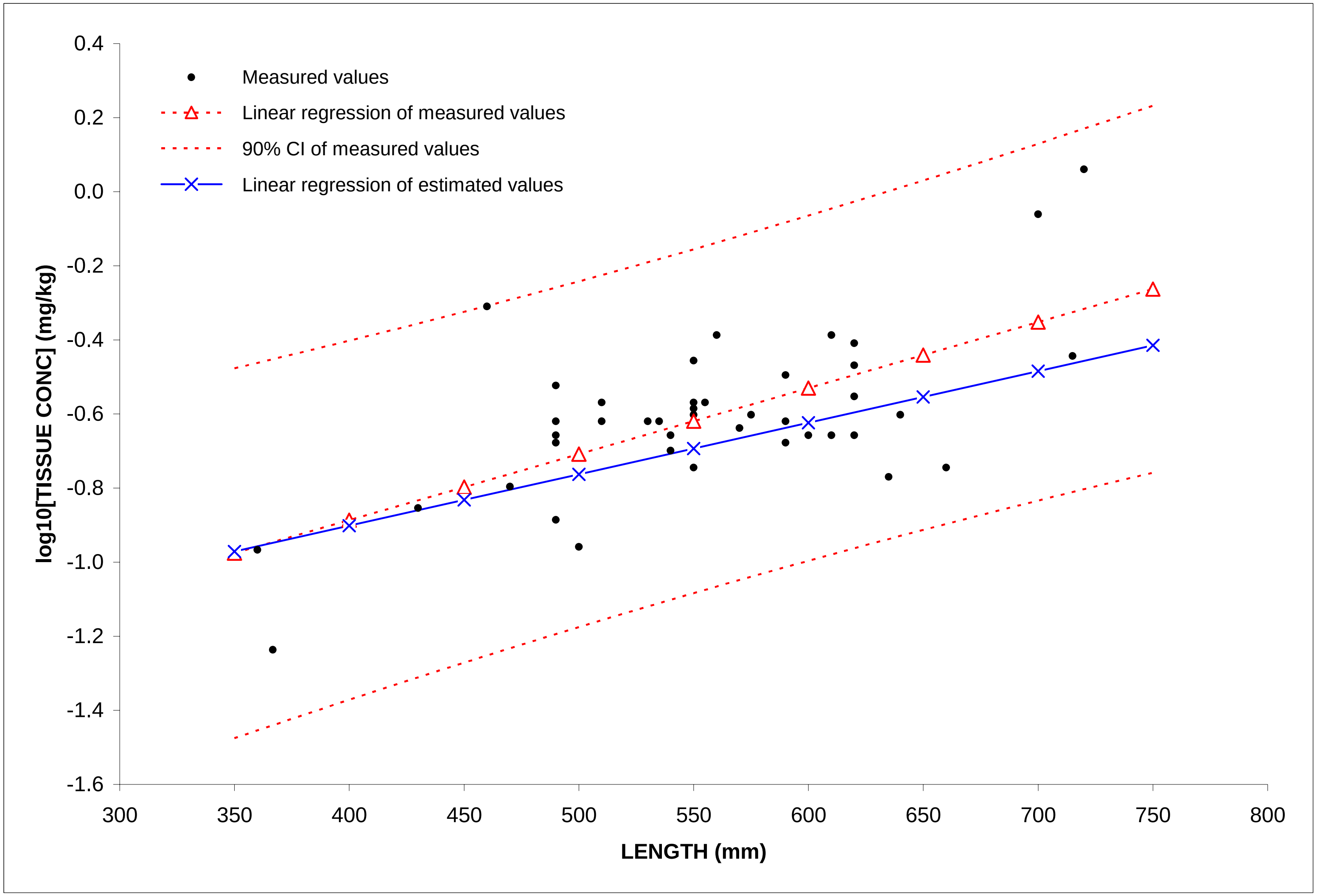

Figure C-8. Comparison of measured (with 90 percent confidence interval) and estimated tissue mercury concentration-body length relationships for common carp (CAR).

REVISED ESTIMATE OF A MERCURY MASS BALANCE FOR THE WILLAMETTE RIVER BASIN

August 2005
5th revised version

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TABLE OF CONTENTS

TABLES & FIGURES

TABLES

FIGURES

INTRODUCTION

This report describes revised simplified mass balance for mercury in the Willamette River Basin (Basin). Mass balance is based on the principle of 'conservation of mass': the amount of mercury entering the Basin should equal the amount of mercury leaving, trapped in, or chemically changed within the Basin. This mass balance provides initial estimates of the magnitude of mass fluxes that constitute the pathways for mercury transport into and out of the Basin, that distribute mercury within the water column and sediment of the mainstem, and that lead to bioaccumulation of mercury into fish. However, because these estimates are derived from different data sources, with differing degrees of uncertainty, and with differing degrees of robustness, they should be seen as only an initial view of mercury movement in the Basin and as a point of departure for further information gathering and analysis.

Additional work would be required to develop the more representative, better parameterized, and calibrated model needed to determine the rate of change in concentrations and inventories of mercury as inputs such as atmospheric and tributary loadings are changed, or other aspects of the system (such as soil erosion rates) are perturbed. Such a calibrated model would also allow us to predict the effectiveness of remediation efforts or sector-specific source category reductions in terms of ultimately achieving reduced environmental/fish tissue concentrations. A more elaborate mass balance model would be a valuable tool to estimate or predict the outcome of alternatives under consideration within the TMDL process.

ESTIMATES OF MERCURY OUTPUTS

The flux of total mercury out of the Basin in the fluvial load at RM 0 was estimated as a function of flow and concentration. Mercury concentrations in surface water, obtained with ultra-low detection methods (USEPA Method 1631E), are available for various locations along the mainstem from sampling performed by ODEQ in 2002-03 and by the Cities of Portland, Wilsonville, Corvallis, and Eugene between 1997 and 2003 (ODEQ, 2004; Association of Clean Water Agencies (ACWA), *personal communication*). Table 1 summarizes the locations at which mercury concentration data were collected and also shows that USGS gages and mercury sampling locations do not coincide either with respect to location or, at RM 180 , with the years when flow was measured (USGS, 2004). It was therefore necessary to estimate flow at sampling locations for the time period during which samples were collected (1997 to 2003).

Table 1. Summary of sampling events and flow measurements in the mainstem.

RM	Description	Sample Date	Flow Data
0.0	Confluence with Columbia River		Daily mean flows (by regression)
6.8	City of Portland sampling location (middle of river below St. Johns Railroad Bridge)	2000-03	Daily mean flows (by regression)
7.0	OODEQ sampling location (LASAR 10332) Willamette River at SP&S Bridge, Portland	2002-03	Daily mean flows (by regression)
12.8	USGS gage 14211720; Willamette River at Portland		Daily mean flows (USGS measured 1972-2002)
17.9	City of Portland sampling location (middle of river across from Waverly Country Club)	2000-03	Daily mean flows (by regression)
37.4	USGS gage 14198000; Willamette River at Wilsonville		Daily mean flows (USGS measured 1948-1957)
38.8	City of Wilsonville sampling location (0.2 miles upstream of the WWTP outfall)	2000-03	Daily mean flows (by regression)
47.9	USGS gage 14197900; Willamette River at Newberg		Mean of daily mean flows: 2001-2002 (real time)
50.1	ODEQ sampling location (LASAR 26339) Willamette River at Rogers Landing, Newberg	2002-03	Daily mean flows (by regression)
71.9	ODEQ sampling location (LASAR 10344) Willamette River at Wheatland Ferry	2002-03	Daily mean flows (by regression)
84.2	USGS gage 14191000; Willamette River at Salem		Daily mean flows (USGS measured 1909-2002)
119.3	USGS gage 14191000; Willamette River at Albany		Daily mean flows (USGS measured 1892-2002)
131.3	City of Corvallis sampling location (middle of river)	2002-03	Daily mean flows (by regression)
132.9	ODEQ sampling location (LASAR 29043) Willamette River at Willamette Park, Corvallis	2002-03	Daily mean flows (by regression)
134.2	City of Corvallis sampling location (middle of river)	2002-03	Daily mean flows (by regression)
161.0	USGS gage 14166000; Willamette River at Harrisburg		Daily mean flows (USGS measured 1944-2002)
176.8	City of Eugene sampling location (middle of river)	1997-2003	Daily mean flows (by regression)
178.6	City of Eugene sampling location (middle of river)	1997-2003	Daily mean flows (by regression)
180.0	ODEQ sampling location (LASAR 29044) Willamette River at Greenway Bridge, Eugene	2002-03	Daily mean flows (by regression)
180.0	USGS gage 14158000; Willamette River at Springfield		Daily mean flows (USGS measured 1917-1957)
183.9	City of Eugene sampling location (middle of river)		Daily mean flows (by regression)
186.9	City of Eugene sampling location (middle of river)		Daily mean flows (by regression)

Based on the five USGS gaging stations on the mainstem (Jasper (RM 195), Harrisburg (RM 161), Albany (RM 119.3), Salem (RM 84.2), and Portland (RM 12.8)) where flow data are available for 1997 to 2003, there is a strong linear relationship (R^2 = 0.9801) between mean flow and river mile (Figure 1).

Similar linear relationships equating flow and river mile for each day between 1997 and 2003 (approximately 2,500 data pairs) were used to estimate mean daily flow at those sampling locations (Table 2) lacking USGS flow data,

$$\hat{Q}_{j,k} = \alpha \cdot RM_k + \beta \quad (1)$$

where:

$\hat{Q}_{j,k}$ Estimated daily mean flow on j^{th} day at k^{th} river mile ($ft^3\ s^{-1}$)

RM_k k^{th} river mile on the mainstem (miles)

α Regression coefficient (unitless)

β Regression coefficient (unitless)

Table 2. Observed total mercury concentrations and estimated flow by mainstem river mile (RM).

Sampling Date	RM	Measured THg Conc. (ng L^{-1})	Adjusted THg Conc. (ng L^{-1})	Estimated Flow (cfs)	Concentration Data Source
26-Sep-00	6.80	0.82	0.98	12705	City of Portland data
27-Dec-00	6.80	3.04	3.63	39953	City of Portland data
26-Mar-01	6.80	1.58	1.89	19812	City of Portland data
14-Jun-01	6.80	0.95	1.13	14085	City of Portland data
14-Aug-01	6.80	1.76	2.10	7276	City of Portland data
29-Nov-01	6.80	4.81	5.75	75616	City of Portland data
2-Feb-02	6.80	1.68	2.01	58358	City of Portland data
15-May-02	6.80	1.00	1.20	23235	City of Portland data
25-Sep-02	6.80	0.71	0.85	9478	City of Portland data
20-Mar-03	6.80	2.11	2.52	45571	City of Portland data
1-Oct-02	7.00	0.79	0.94	11051	ODEQ data
17-Dec-02	7.00	3.58	4.28	68494	ODEQ data
20-Mar-03	7.00	1.45	1.73	45523	ODEQ data
19-Jun-03	7.00	0.64	0.77	10932	ODEQ data
26-Sep-00	17.90	0.98	1.17	12198	City of Portland data
27-Dec-00	17.90	3.02	3.61	37717	City of Portland data
26-Mar-01	17.90	0.96	1.14	18704	City of Portland data
14-Jun-01	17.90	1.26	1.51	13315	City of Portland data
14-Aug-01	17.90	1.08	1.29	6984	City of Portland data
29-Nov-01	17.90	4.97	5.94	71524	City of Portland data
2-Feb-02	17.90	1.55	1.85	55030	City of Portland data
15-May-02	17.90	1.08	1.29	22086	City of Portland data
25-Sep-02	17.90	0.80	0.95	9130	City of Portland data
20-Mar-03	17.90	2.07	2.47	42930	City of Portland data
17-Dec-02	38.80	3.90	4.66	57395	Wilsonville data
13-Jan-03	38.80	1.70	2.03	48307	Wilsonville data
22-Jan-03	38.80	1.70	2.03	23512	Wilsonville data
12-Feb-03	38.80	1.80	2.15	30139	Wilsonville data
26-Feb-03	38.80	1.90	2.27	27435	Wilsonville data
26-Mar-03	38.80	1.40	1.67	76817	Wilsonville data
20-May-03	38.80	1.00	1.20	18265	Wilsonville data
1-Oct-02	50.10	0.60	0.72	9356	ODEQ data
17-Dec-02	50.10	7.12	8.51	53451	ODEQ data
20-Mar-03	50.10	1.41	1.69	35269	ODEQ data
19-Jun-03	50.10	0.60	0.72	8894	ODEQ data
1-Oct-02	71.90	0.57	0.68	8498	ODEQ data
17-Dec-02	71.90	6.08	7.27	45842	ODEQ data
20-Mar-03	71.90	1.19	1.42	30082	ODEQ data
19-Jun-03	71.90	0.91	1.09	7863	ODEQ data
22-Jul-02	131.30	0.81	0.97	5112	Corvallis data
23-Jul-02	131.30	0.87	1.04	5077	Corvallis data
23-Jul-02	131.30	0.78	0.93	5077	Corvallis data
24-Jul-02	131.30	0.88	1.06	5033	Corvallis data
17-Sep-02	131.30	0.86	1.03	5871	Corvallis data
18-Sep-02	131.30	0.99	1.18	6132	Corvallis data

Table 2. Observed total mercury concentrations and estimated flow by mainstem river mile (RM).

Sampling Date	RM	Measured THg Conc. (ng L^{-1})	Adjusted THg Conc. (ng L^{-1})	Estimated Flow (cfs)	Concentration Data Source
19-Sep-02	131.30	0.90	1.07	6180	Corvallis data
21-Jul-03	131.30	1.30	1.55	4917	Corvallis data
22-Jul-03	131.30	1.47	1.76	4857	Corvallis data
23-Jul-03	131.30	0.86	1.03	4842	Corvallis data
2-Sep-03	131.30	1.16	1.39	4922	Corvallis data
3-Sep-03	131.30	0.98	1.17	4909	Corvallis data
4-Sep-03	131.30	0.88	1.05	4881	Corvallis data
2-Oct-02	132.90	0.39	0.47	6237	ODEQ data
17-Dec-02	132.90	9.44	11.29	24552	ODEQ data
19-Mar-03	132.90	1.02	1.22	15548	ODEQ data
19-Jun-03	132.90	0.63	0.75	4978	ODEQ data
22-Jul-02	134.20	1.00	1.20	5020	Corvallis data
23-Jul-02	134.20	0.77	0.91	4986	Corvallis data
24-Jul-02	134.20	0.79	0.94	4945	Corvallis data
17-Sep-02	134.20	0.89	1.07	5775	Corvallis data
18-Sep-02	134.20	1.06	1.27	6040	Corvallis data
19-Sep-02	134.20	1.29	1.54	6066	Corvallis data
19-Sep-02	134.20	1.14	1.36	6066	Corvallis data
21-Jul-03	134.20	1.17	1.40	4824	Corvallis data
21-Jul-03	134.20	1.24	1.48	4824	Corvallis data
22-Jul-03	134.20	0.94	1.13	4768	Corvallis data
23-Jul-03	134.20	0.88	1.05	4757	Corvallis data
23-Jul-03	134.20	0.96	1.15	4757	Corvallis data
2-Sep-03	134.20	1.43	1.71	4830	Corvallis data
2-Sep-03	134.20	1.20	1.43	4830	Corvallis data
3-Sep-03	134.20	0.93	1.12	4807	Corvallis data
4-Sep-03	134.20	1.48	1.77	4779	Corvallis data
4-Sep-03	134.20	1.16	1.39	4779	Corvallis data
18-Mar-97	176.80	3.09	3.69	18012	Eugene data
14-May-97	176.80	1.09	1.30	5525	Eugene data
25-Aug-97	176.80	0.63	0.75	4679	Eugene data
30-Sep-97	176.80	2.17	2.59	5608	Eugene data
19-Nov-97	176.80	0.99	1.18	6489	Eugene data
20-Jan-98	176.80	3.50	4.18	23324	Eugene data
17-Mar-98	176.80	2.42	2.89	3900	Eugene data
12-May-98	176.80	1.96	2.34	3217	Eugene data
21-Jul-98	176.80	1.64	1.96	4563	Eugene data
15-Sep-98	176.80	1.02	1.22	3832	Eugene data
10-Nov-98	176.80	1.41	1.69	7180	Eugene data
19-Jan-99	176.80	12.50	14.94	24364	Eugene data
20-Apr-99	176.80	2.99	3.57	6292	Eugene data
18-May-99	176.80	2.60	3.11	13897	Eugene data
27-Jul-99	176.80	2.27	2.71	4339	Eugene data
9-Nov-99	176.80	2.14	2.56	5141	Eugene data
25-Jan-00	176.80	8.47	10.13	21933	Eugene data
21-Mar-00	176.80	2.32	2.77	8751	Eugene data
16-May-00	176.80	2.90	3.47	8997	Eugene data
18-Jul-00	176.80	1.39	1.66	3722	Eugene data
26-Sep-00	176.80	0.88	1.06	4943	Eugene data
14-Nov-00	176.80	1.37	1.64	6199	Eugene data
23-Jan-01	176.80	2.82	3.37	2881	Eugene data
20-Mar-01	176.80	2.22	2.65	3806	Eugene data
10-Jul-01	176.80	1.02	1.22	2232	Eugene data
25-Sep-01	176.80	1.55	1.85	3561	Eugene data
11-Dec-01	176.80	2.71	3.24	10628	Eugene data
8-Jan-02	176.80	4.45	5.32	10137	Eugene data
19-Mar-02	176.80	2.15	2.57	5440	Eugene data
28-May-02	176.80	1.16	1.39	5551	Eugene data
23-Jul-02	176.80	1.21	1.45	3648	Eugene data
5-Nov-02	176.80	0.67	0.80	3274	Eugene data
28-Jan-03	176.80	4.50	5.38	17311	Eugene data

Table 2. Observed total mercury concentrations and estimated flow by mainstem river mile (RM).

Sampling Date	RM	Measured THg Conc. (ng L^{-1})	Adjusted THg Conc. (ng L^{-1})	Estimated Flow (cfs)	Concentration Data Source
18-Mar-97	178.60	2.99	3.57	17085	Eugene data
14-May-97	178.60	1.10	1.32	5280	Eugene data
25-Aug-97	178.60	0.56	0.67	4599	Eugene data
30-Sep-97	178.60	0.99	1.18	5482	Eugene data
19-Nov-97	178.60	0.88	1.05	6251	Eugene data
20-Jan-98	178.60	3.34	3.99	22235	Eugene data
17-Mar-98	178.60	2.17	2.59	3577	Eugene data
12-May-98	178.60	1.42	1.70	3068	Eugene data
21-Jul-98	178.60	1.52	1.82	4504	Eugene data
15-Sep-98	178.60	1.96	2.34	3755	Eugene data
10-Nov-98	178.60	1.49	1.78	6993	Eugene data
19-Jan-99	178.60	12.20	14.58	23052	Eugene data
20-Apr-99	178.60	3.58	4.28	5978	Eugene data
18-May-99	178.60	3.38	4.04	13635	Eugene data
27-Jul-99	178.60	0.87	1.04	4265	Eugene data
9-Nov-99	178.60	0.94	1.12	4999	Eugene data
25-Jan-00	178.60	5.51	6.59	21365	Eugene data
21-Mar-00	178.60	1.12	1.34	8308	Eugene data
16-May-00	178.60	2.98	3.56	8654	Eugene data
18-Jul-00	178.60	2.14	2.56	3652	Eugene data
26-Sep-00	178.60	1.58	1.89	4861	Eugene data
14-Nov-00	178.60	0.92	1.10	6069	Eugene data
23-Jan-01	178.60	2.52	3.01	2726	Eugene data
20-Mar-01	178.60	2.23	2.67	3588	Eugene data
15-May-01	178.60	1.47	1.76	6972	Eugene data
10-Jul-01	178.60	1.02	1.22	2171	Eugene data
25-Sep-01	178.60	1.43	1.71	3509	Eugene data
11-Dec-01	178.60	2.71	3.24	9954	Eugene data
8-Jan-02	178.60	4.44	5.31	9117	Eugene data
19-Mar-02	178.60	2.30	2.75	4911	Eugene data
28-May-02	178.60	1.02	1.22	5348	Eugene data
23-Jul-02	178.60	0.92	1.10	3592	Eugene data
24-Sep-02	178.60	0.87	1.04	3967	Eugene data
5-Nov-02	178.60	0.76	0.91	3203	Eugene data
28-Jan-03	178.60	4.16	4.97	16705	Eugene data
2-Oct-02	180.00	0.55	0.65	4305	ODEQ data
12-Dec-02	180.00	1.21	1.45	1913	ODEQ data
19-Mar-03	180.00	1.79	2.14	3806	ODEQ data
17-Jun-03	180.00	0.75	0.90	2990	ODEQ data
18-Mar-97	183.90	2.84	3.40	14355	Eugene data
14-May-97	183.90	1.16	1.39	4488	Eugene data
25-Aug-97	183.90	0.78	0.93	4365	Eugene data
30-Sep-97	183.90	0.88	1.05	5109	Eugene data
19-Nov-97	183.90	0.68	0.81	5551	Eugene data
20-Jan-98	183.90	3.02	3.61	19028	Eugene data
17-Mar-98	183.90	2.44	2.92	2625	Eugene data
12-May-98	183.90	1.26	1.51	2629	Eugene data
21-Jul-98	183.90	1.95	2.33	4329	Eugene data
15-Sep-98	183.90	0.97	1.16	3530	Eugene data
10-Nov-98	183.90	1.24	1.48	6440	Eugene data
19-Jan-99	183.90	8.83	10.56	19187	Eugene data
20-Apr-99	183.90	3.13	3.74	5055	Eugene data
18-May-99	183.90	2.99	3.57	12863	Eugene data
27-Jul-99	183.90	1.42	1.70	4047	Eugene data
9-Nov-99	183.90	0.85	1.01	4583	Eugene data
25-Jan-00	183.90	6.14	7.34	19691	Eugene data
21-Mar-00	183.90	1.03	1.23	7003	Eugene data
16-May-00	183.90	1.96	2.34	7644	Eugene data
18-Jul-00	183.90	1.57	1.88	3444	Eugene data
26-Sep-00	183.90	1.33	1.59	4619	Eugene data
14-Nov-00	183.90	1.00	1.19	5686	Eugene data

Table 2. Observed total mercury concentrations and estimated flow by mainstem river mile (RM).

Sampling Date	RM	Measured THg Conc. (ng L^{-1})	Adjusted THg Conc. (ng L^{-1})	Estimated Flow (cfs)	Concentration Data Source
20-Mar-01	183.90	2.29	2.74	2944	Eugene data
15-May-01	183.90	1.76	2.10	6390	Eugene data
10-Jul-01	183.90	0.82	0.97	1993	Eugene data
25-Sep-01	183.90	1.37	1.64	3357	Eugene data
11-Dec-01	183.90	2.47	2.95	7970	Eugene data
8-Jan-02	183.90	4.27	5.10	6115	Eugene data
19-Mar-02	183.90	2.71	3.24	3354	Eugene data
28-May-02	183.90	1.16	1.39	4748	Eugene data
23-Jul-02	183.90	1.00	1.20	3425	Eugene data
24-Sep-02	183.90	1.10	1.32	3788	Eugene data
5-Nov-02	183.90	0.95	1.13	2994	Eugene data
28-Jan-03	183.90	3.75	4.48	14923	Eugene data
18-Mar-97	186.90	2.91	3.48	12810	Eugene data
14-May-97	186.90	1.18	1.41	4160	Eugene data
25-Aug-97	186.90	0.52	0.63	4232	Eugene data
30-Sep-97	186.90	0.69	0.82	4898	Eugene data
19-Nov-97	186.90	0.63	0.75	5154	Eugene data
20-Jan-98	186.90	3.59	4.29	17214	Eugene data
17-Mar-98	186.90	4.02	4.81	2087	Eugene data
12-May-98	186.90	3.25	3.89	2381	Eugene data
21-Jul-98	186.90	1.58	1.89	4230	Eugene data
15-Sep-98	186.90	2.26	2.70	3402	Eugene data
10-Nov-98	186.90	1.89	2.26	6127	Eugene data
19-Jan-99	186.90	6.59	7.88	17000	Eugene data
20-Apr-99	186.90	2.81	3.36	4532	Eugene data
18-May-99	186.90	4.14	4.95	12427	Eugene data
27-Jul-99	186.90	0.71	0.84	3923	Eugene data
9-Nov-99	186.90	1.91	2.28	4347	Eugene data
25-Jan-00	186.90	10.80	12.91	18744	Eugene data
21-Mar-00	186.90	1.51	1.81	6265	Eugene data
16-May-00	186.90	3.12	3.73	7073	Eugene data
18-Jul-00	186.90	1.68	2.01	3326	Eugene data
26-Sep-00	186.90	1.00	1.20	4482	Eugene data
14-Nov-00	186.90	0.84	1.00	5470	Eugene data
20-Mar-01	186.90	1.40	1.67	2580	Eugene data
15-May-01	186.90	1.83	2.19	6061	Eugene data
10-Jul-01	186.90	0.63	0.76	1893	Eugene data
25-Sep-01	186.90	1.12	1.34	3270	Eugene data
11-Dec-01	186.90	1.72	2.06	6846	Eugene data
8-Jan-02	186.90	4.24	5.07	4415	Eugene data
19-Mar-02	186.90	2.41	2.88	2472	Eugene data
28-May-02	186.90	1.05	1.26	4408	Eugene data
23-Jul-02	186.90	0.94	1.12	3331	Eugene data
24-Sep-02	186.90	1.03	1.23	3686	Eugene data
5-Nov-02	186.90	0.70	0.84	2876	Eugene data
28-Jan-03	186.90	3.11	3.72	13915	Eugene data

A flow-concentration relationship (Figure 2) was formed between bias-adjusted (see text below) total mercury concentrations measured on a given day and river flow estimated for that day with Equation 1 (Table 2) (Cohn et al., 1992; Colman and Breault, 2000),

$$C_{j,k} = \exp\left(\alpha \cdot \ln\left(\hat{Q}_{j,k}\right) - \beta\right) \qquad (2)$$

where:

$\hat{C}_{j,k}$ Bias-adjusted total mercury concentration measured in surface water on j^{th} day at k^{th} river mile (ng L^{-1})

$\hat{Q}_{j,k}$ Estimated daily mean flow on j^{th} day at k^{th} river mile (ft^3 s^{-1})

α Regression coefficient for the concentration estimate (unitless)
β Regression coefficient for the concentration estimate (unitless)

In order for concentrations estimated from the regression model to be reliable, the residuals (the differences between the predicted and observed concentrations used to calculate the regression model) must be normally distributed. In addition, it is desirable for the data to be well spread out over the range of observations. For these and several other reasons, regression models relating concentration to flow usually use log-transformed values. In order to be of much use, however, the resulting data must be back-transformed before calculating the loads. The obvious way to do this is by taking the anti-logs of the estimated concentrations. Statistical theory tells us, however, that when these back-transformed values are used to calculate average daily loads or total annual loads, the results will be biased low (Ferguson, 1986; Cohn *et al.*, 1992). In order to avoid this bias, a value (here the variance of the residuals of the regression model) was added to each estimated log-concentration before it is back-transformed (Ferguson, 1986; Cohn, *et al.* 1992). The values for α and β were 0.3629 and 2.5994, respectively (n = 213, R^2 = 0.2049).

The fluvial load out of the Basin was estimated as a function of the seasonally-varying daily mean flow at RM 0 and total mercury concentration estimated with Equation 2,

$$F_0 \sim \left[\exp\left(\alpha'' \cdot \ln\left(\tilde{Q}_0\right) - \beta''\right)\right] \cdot \tilde{Q}_0 \cdot CF_{Lfsy} \cdot CF_{kn} \quad (3)$$

where:
F_0 Output from Basin as fluvial load (kg yr^{-1})
$\tilde{Q}_0$ Distribution of mainstem flow at RM 0 (ft^3 s^{-1}); Lognormal[34621, 33602, min = 7115]
CF_{Lfsy} Conversion factor (893,099,520 L $ft^{-3}\cdot s$ yr^{-1})
CF_{kn} Conversion factor (10^{-12} kg ng^{-1})
α” Regression coefficient for the concentration estimate (unitless)
β” Regression coefficient for the concentration estimate (unitless)

An average of 126.8 kg [16.5-416.6, 90th percentile range] of total mercury is discharged from the Basin (RM 0.0) each year (Equation 3). This yearly average obscures considerable variation in an output that is driven primarily by seasonal changes in flow rates which effect the presence of Total Suspended Solids (TSS) in the mainstem. During the wet season (December), increases in soil erosion due to storm events and resuspension of bed sediment by higher shear velocities associated with higher flow rates combine to produce higher TSS levels. Because mercury is both contained in, and bound to, soil and sediment particles, there is a positive correlation between total mercury concentrations and TSS (Figure 3). This relationship creates higher total and dissolved mercury concentrations during the wet season (Figure 4). Output during the wet (high flow) season was estimated to be 416.6 kg yr^{-1}, based on the 95th percentile of flows at the confluence.

Figure 1. Relationship between mainstem flow and river mile.

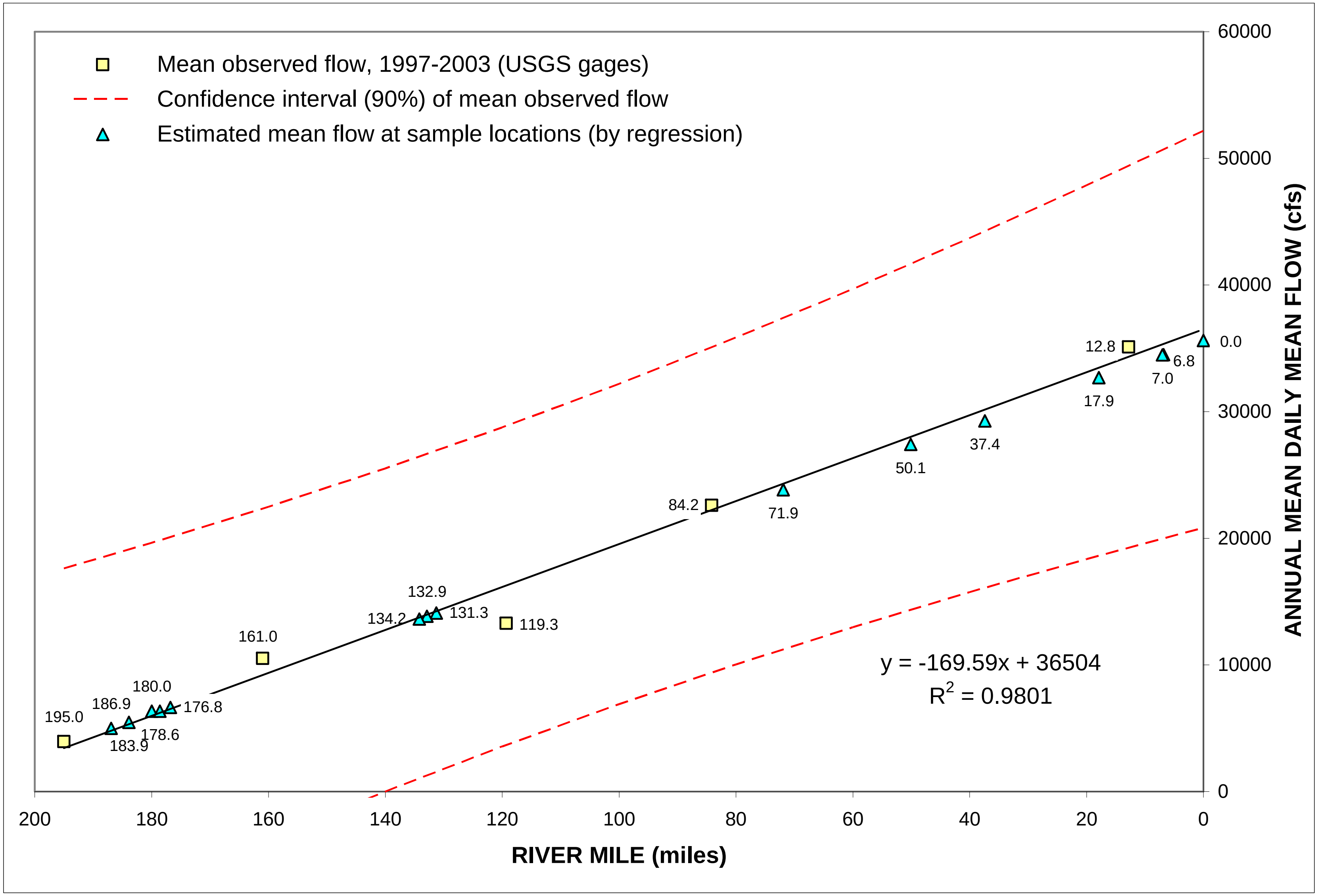


Figure 2. Relationship between flow and bias-adjusted total (unfiltered) mercury concentration (90% confidence intervals).

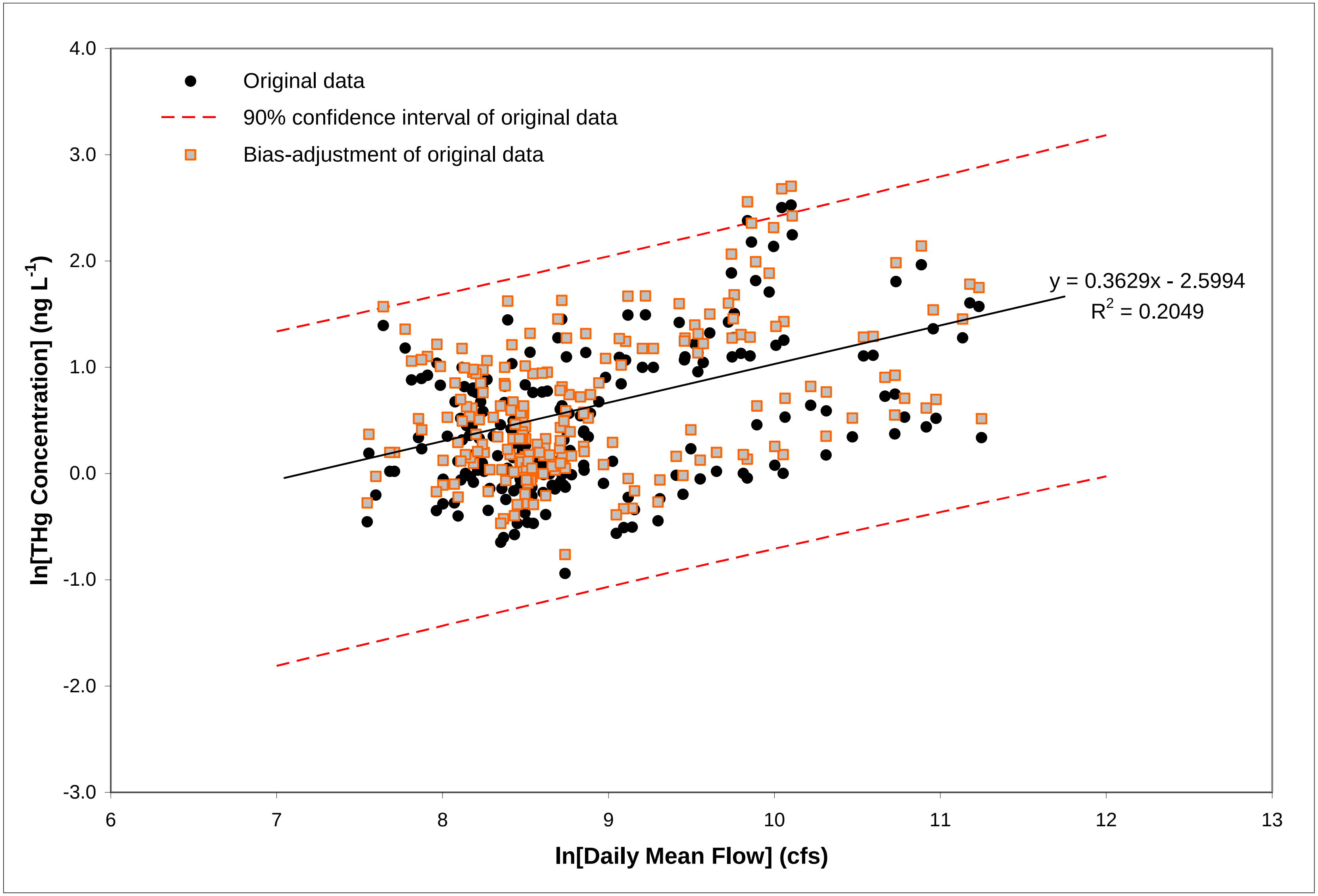


Figure 3. Relationship between total and dissolved mercury and total suspended solids in the mainstem.

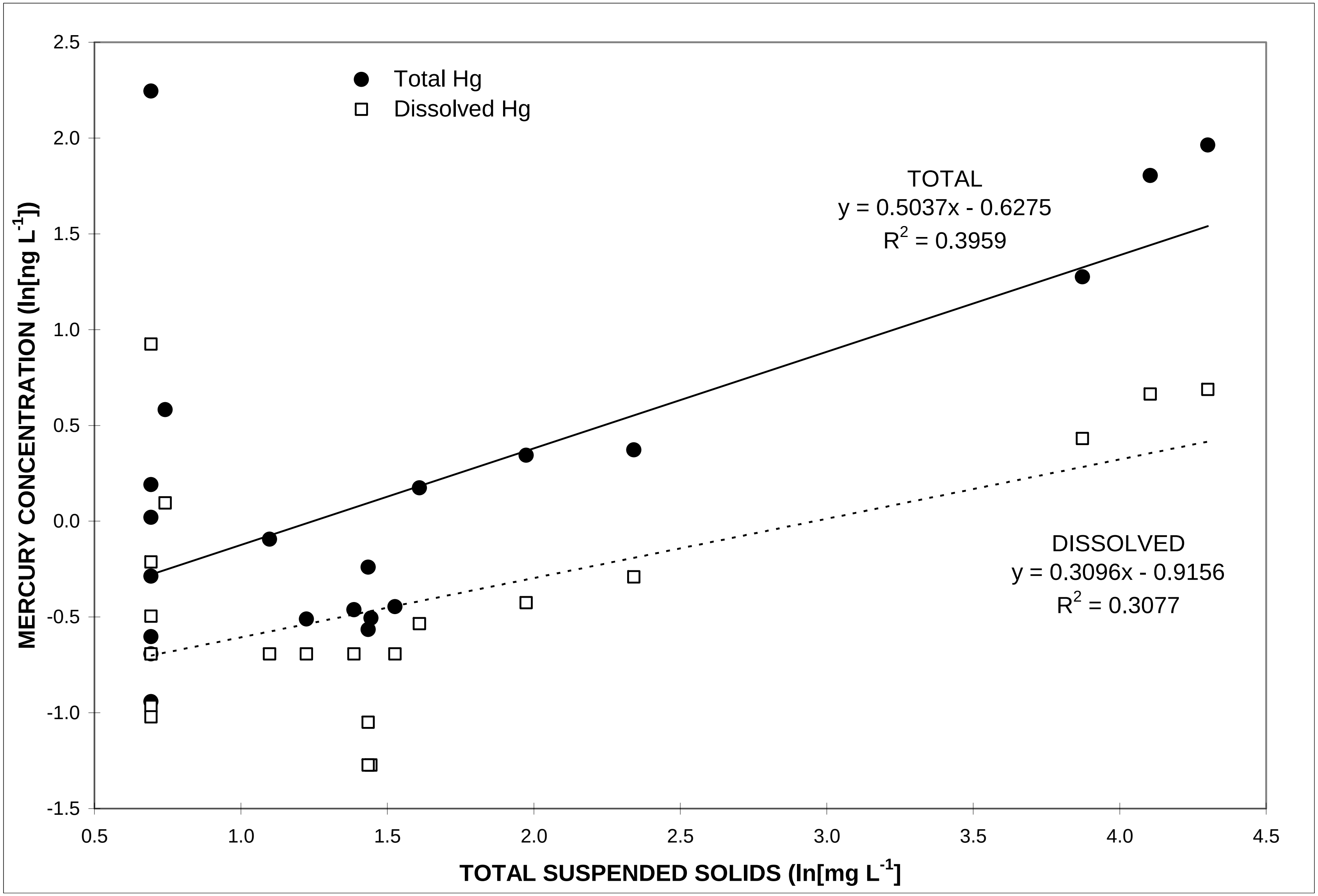
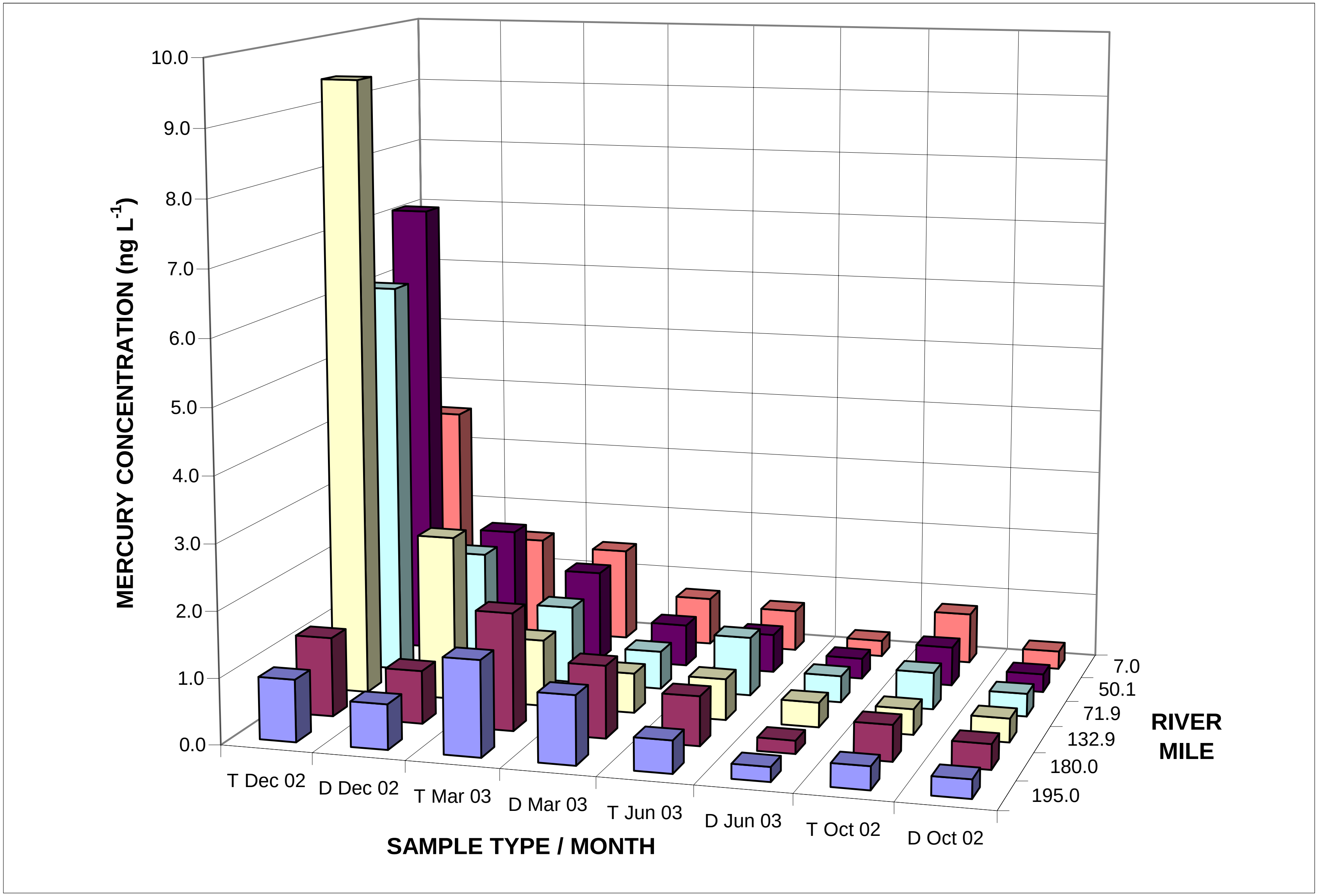


Figure 4. Seasonal and spatial trends in total (T) and dissolved (D) mercury concentrations.



ESTIMATES OF MERCURY INPUTS

A variety of available data and informed assumptions were used to identify and quantify principal inputs of total mercury to the Basin. Data are presently insufficient to support calculation of input estimates for specific river segments or for different species (i.e., divalent, methyl, elemental) of mercury.

Atmospheric Deposition

Some fraction of the mercury emitted into the atmosphere, from either natural or anthropogenic local or global sources, is likely to be deposited on land within the Basin. Some fraction of this deposited mercury may be transported by runoff (overland flow) to surface water. The amount of mercury entering the mainstem annually was estimated as,

$$F_{AD} \sim \sum_{k=1}^{m} \left(\left(F_{LOC} + F_{GLO} \right) \cdot LU_k \cdot DR_k \right) \quad (4)$$

where:
F_{AD} Annual input of mercury to surface water from air deposition (kg yr^{-1})
m Number of air sources (unitless)
F_{LOC} Annual input of mercury to the Basin from local air emissions (kg yr^{-1})
F_{GLO} Annual input of mercury to the Basin from global air emissions (kg yr^{-1})
LU_k Fraction of land in the Basin of k^{th} land use type (unitless)
DR_k Delivery ratio of mercury for the k^{th} land use type (unitless)

Local Air Emissions

Contributions from near-field (local) air emission sources were estimated for ten counties (Benton, Clackamas, Columbia, Lane, Linn, Marion, Multnomah, Polk, Washington, Yamhill) fully or partially contained within the Basin using the 2002 emissions inventory (J. Stocum, ODEQ Air Quality Division, *personal communication*). Because portions of some of these counties fall outside the Basin, actual inter-Basin (local) emissions may be over-estimated. Mercury contributed to the Basin from local sources (F_{LOC}) is estimated to be 162.03 kg yr^{-1}, distributed as follows: point (62.98 kg yr^{-1}), on-road mobile (0.03 kg yr^{-1}), nonroad (2.36 kg yr^{-1}), and area (66.66 kg yr^{-1}). Point sources are fixed locations, on-road mobile sources are automobiles and other motorized vehicles; nonroad sources include (for example) heavy construction and equipment and stationary diesel generators; area sources include non-anthropogenic contributions from forest fires, a potential source in some counties (Friedli et al., 2003); nonroad includes both mobile and stationary sources not operating on highways.

Global Air Emissions

In addition to near-field (local) mercury sources, there are likely (but difficult to quantify) far-field (global) sources that contribute to mercury deposition in the Basin (Bernsten and Karlsdottir, 1999). Mercury entering the Basin from global sources was estimated as,

$$F_{GLO} = \left(DP_w + DP_d \right) \cdot \left(A_1 + A_2 + \left(A_3 \cdot F_m \right) + A_4 \right) \cdot CF_{ku} \quad (5)$$

where:
F_{GLO} Annual input of mercury to Basin from global sources (kg yr^{-1})
DP_w Wet deposition rate (µg m^{-2} yr^{-1})
DP_d Dry deposition rate, global sources (µg m^{-2} yr^{-1})
A_1 Urban land area (m^2)
A_2 Mixed land area (m^2)
A_3 Forest land area (m^2)
A_4 Agricultural land area (m^2)
F_m Forest deposition multiplier (4, unitless)
CF_{ku} Conversion factor (10^{-9} kg µg^{-1})

Volume-weighted average mercury concentrations in air over the Pacific Ocean off the Pacific Northwest coast of Washington have been reported at 2.8 to 3.2 ng L^{-1} (Tsai and Hoenicke, 2001). Assuming that a concentration of 3.0 ng L^{-1} represents a global background level of Hg in air masses approaching Oregon from the west, and given an average rainfall over the entire Basin of approximately 1.48 m yr^{-1} (≈58 in yr^{-1}, range 30-80 in yr^{-1} (OCS, 2004)), the global contribution to the Basin via wet deposition would be 4.4 μg m^{-2} yr^{-1}, a value similar to the lowest value measured at Oregon's Mercury Deposition Network (MDN) Site OR10 in the Cascade foothills (NADP, 2004). Due to a lack of Basin-specific data, the dry deposition rate was estimated on the basis of settling velocities and particulate concentrations. Settling velocities for divalent ($SV_{Hg(II)}$) and particulate (SV_{HgP}) mercury are those assumed by Tsai and Hoenicke (2001). Concentrations for divalent ($C_{Hg(II)}$, 0.0016 ng m^3) and particulate (C_{HgP}, 0.0005 ng m^3) mercury are based on measurements in the marine boundary layer near the Washington coast (Weiss-Penzias et al., 2003). These values were used to estimate a mean dry deposition rate of 5.41 μg m^{-2} yr^{-1}, recognizing that use of a single rate based on global background levels may underestimate the impact of any highly localized dry deposition sources within the Basin. Deposition on Forest land is increased by a factor of four to reflect reports that deposition rates in forests, because of throughfall and litterfall, are approximately four times higher than in other land use categories. Atmospheric deposition of mercury to forests is about four times open precipitation because of additions via throughfall, washoff of dry deposition, and litterfall, dropping of senescent leaves that have accumulated atmospheric mercury. Atmospheric deposition of mercury to lakes is only about one-fourth that to forests in the same geographic area because the lakes lack the forest canopy and hence surfaces for both dry deposition and foliar accumulation (Frescholtz et al., 2003; Grigal, 2002).

These estimates of total mercury deposition are within range of those proposed by others, specifically:

- U.S. EPA's Regional Langrangian Model of Air Pollution (RELMAP), which simulates atmospheric deposition in the U.S. from all inventoried anthropogenic U.S. sources. This model predicts an annual average total deposition rate for the Basin region of between 3 and 10 μg m^{-2} yr^{-1} (Bullock, 2000; USEPA, 1997).
- U.S. EPA's Regional Modeling System for Aerosols and Deposition (REMSAD) model estimates an average total deposition rate for the Basin (by subbasin) of 9.9 μg m^{-2} yr^{-1} with a maximum deposition rate in the state of 12.7 μg m^{-2} yr^{-1} (Dwight Atkinson, USEPA Region 10, *personal communication*).
- A global/regional chemical transport model, the Trace Element Analysis Model (TEAM), predicts total mercury wet and dry deposition range in Oregon from 5 to 30 μg m^{-2} yr^{-1} and from 2 to 5 μg m^{-2} yr^{-1}, respectively, for a total deposition of 7 to 35 μg m^{-2} yr^{-1} (Seigneur *et al.*, 2001).

Using Equation 5, mercury contributions to the Basin from global sources (F_{GLO}) were estimated to be 817.1 kg yr^{-1}.

LAND USE IN THE BASIN

The amount of air deposited mercury conveyed to a water body has been shown to be a function of land use (Grigal, 2002; USEPA, 2001). The land area of the Basin was divided among four land use categories: Urban, Mixed, Forest, and Agricultural. The Urban and Agricultural categories are as defined by the Natural Resource Conservation Service (NRCS, 1998). Forest land includes both private and federal land (as defined by NRCS (1998)) with a tree cover of ≥ 25 percent. Mixed land is defined here as that with < 25% tree cover and with uses not otherwise covered in the other three categories, including alpine terrain, shrub and grasslands, and recently harvested forests both on federal and private lands. The areal extent of these land use categories is summarized in Table 3.

Table 3. Areal extent of various land use categories in the Basin (HUC 170900).

Land Use Category	acres	m^2	% Basin
Urban land	465,300	1,883,002,283	**6.3%**
Mixed land (<25% tree cover)	738,550	2,988,805,794	**10.0%**
federal land [(a)]	738,550	2,988,805,794	
Forest land (≥25% tree cover)	4,405,750	17,829,437,584	**59.7%**
forest land [(b)]	2,611,900	10,569,984,231	
federal land [(c)]	1,793,850	7,259,453,353	
Agricultural land	1,677,500	6,788,601,611	**22.7%**
cultivated cropland	862,400	3,490,008,959	
non-cultivated cropland	161,200	652,353,252	
CRP land [(d)]	800	3,237,485	
pastureland	404,200	1,635,739,357	
rangeland	0	0	
other rural lands	160,100	647,901,710	
rural transportation	88,800	359,360,848	
Open Water areas	98,400	398,210,670	**1.3%**
large water	51,800	209,627,162	
small water	46,600	188,583,508	
TOTAL BASIN AREA	7,385,500	29,888,057,942	**100.0%**
TOTAL LAND AREA	7,287,100	29,489,847,272	**98.7%**

(a) It was assumed that tree cover on 10% of federal land was < 25%, due either to natural or anthropogenic causes.

(b) Land at least 10% stocked by single-stemmed woody species of any size that will be at least 4 meters (13 feet) tall at maturity. Also included is land bearing evidence of natural regeneration of tree cover (cut over forest or abandoned farmland) and not currently developed for non-forest use.

(c) Land owned by the federal government. It does not include trust lands administered by the Bureau of Indian Affairs. With the exception of large water, acreage estimates for federal land are not classified into specific land cover/use categories, such as forestland, rangeland, etc. The majority of federal lands are along the Cascade Range on the eastern side of the Basin.

(d) Conservation Reserve Program (CRP). A federal program established under the Food Security Act of 1985 to assist private landowners to convert highly erodible cropland to vegetative cover for 10 years.

Delivery Ratio

The delivery ratio (DR_K) is the fraction of mercury deposited on land that will be transported by overland flow to a water body. Its value varies widely as a function of land use and season. The San Francisco Regional Water Quality Control Board (RWQCB) TMDL assumed that 0.1 - 1% of mercury deposited on undisturbed (forested) soils was conveyed to the Bay (SRWP, 2002; RWQCB, 2000). In relatively undeveloped forested areas of Wisconsin, only 4% of the mass of total mercury deposited in a watershed reached the river system (Krabbenhoft *et al.*, 1995). In a Canadian study at a remote experimental area, only 0.5 to 2% of the total mass reached a downstream lake (quoted in SRWP, 2002). Grigal (2002) estimates a delivery ratio of approximately 5% for air deposited mercury reaching waterbodies from forested watersheds. The San Francisco RWQCB TMDL assumed that 10 - 50% of mercury deposited on areas with disturbed soils (e.g., agricultural lands) was conveyed to the Bay (SRWP, 2002; RWQCB, 2000). USEPA (2001) assumed an annual average delivery ratio of 20% for a variety of land use types. A delivery ratio of 5% was used for Forest land. A value of 20% was selected for Agricultural, Urban, and Mixed land (Porvari *et al.*, 2003; USEPA, 2000).

Table 4. Inputs from air deposition via runoff from different land use types in the Basin.

Land Use	Land Use (LU_k)	Delivery Ratio (DR_k)	Load (kg yr^{-1}) [(a)]
Urban land	6.3%	0.20	6.4
Mixed land	10.0%	0.20	10.0
Forest land	59.7%	0.05	14.7
Agricultural land	22.7%	0.20	22.5
Water	1.3%	1.00	7.6
Total			61.3

(a) Airborne mercury transport and fate modeling by USEPA Region 6 and with REMSAD by Region 10 for Oregon, suggest that not all of the mercury that enters the Basin from either anthropogenic or global sources is retained within the Basin. For example, ≈50% of emissions from combustion facilities may enter the global atmospheric reservoir as opposed to being deposited near a facility (Kalari, 2000). The combined effects of advection from the Basin was accounted for by multiplying total input (FGLO + FLOC) by an advection fraction of 50%.

Estimates of the average annual input of mercury from air deposition (M_{AD}) conveyed to the mainstem from various land use types are summarized in Table 4. Total input to the mainstem due to deposition from all air sources is 61.3 kg yr^{-1}.

Soil Erosion

Mercury input associated with water-induced sheet and rill erosion of soils from various land use types was estimated as a function of erosion rates provided by the NRCS and the estimated concentration of mercury in surficial soils,

$$F_{SE} \sim \sum_{k=1}^{m} \left(\left(ER_k \cdot SD \cdot EF \right) \cdot C_{soil} \cdot 10^{-6} \cdot f_{ps} \cdot A_k \right) \tag{6}$$

$$SD = 0.33 \cdot A_K^{0.125} \tag{7}$$

where:

F_{SE} Mean annual input of mercury to surface water from soil erosion (kg yr^{-1})
m Number of land use types
ER_k Erosion loss rate of k^{th} land use type (kg $m^{-2} \cdot yr^{-1}$)
SD Sediment delivery ratio (unitless)
EF Soil enrichment factor (unitless)
C_{soil} Concentration of total mercury in surficial soil (mg kg^{-1})
f_{ps} Soil mercury solid fraction at equilibrium (unitless)
A_k Area of k^{th} land use type (m^2)

Mercury has an average crustal abundance of 0.05 mg kg^{-1} (UNEP, 2003). The concentration of mercury in Willamette Basin soils has been estimated as 0.09 mg kg^{-1} in the “A” horizon and 0.05 mg kg^{-1} in the “B” horizon (Khandoker, 1997). A value of 0.07 mg kg^{-1} was used for the soil erosion input estimation. The Natural Resources Conservation Service (NRCS) provides estimates of water-induced sheet and rill erosion for agricultural land (NRCS, 1998, 2000). The erosion loss rate for Forest land was assumed to be equal to those from Conservation Reserve Program (CRP) lands. Default values for soil enrichment factor (2) and f_{ps} (0.99) are from USEPA (2000). The enrichment factor is the ratio of the mercury concentration in a weathered material to that in fresh parent material. The sediment delivery ratio value (0.13) was calculated for the total agricultural land area of the Basin using Equation 7 (from USEPA, 1999: Table C.3-14). Results of calculations with Equation 6 are shown in Table 5.

Table 5. Estimated inputs to the Basin from native soil erosion.

Land Use	Area (m^2)	Erosion loss rate (kg $m^{-2} \cdot yr^{-1}$)	Input from erosion (kg yr^{-1})
Agricultural land	6,788,601,611	0.31	38.1
Forest land	17,829,437,585	0.05	15.1
Mixed land	2,988,805,794	0.12	6.5
Urban land	1,883,002,283	0.05	1.6
Total			61.4

Landfill Emissions

Mercury-containing wastes are likely present in permitted land waste disposal units (i.e., landfills). Although modern units are designed and constructed to contain these wastes, historic operations (or illegal dumping or failed modern units) may be sources of mercury to the atmosphere or surface waters. However, data on the occurrence or quantity of such releases are not currently available and thus estimates for these have not been included in this analysis.

MERCURY MINES

Historical information and ODEQ site assessment investigations have identified 41 mercury mining-related sites within the Basin (Jeff Christensen, ODEQ Land Quality Division, *personal communication*). These sites are summarized in Table 6 below. It is important to note that there are few actual mercury mines in the Basin; several of the listings in Table 6 are for gold mines that used mercury in the extraction process. The list also does not differentiate between significant mining activities (such as the Black Butte Mine and the Bohemia Mining District) and much smaller mining efforts or even simple prospects.

Table 6. Mining activities in the Basin which directly or indirectly involved mercury.

Name	County	Subbasin	Comments
Aimes-Bancroft Group	Clackamas	Clackamas River	Old structures are present. Adit is caved.
Kiggins Mine	Clackamas	Clackamas River	Discharge (1gpm, pH 8.3) to Oak Grove fork of Clackamas River; flow. Mercuric oxides present in waste rock. Mill structure and other buildings present. Open adits.
Nisbet Mine	Clackamas	Clackamas River	Oak Grove fork of Clackamas River is eroding tailings. Old structures are still present on site. Adit is still open.
North Fork Claims	Clackamas	Clackamas River	
Cheeney Creek	Clackamas	Clackamas River	Clear discharge (@ 5gpm, pH 8.1) to Cheeney Creek and Salmon River. Has eroded rock waste pile. Adit is open. Shaft appears caved.
Helena Mine	Lane	Coast Fork, Willamette River	Discovered in 1896. Mine had gold, silver, copper, lead, barium, antimony, and zinc and has 3 principal levels with 2,000 feet of drifts and crosscuts and about 500 feet of raises plus stopes. Major years of production were from 1896-1907, 1931, and 1949. Discolored discharge (15 gpm, pH 4) to Horse Heaven and Steamboat Creeks. Open adit - wooden covering.
Graham Property	Lane	Coast Fork, Willamette River	
Knott Claim	Lane	Coast Fork, Willamette River	
Treasure	Lane	Coast Fork, Willamette River	4000' of workings. Mill on-site.
Union	Lane	Coast Fork, Willamette River	1200' of workings. Mill on-site.
Bald Butte Prospect	Lane	Coast Fork, Willamette River	
Black Butte Mine	Lane	Coast Fork, Willamette River	Was a silver and mercury mine with three mills during its operating years from 1890-1909, 1916-1943, and 1956. Mine had two main tailing piles. The lower tailing pile was 30 feet away from Dennis Creek, which flows westerly to Garoutte Creek, which flows northerly to the Coast Fork of the Willamette River. Elevated mercury levels have been found in the sediment (267 mg/kg) and soil (350 mg/kg). Hg contamination of fish in Cottage Grove Reservoir is presumed to come from high Hg levels in the Coast Fork of the Willamette River, which drains into the reservoir.

Table 6. Mining activities in the Basin which directly or indirectly involved mercury.

Name	County	Subbasin	Comments
Champion & Evening Star Mine	Lane	Coast Fork, Willamette River	Discovered in 1892 near the Champion Saddle on the divide of Champion and City Creeks. Mine had gold, silver, copper, lead, and zinc. Ore was processed in 3 mills. Mine has more than 15,000 feet of drifts and crosscuts, and about 3,000 feet of raises on 9 levels. Major years of production were from 1932 through 1939. Discolored discharge to Champion Creek. (10 gpm, pH 5.5). Champion Creek flows to Brice Creek which dumps into the Row River. No structures.
Columbia Vein	Lane	Coast Fork, Willamette River	Champion Creek watershed. Drainage (5 gpm, pH 7.2) not to surface water.
Excelsior Vein	Lane	Coast Fork, Willamette River	Champion Creek watershed. Part of Champion Mine.
Leroy Mine	Lane	Coast Fork, Willamette River	Champion Creek watershed
Mayflower Mine	Lane	Coast Fork, Willamette River	
Lower Musick	Lane	Coast Fork, Willamette River	Adit and dump. No structures. Discharge (10 gpm, pH~7.5) directly to Sharps Creek (tributary to Brice Creek).
Musick	Lane	Coast Fork, Willamette River	Discovered in 1891 and worked extensively during early part of the century by various organizations. Mine had gold, silver, copper, lead, and zinc, with about 7,200 feet of drifts and crosscuts plus numerous stopes, raises and winzes on the Musick vein. Numerous pits and short adits explore the branching California vein. Discharge (3-5 gpm, 3.9 pH) to City Creek tributary to Steamboat Creek.
Noonday Mine	Lane	Coast Fork, Willamette River	Major producer of gold, silver, copper, and lead. Mill on-site.
Peekaboo Mine	Lane	Coast Fork, Willamette River	Mill on-site.
Pitcher Prospect	Lane	Coast Fork, Willamette River	
Star Mine	Lane	Coast Fork, Willamette River	1300' of workings. Brice Creek watershed.
Sultana Mine	Lane	Coast Fork, Willamette River	2000' of workings. Mill on-site. Champion Creek watershed.
Sweepstakes	Lane	Coast Fork, Willamette River	1000' of workings. Champion Creek watershed.
Vesuvius	Lane	Coast Fork, Willamette River	6000' of workings. Mill on-site. Brice Creek watershed.
Woodard Prospects	Lane	Coast Fork, Willamette River	
Sullivan (Bald Butte)	Lane	Coast Fork, Willamette River	
Portland Tunnel	Multnomah	Lower Willamette River	
Amalgamated Mine	Marion	North Santiam River	
Black Eagle Mine	Marion	North Santiam River	
Blue Jay Mine	Marion	North Santiam River	
Bonanza Mine	Marion	North Santiam River	
Crown Mine	Marion	North Santiam River	

Table 6. Mining activities in the Basin which directly or indirectly involved mercury.

Name	County	Subbasin	Comments
Silver King Mine	Marion	North Santiam River	
Silver Star Mine	Marion	North Santiam River	
Breitenbush Mineral Springs	Marion	Breitenbush River, North Santiam River	
Bob & Betty	Linn	Quartzville Creek, Middle Santiam River	1650' of workings.
Poorman	Linn	Quartzville Creek, Middle Santiam River	Mill on-site.
Albany Mine	Linn	Quartzville Creek, Middle Santiam River	Gold mine first prospected in 1888. Ore was processed in 3 mills. There were approximately 1,090' of workings.
Lawler	Linn	Quartzville Creek, Middle Santiam River	Discovered in 1861 on White Bull Mountain and Dry Gulch. Mine had gold, silver, lead, copper, and zinc. There were 2,000' of workings by 1903, with four principal adit levels and numerous open cuts.

Nine of the 18 TMDL sampling stations are located above, in, and below Cottage Grove and Dorena reservoirs at the southern headwaters of the Basin. These reservoirs are located downstream of the two largest legacy mercury mining areas in the Basin: the Black Butte Mine and the Bohemia Mining District (in the Row River watershed). Mercury levels are significantly elevated (to 12.9 ng L^{-1}) in Dennis Creek, which drains from the Black Butte mine into Cottage Grove Reservoir. Both reservoirs discharge to the Coast Fork of the Willamette River. Although historical mining sites are also located in the headwaters of the Santiam and Clackamas Rivers (above their respective dams), available water quality data collected within these drainages does not indicate any elevations in total mercury concentrations that could be attributed to mine discharges. The Dorena and Cottage Grove reservoirs are therefore assumed to be the most significant mining inputs to the Coast Fork, and the Coast Fork the most significant such input to mainstem. To estimate the mass of total mercury escaping capture in the reservoirs, USGS daily mean flow data (USGS, 2004) were regressed against total mercury surface water concentration data (ODEQ, 2004) for specific sampling dates to form flow-concentration relationships (Cohn et al., 1992) for discharges from the reservoirs,

$$C_{CG} = -0.4407 \cdot \mathrm{Q}_{\mathrm{CG}}^{3.1562} \quad n = 4,\ R^2 = 0.277 \tag{8}$$

$$C_{DR} = -1.1006 \cdot \mathrm{Q}_{\mathrm{DR}}^{6.5850} \quad n = 4,\ R^2 = 0.754 \tag{9}$$

$$F_{MINE} = \left(C_{CG} \cdot Q_{CG} + C_{DR} \cdot Q_{DR}\right) \cdot CF_{Lfsy} \cdot CF_{kn} \tag{10}$$

where:

C_{CG} Total mercury concentration in surface water downstream of Cottage Grove Reservoir (ng L^{-1})
Q_{CG} Daily mean flow below Cottage Grove Reservoir (246 $ft^3\ s^{-1}$)
C_{DR} Total mercury concentration in surface water downstream of Dorena Reservoir (ng L^{-1})
Q_{DR} Daily mean flow below Dorena Reservoir (763 $ft^3\ s^{-1}$)
F_{MINE} Load of mining-related mercury entering the mainstem (kg yr^{-1})
CF_{Lfsy} Conversion factor (893,099,520 L $ft^{-3} \cdot s\ yr^{-1}$).

Using Equation 10, the mean mine-related flux is estimated to be 0.75 kg yr^{-1} (Table 7). These results suggest that mining-related inputs are small relative to total inputs to the Basin.

Table 7. Inputs from Coast Fork due to mercury mining activities.

Location	Total Hg load (mean [90%-tile range] kg yr^{-1})
Dorena Reservoir	0.36 [0.29-0.43]
Cottage Grove Reservoir	0.40 [0.12-0.88]
Total	0.75 [0.47-1.24]

Although mercury inputs from mines are small relative to other inputs to the mainstem, their potential impact on mercury levels in fish tissue is of concern, since fish consumption is the primary human exposure pathway for mercury. This issue was examined by combining 30 years of ODEQ tissue residue data into four categories: (1) largemouth bass (a popular game fish and top predator species) data from the Coast Fork (as this is the segment most likely to be impacted by mercury discharged from mines), (2) largemouth bass data from locations in the Basin other than the Coast Fork, (3) data from fish collected in the Coast Fork, and (4) data from fish collected elsewhere in the Basin. As shown in Figure 5, median tissue levels in bass and other fish species collected in the mainstem are less than those of fish collected in the Coast Fork (bass, 0.29 versus 0.43 mg/kg; all fish, 0.21 versus 0.35 mg/kg). This suggests that discharges from historical mercury mining activities impact fish tissue levels in the Coast Fork behind the reservoirs, but such impacts on tissue levels apparently do not extend below the reservoirs into the mainstem.

DOMESTIC (POTW) DISCHARGES

Publicly operated treatment works (POTW) within the Basin were identified using the National Point Discharge Elimination System (NPDES) permit data base maintained by ODEQ's Water Quality Division. Data on flow rates and total mercury concentrations in POTW effluents were obtained from 2002 Pretreatment reports (no such reports were available for Stayton, Lebanon, Sweet Home). Results are summarized in Table 8. The input from all POTW discharges combined was estimated as,

$$F_{POTW} \sim \sum_{i=1}^{g} Q_i \cdot GC \cdot C_i \cdot FC \cdot UC \cdot TC \qquad (11)$$

where:

F_{POTW} Average annual input of mercury from POTW sources listed in Table 8 (kg yr^{-1})
Q_i Annual average discharge from the i^{th} POTW (MGD)
GC Unit conversion factor (10^6 gal MGD^{-1})
C_i Average concentration of total mercury in effluent of the i^{th} POTW (ng L^{-1})
FC Flow rate conversion factor (3.785412 L gal^{-1})
UC Unit conversion factor (10^{-12} kg ng^{-1})
TC Time conversion factor (365 d yr^{-1}); *g* = Number of POTWs

Table 8. Effluent discharge rates and mercury concentrations for publicly operated treatment works with permitted discharges ≥ 2 million gallons per day (MGD).

POTW	Geomean Dry, Peak Wet Flow (MGD)	Reported Concentration (ng L^{-1})	Conc Used in Calculation (ng L^{-1})	Estimated Load (kg yr^{-1})
Clackamas (Kellogg Creek)	7.90	200.0	10.0	0.11
Tryon Creek (Portland)	11.22	282.0	10.0	0.16
Tri-City Service (Tri-City)	8.59	30.0	10.0	0.12
Clean Water Services (Durham)	36.99	50.0	10.0	0.51

Table 8. Effluent discharge rates and mercury concentrations for publicly operated treatment works with permitted discharges ≥ 2 million gallons per day (MGD).

POTW	Geomean Dry, Peak Wet Flow (MGD)	Reported Concentration (ng L^{-1})	Conc Used in Calculation (ng L^{-1})	Estimated Load (kg yr^{-1})
Clean Water Services (Rock Creek)	50.27	50.0	10.0	0.69
Clean Water Services (Hillsboro)	7.00	50.0	10.0	0.10
Clean Water Services (Forest Grove)	4.38	50.0	10.0	0.06
Canby	1.71	200.0	10.0	0.02
Woodburn	3.12	100.0	10.0	0.04
Wilsonville	2.60	58.0	10.0	0.04
Newberg	2.57	250.0	10.0	0.04
McMinnville	8.50	5.0	5.0	0.06
Salem (Willow Lake)	53.85	50.0	10.0	0.74
Dallas	3.72	2.1	2.1	0.01
Albany	10.26	190.0	10.0	0.14
Corvallis	13.09	40.0	10.0	0.18
Eugene-Springfield	70.00	5.0	5.0	0.48

Mean flow rate (Q_i) in Equation 11 (for each POTW) was estimated as the geometric mean of the reported Actual Dry Weather [Average] Flow and the Actual Peak Wet Weather Flow values. The majority of POTWs use analytical techniques for mercury with detection limits ≥ 50 ng L^{-1}, which provide estimates of C_i that are potentially biased high. The benefit of the doubt (regarding actual mercury concentrations) was extended to these sources by assuming a mean value for C_i of 10.0 ng L^{-1}, a value near the average of values reported by POTWs using low level analytical methods (and close to the USEPA default mean value of 7.0 ng L^{-1} (USEPA, 2001)). The average annual input of total mercury to the Basin from POTW discharges was estimated at 3.5 kg yr^{-1}.

INDUSTRIAL DISCHARGES

Mercury inputs from industrial discharges were estimated as,

$$F_{IND} \sim \sum_{i=1}^{u} C_i \cdot Q_{Mi} \cdot GC \cdot FC \cdot TC \cdot UC \qquad (12)$$

where:

F_{IND} Average annual input of mercury from industrial sources (kg/yr)
C_i Concentration of total mercury in industrial effluent (ng L^{-1})
Q_{Mi} Annual flow rate from i^{th} industrial source (MGD)
GC Unit conversion factor (10^6 gal MGD^{-1})
FC Flow rate conversion factor (3.785412 L gal^{-1})
UC Unit conversion factor (10^{-12} kg ng^{-1})
TC Time conversion factor (365 d yr^{-1})
u Number of industrial sources (unitless).

In the industrial sector, mercury is most often associated with discharges from chlor-alkali plants and pulp and paper mills (USEPA, 2001). There are no chlor-alkali plants in the Basin, but the NPDES permit data base maintained by ODEQ's Water Quality Division contains eight pulp and paper-related operations with major industrial discharge permits (NPDES) within the Basin (Table 9). All of these operations have data available on effluent discharge rates. However, none have data available on total mercury concentrations in their effluent, so 13 ng L^{-1}, a default value used by U.S. EPA (USEPA, 2001) to represent the average mercury concentration in pulp and paper mill effluent, was used to bridge this data gap.

It is important to note that there may well be as yet unrecognized inputs of mercury from permitted discharges within the Basin other than those associated with pulp and paper. Due to the lack of region-specific data on mercury concentrations in all industrial discharges, these estimates **should not** be taken as an adequate, long-term substitute for obtaining actual data on discharge rates and mercury concentrations in industrial effluents.

Table 9. Mercury inputs from permitted industrial operations within the Basin.

Permittee	Location	Flow (MGD)	Estimated Input (kg yr^{-1})
Blue Heron Paper Company	Oregon City	10.5	0.2
Evanite Fiber Corporation	Corvallis	1.7	0.03
Fort James Operating Company	Halsey	4.5	0.08
Pope & Talbot, Inc.	Halsey	17	0.3
Virginia Paper Manufacturing Corp	Newberg	17	0.3
West Linn Paper Company	Oregon City	6	0.1
Weyerhaeuser Company	Albany	15	0.3
Weyerhaeuser Company	Springfield	17	0.3
Total			1.6

STORMWATER DISCHARGES

There are six Phase I Municipal Separate Storm Sewer System (MS4s) permittees (plus their co-permittees): Eugene, Salem, Clackamas County, Cleanwater Services, Portland, and Gresham and a number of designated Phase II permittees within the Basin, plus many other cities that are not currently part of the MS4 permit program, but discharge stormwater within the Basin. These may be potential sources of mercury to the mainstem but, at present, no data are available on discharge rates or mercury concentrations in these or any other stormwater discharges.

SEDIMENT RE-SUSPENSION AND DEPOSITION

Sediment re-suspension is an input and deposition an output for mercury in surface water. Mercury is typically associated with smaller (< 0.20 mm) sediment particles (Rickert *et al*., 1977) which are potentially readily re-suspended and transported when their relatively lower shear velocity is exceeded during moderate to high flow events. During winter high flow events when the shear velocity is likely to be exceeded, re-suspension of deposited sediment brings mercury into the water column. Average mercury concentrations in bed sediment range from 0.13 mg/kg (near the background for streams of 0.085 mg/kg (Rice, 1999)) within the mainstem to 0.47 mg/kg in areas of the Coast Fork impacted by historic mining activities (Figure 6) (ODEQ, 2003; Rickert *et al*., 1977). Given that sediment concentrations in the mainstem are approximately three-times those of “A” horizon soil concentrations, even a small amount of re-suspension could make a significant contribution to total input (McCoy and Black, 1998). Conversely, during low flows (summer), when the shear velocity of small particles is unlikely to be exceeded, deposition removes mercury from the water column.

Figure 5. Distribution of total mercury concentrations in fish tissues collected in the Basin (1969 - 1997).

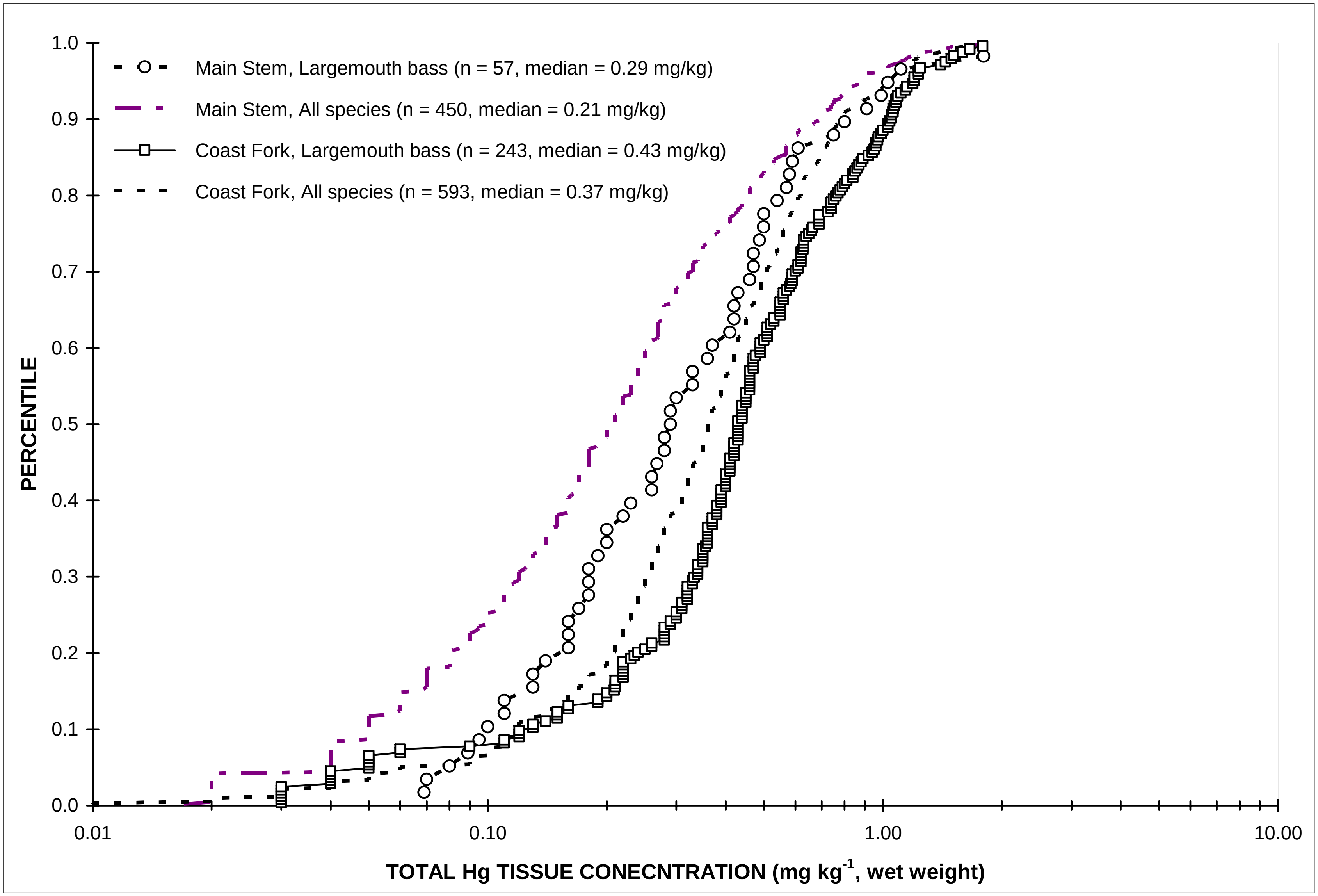
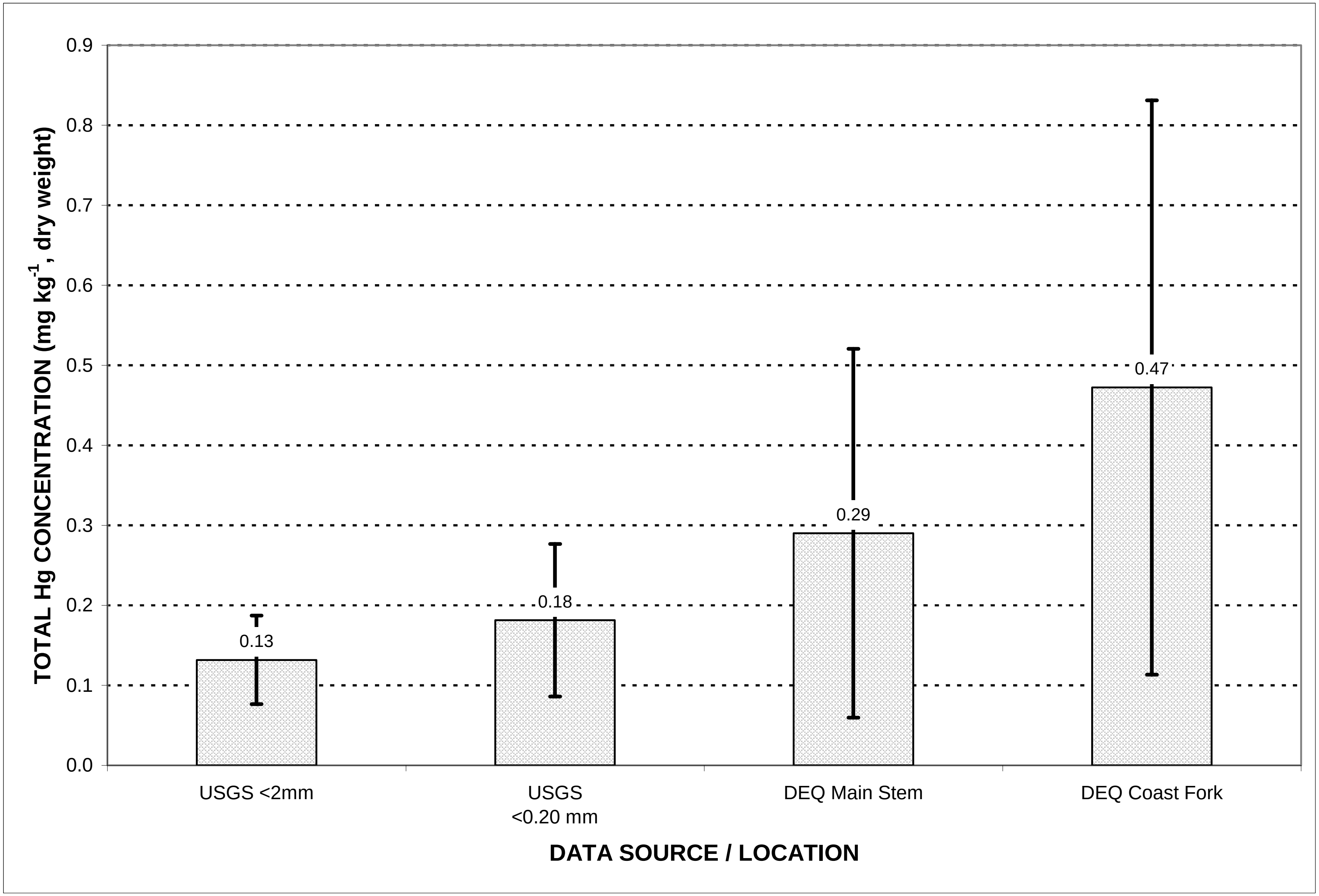


Figure 6. Measured mercury concentrations in sediment from various Basin locations (1977 - 2003)



REVISED MASS BALANCE

Basinwide

Estimates for average annual mercury inputs to and outputs from the Basin are summarized in Table 10. A mass balance is achieved by matching the estimated output (from Section 1) to the sum of the estimated inputs (from Section 2). Figure 7 summarizes the relationship of the various inputs to the average annual cumulative output from the Basin (126.8 kg yr^{-1}). This figure serves to illustrate that inputs from air deposition and soil erosion are accounted for separately and have not necessarily been "double-counted". Air deposition supplies a total of 61.3 kg yr^{-1} to the mainstem, of which 7.6 kg yr^{-1} comes from direct deposition to water, and 6.4 kg yr^{-1}, 10.0 kg yr^{-1}, 14.7 kg yr^{-1}, and 22.5 kg yr^{-1} result from urban, mixed, forest, and agricultural land runoff, respectively. Erosion of native soil from land contributes 61.4 kg yr^{-1} to the mainstem. The total from all non-point sources is 122.7 kg yr^{-1} and that from all known and currently quantified point sources is 5.9 kg yr^{-1}, for a total annual average input of 128.5 kg/yr. The differential between total inputs and outputs (1.7 kg yr^{-1}) is essentially negligible, but could be attributed to deposition.

Figure 8 shows the relative contributions of various sources to the mainstem, based on the values given in Table 10. Erosion of native soil (≈ 48%) and air deposition (≈ 42%) are approximately evenly divided as the main sources of mercury to the mainstem. The majority (82.9%) of air deposited mercury is estimated to come from global sources. Average inputs from all currently quantifiable point sources are, at ≈ 5%, relatively small contributors to total input. Figure 9 shows that the agricultural land use category contributes, via runoff (17.5%) and erosion (29.7%), the most to the mainstem. Although forest land has lower erosion and runoff rates, its sheer size (≈ 60% of the Basin) makes it a noticeable contributor to mainstem total load.

These averages obscure, however, significant seasonal fluctuations in both the magnitude and source of inputs. Seasonal variation in precipitation and snow melt can affect flow rate, which determines whether sediment is re-suspended or deposited, wet deposition, which affects air inputs to land, and surface runoff and erosion, which together affect outputs from land to water. Development of useful mercury management strategies will require future mercury mass balance analyses to explicitly account for seasonal influences.

Table 10. Summary balance of mercury inputs and outputs for the Basin.

Description of Input or Output	Report Section	Annual Mean Rate (kg yr^{-1})
Average annual output	2.0	126.8
Average annual inputs		
Non-point Sources		
Runoff of air deposition	3.1	53.7
Direct deposition to open water	3.1	7.6
Surface soil erosion	3.2	61.4
Point Sources		
Landfill Emissions	3.3	0.0 [a]

Mine Discharges	3.4	0.8
POTW Discharges	3.5	3.5
Industrial Discharges	3.6	1.5
Stormwater Discharges	3.7	0.0 [a, d]
Sediment Re-suspension (input to water column)	3.8	0.0 [b]
Total Inputs		128.6
Sediment Deposition (output from water column)		1.7 [c]

(a) Placeholder value; no data currently available with which to estimate an actual value.
(b) Seasonal average value, expected to be significantly higher during the wet (high flow) season.
(c) Estimated indirectly as Output minus Total Inputs (126.8- 128.6 = -1.7). Long-term average value, surrounded by considerable variation due to seasonal changes in flow.
(d) Expected to include only discharges in excess of those already included under runoff of air deposition and surface soil erosion.

Coast Fork Subbasin

Because discharges from historical mercury mining activities appear to impact fish tissue levels in the Coast Fork behind the reservoirs (see Section 3.4), estimates of average annual mercury fluxes for this subbasin were made separately from those for the mainstem. These estimates used the same calculation methods and assumptions regarding the percentage distribution of land uses (see Table 3) as described previously in this report. Basin-wide land use assumptions were applied to the Coast Fork for consistency but may not accurately reflect current uses within this subbasin. As of 1980, urban development (located primarily along the lower stream reaches) was minimal within the Coast Fork, while agricultural and rangeland (i.e, mixed) uses dominated the lower watershed (≈45% of subbasin) and forest land for timber production dominated its upper reaches (≈50% of subbasin). It may be necessary to revise these calculations in response to more recent data on actual land uses within the Coast Fork. The calculations were adjusted to reflect the smaller total land area in the watershed (Coast Fork (Cottage Grove Reservoir) watershed: 104 mi^2; Row River (Dorena Reservoir) watershed: 270 mi^2), data source USGS (2004). Results are summarized in Table 11.

Estimates of output and input of total mercury (Table 11) were developed independently of one another. Reconciliation of these estimates was done by assigning any differences to a “deposition” category, for the mass of total mercury (most likely the particulate-bound component) estimated to be retained behind the dams. Retention in Dorena Reservoir was estimated at 1.73 kg yr^{-1}, while that in Cottage Grove Reservoir was estimated at 2.69 kg yr^{-1}. This differential in retention is driven primarily by differences in watershed area and by assumptions regarding the mass of mining-related mercury entering the watershed. Extensive historical mining activity has contributed significant mercury to Cottage Grove Reservoir; however, such mining activity appears to have had a barely discernible impact on Dorena Reservoir. This is suggested by the following lines of evidence: (a) Total mercury surface water concentrations in Dennis Creek (which drains from the Black Butte Mine complex) have reached 18.5 ng L^{-1}, while those in Brice Creek (which drains from the Bohemia Mining District) have only reached 1.8 ng L^{-1} (ODEQ, 2004); (b) Total mercury concentrations in sediment in Dennis Creek have reached 0.90 mg kg^{-1} (all sediment concentrations are dry weight), while those in Brice Creek (0.04 mg kg^{-1}) are the same as those in Laying Creek[†], a background sampling station; and (c) A recent study (Morgans, 2003) of

[†] “Laying Creek” for USGS gage 14154000; “Layng Creek” on USGS topographic maps.

Cottage Grove Reservoir reported mercury concentrations in sediment immediately downstream of the dam from <0.02 to 0.07 mg kg^{-1} but from 0.68 to 3.60 mg kg^{-1} in sediment within the reservoir. ODEQ found a sediment concentration of 0.88 mg kg^{-1} in Cottage Grove Reservoir, but only 0.17 mg kg^{-1} in Dorena Reservoir (ODEQ, 2004). In comparison, average mercury concentrations in mainstem sediment range from 0.13 to 0.29 mg kg^{-1} (dry weight) (ODEQ, 2004).

Relative contributions of different mercury sources in the Coast Fork subbasin are summarized in Figures 10 and 11. Soil erosion is the largest source (~70%) for the Dorena Reservoir subbasin, while discharges from legacy mining activities are the largest (~74%) source for the Cottage Grove Reservoir subbasin.

Table 11. Summary balance of mercury inputs and outputs For the Coast Fork.

Description	Estimated Inputs / Outputs (kg yr^{-1})	
	Row River (Dorena Reservoir)	**Coast Fork (Cottage Grove Reservoir)**
Average annual output [(a)]	0.36	0.40
Average annual inputs		
Runoff of air deposition from urban land	0.07	0.03
Runoff of air deposition from mixed land	0.11	0.04
Runoff of air deposition from forest land	0.16	0.06
Runoff of air deposition from agricultural land	0.24	0.09
Air deposition directly to water	0.07	0.03
Soil erosion from agricultural land	0.89	0.34
Soil erosion from forest land	0.35	0.14
Soil erosion from mixed land	0.15	0.06
Soil erosion from urban land	0.04	0.01
POTWs	0.00	0.01
Mines	0.00 [(b)]	2.33 [(b)]
Total Inputs	2.08	3.14
Retained behind dams	1.72 [(c)]	2.74 [(c)]

(a) Amount not being retained by a dam; value estimated in Section 3.4 (Table 7).
(b) Mine loading to Coast Fork estimated by pairing concentrations measured at Dennis Creek with flows at USGS gage 14152500. Mine loading to Row River assumed to be zero (see text).
(c) Estimated indirectly as Total Input minus Output (past dams).

Figure 7. Relationships of average annual mercury movement within the Basin.

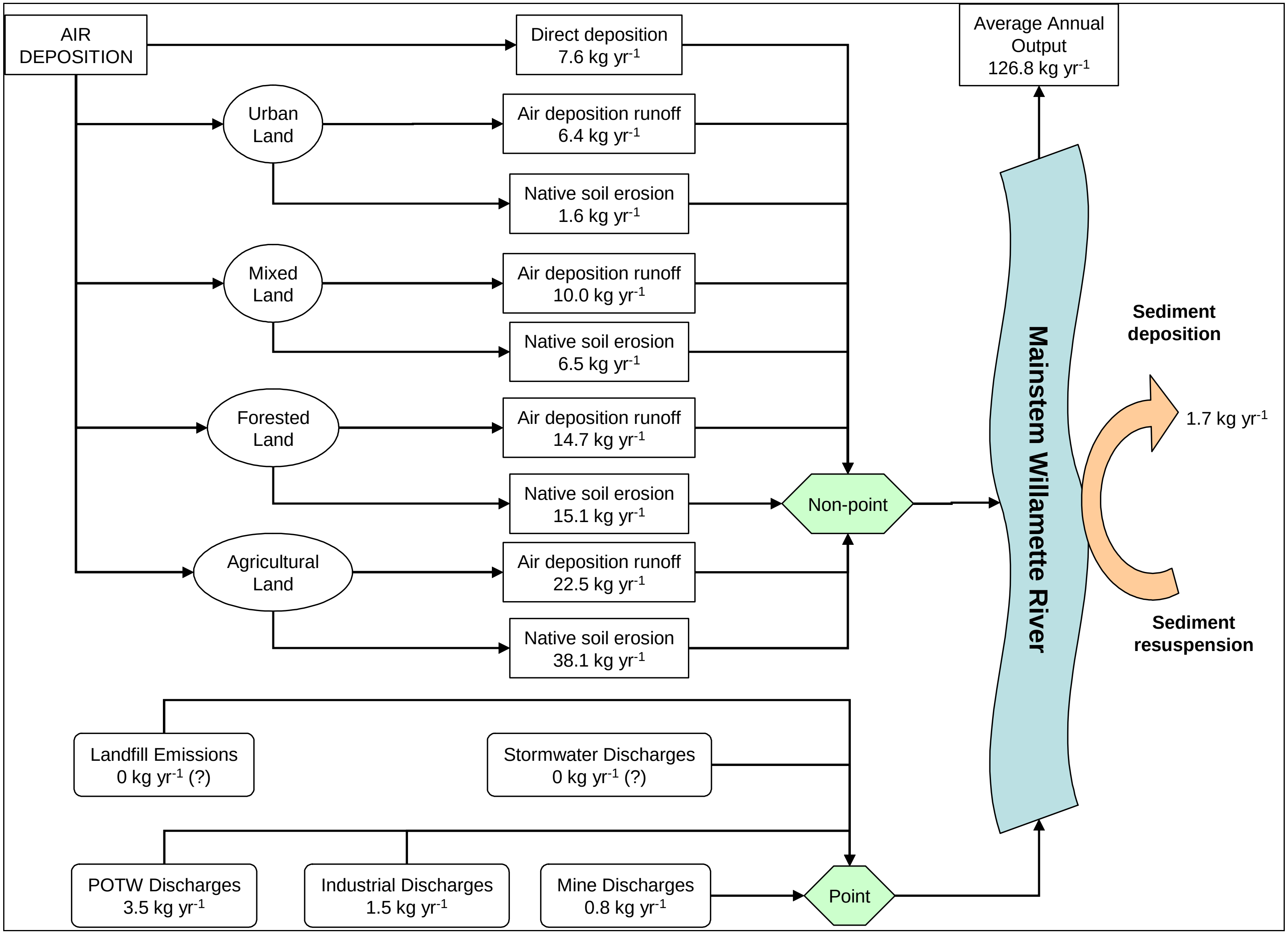


Figure 8. Relative contributions to the mainstem by source category.

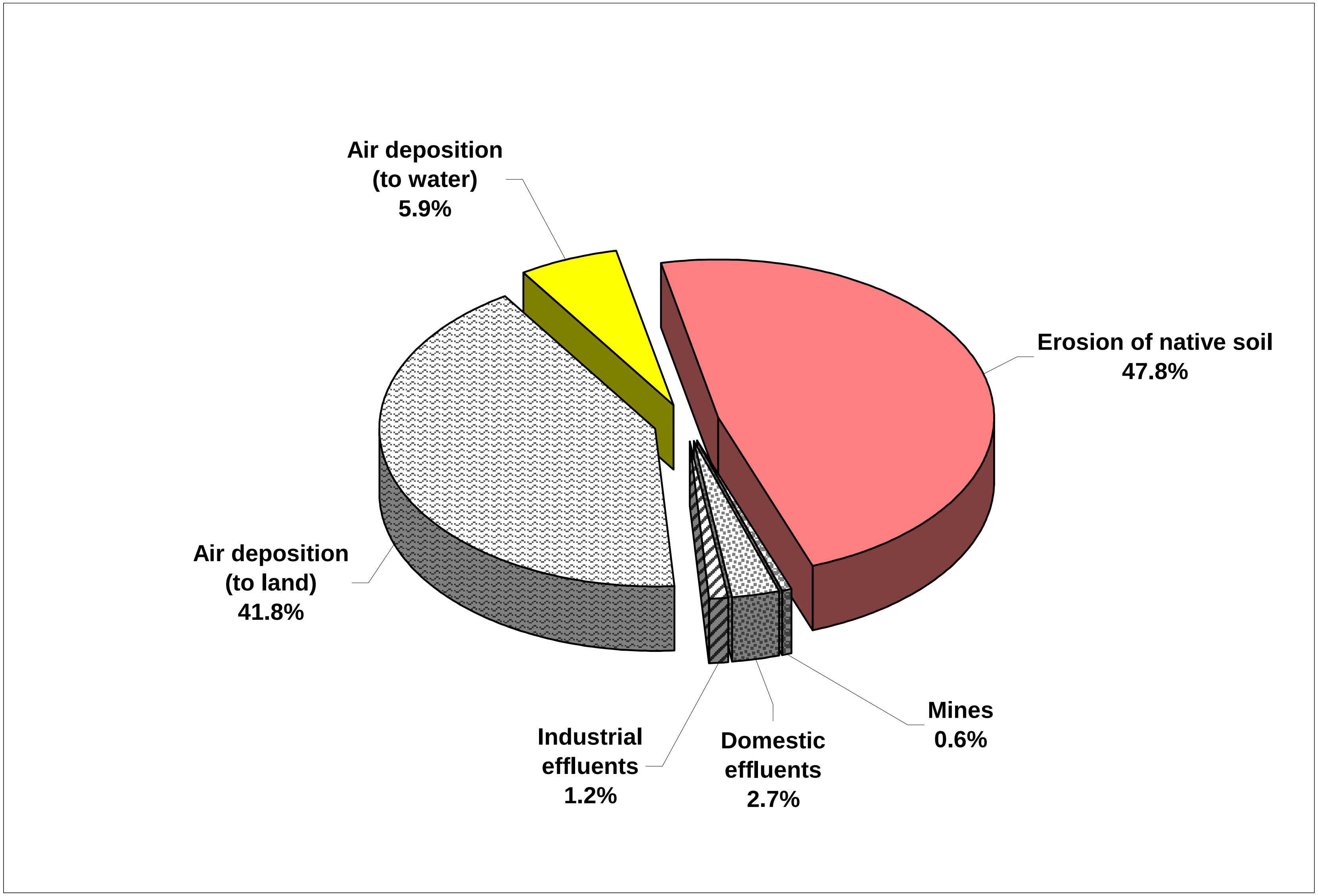


Figure 9. Relative contributions to the mainstem by land use category.

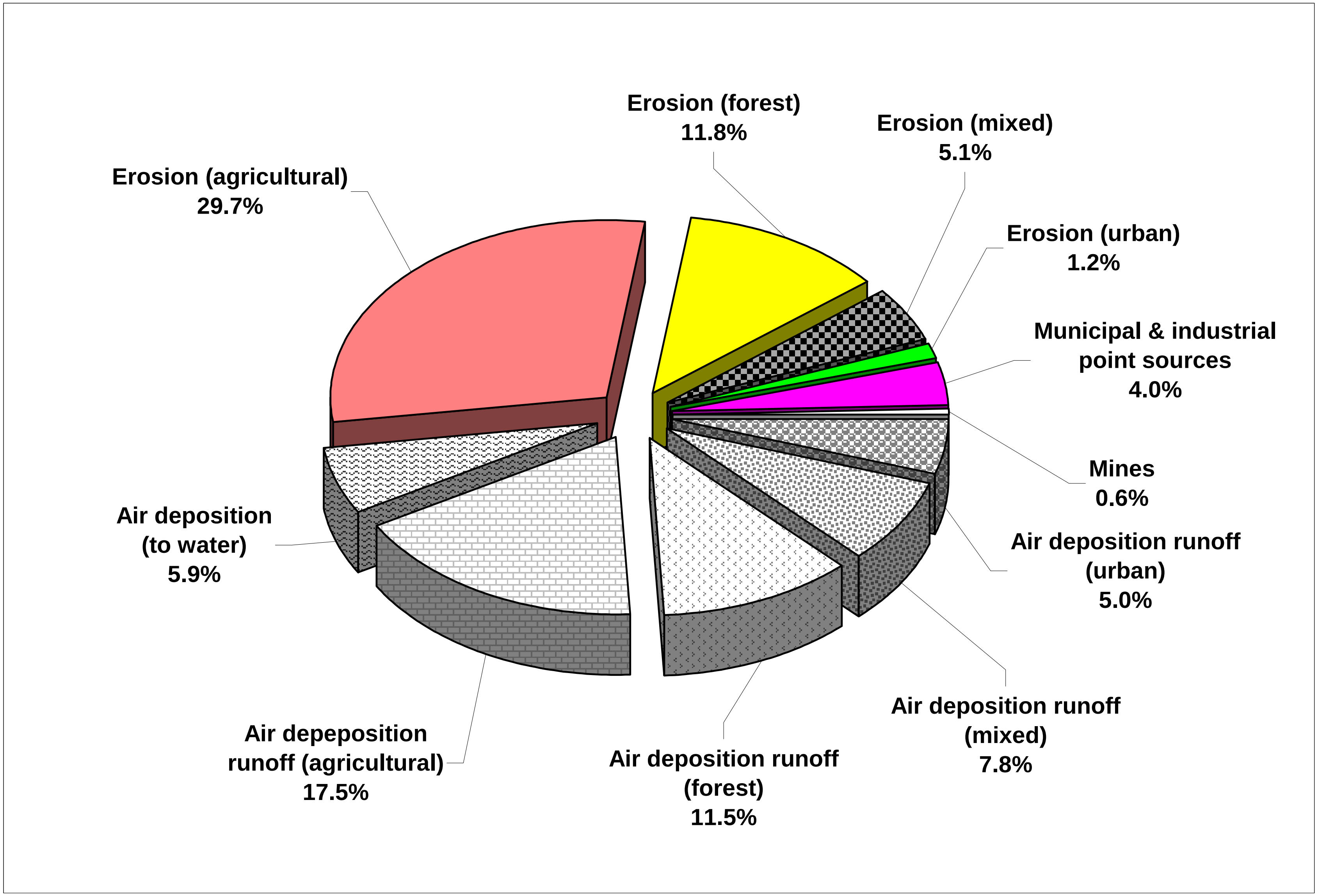


Figure 10. Relative contributions to the Coast Fork (Cottage Grove Reservoir) by source category.

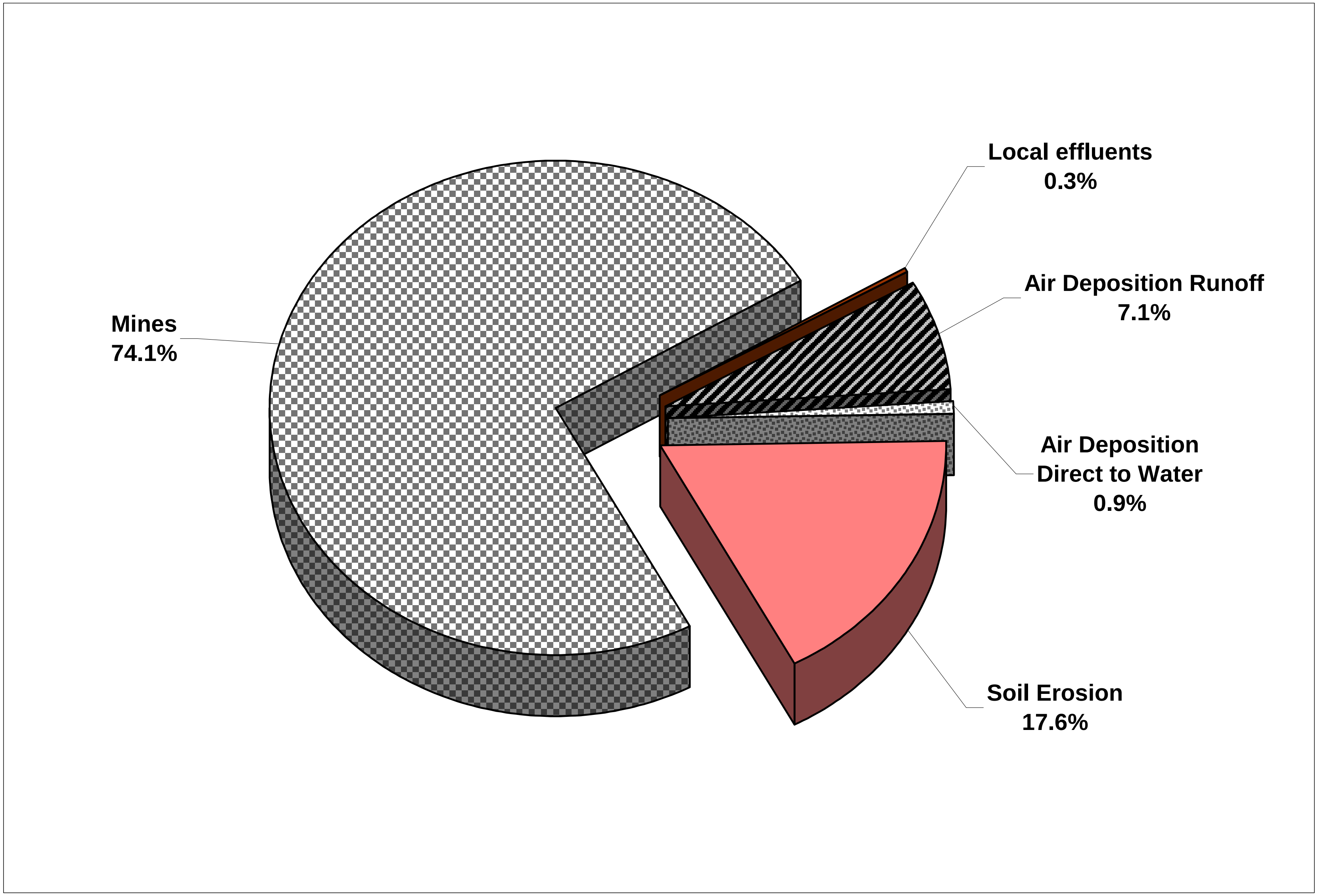
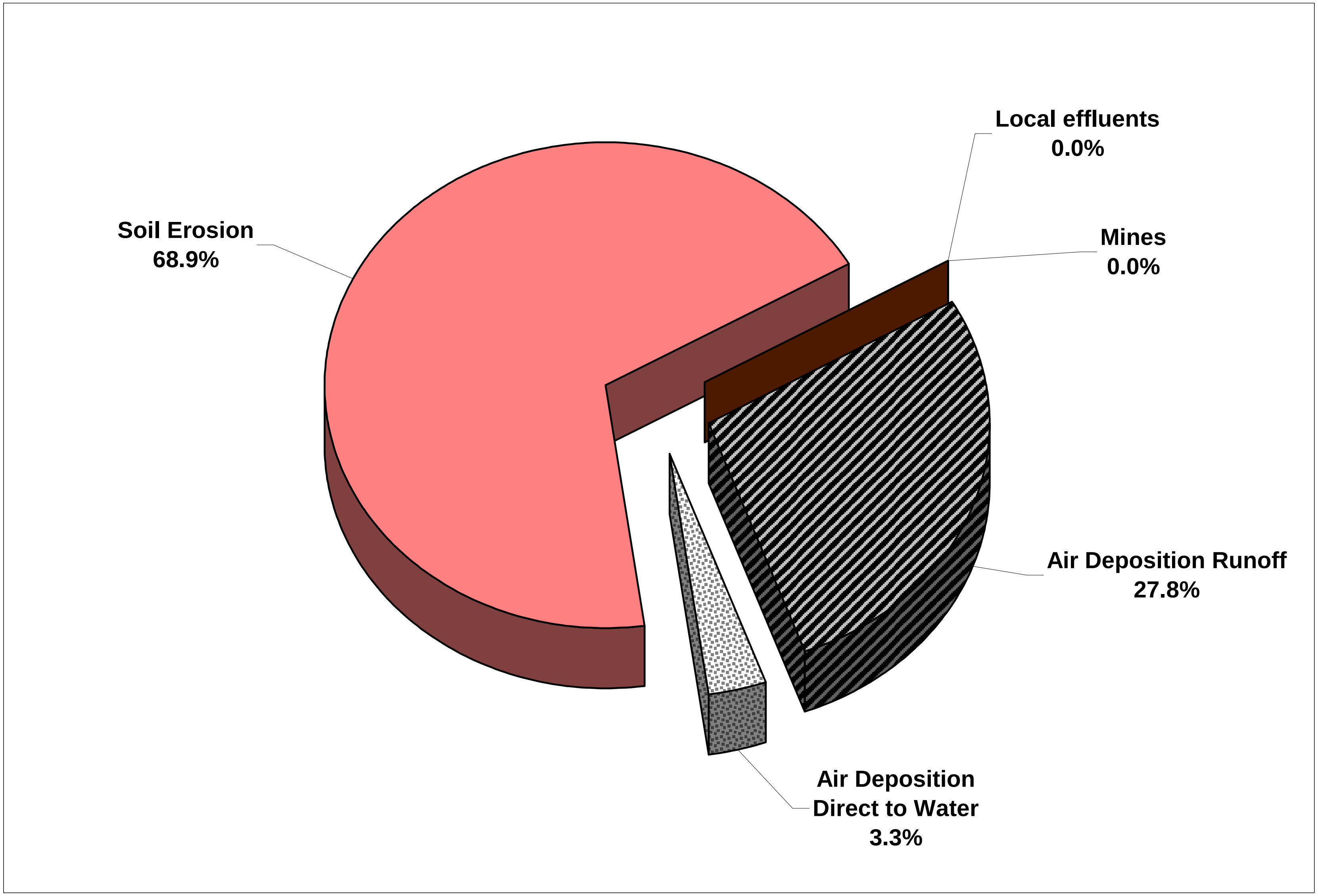


Figure 11. Relative contributions to the Row River (Dorena Reservoir) by source category.



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MERCURY MONITORING DATA TABLES

Willamette Basin TMDL: Appendix B: Mercury Monitoring Data

Water Quality Data										
SITE NAME -RIVER MILE	LASAR	Sample Date				MERCURY (ng/L)				
		Quarter 1	Quarter 2	Quarter 3	Quarter 4	Quarter 1		Quarter 2		Quar
MAINSTEM WILLAMETTE AND TRIBS		*Fall*	*Winter*	*Spring*	*Summer*	Total	Dissolved	Total	Dissolved	Total
Willamette River at SP&S Bridge (Portland) -RM 7	10332	10/01/2002	12/17/2002	03/20/2003	06/19/2003	0.787	0.28	3.58	1.54	1.45
Clackamas River at Riverside Park -RM 24.8	29045	10/02/2002	12/17/2002	03/20/2003	06/19/2003	0.380	0.34	3.08	1.65	1.00
Willamette River at Rogers Landing (Newberg) -RM 50.1	26339	10/01/2002	12/17/2002	03/20/2003	06/19/2003	0.607	0.28	7.12	1.99	1.41
Willamette River at Wheatland Ferry -RM 71.9	10344	10/01/2002	12/17/2002	03/20/2003	06/19/2003	0.568	0.35	6.08	1.94	1.19
Santiam River at Jefferson -RM109	10775	10/02/2002	12/17/2002	03/20/2003	06/19/2003	0.240	0.22	2.77	1.17	0.85
Willamette River at Willamette Park (Corvallis) -RM 132.9	29043	10/02/2002	12/17/2002	03/19/2003	06/19/2003	0.390	0.360	9.44	2.52	1.02
Willamette River at Greenway Bridge (Eugene) -RM 180	29044	10/02/2002	12/12/2002	03/19/2003	06/18/2003	0.547	0.380	1.30	0.935	1.79
MIDDLE FORK WILLAMETTE										
Middle Fork Willamette River at Jasper	10386	10/02/2002	12/12/2002	03/18/2003	06/17/2003	0.350	0.280	0.943	0.683	1.450
Middle Fork Willamette River above Hills Crk. Res. -RM 52.9	27986	10/03/2002	12/10/2002	03/18/2003	06/17/2003	< 0.2	< 0.2	1.45	0.790	0.62
COAST FORK WILLAMETTE AND TRIBS										
Row River below Dorena Reservoir (Trib to CFW RM 20.8)	10991	10/03/2002	12/11/2002	03/19/2003	06/18/2003	0.519	0.260	2.40	1.08	2.66
Dorena Reservoir on Row River (Trib to CFW RM 20.8)	13769	10/03/2002	12/11/2002	03/19/2003	06/18/2003	0.400	< 0.2	3.87	1.71	2.63
Row River above Dorena Reservoir (Trib to CFW RM 20.8)	10993	10/03/2002	12/11/2002	03/18/2003	06/17/2003	1.110	1.030	1.87	1.96	1.94
Brice Creek at RM 0.7 (Trib to Row RM 21.1, to CFW 20.8)	29048	10/03/2002	12/11/2002	03/18/2003	06/17/2003	0.800	0.827	2.24	2.38	1.33
Laying Creek at Mouth (Trib to Row RM 21.1, to CFW 20.8)	29049	10/03/2002	12/11/2002	03/18/2003	06/17/2003	0.867	0.715	1.80	1.58	1.52
Coast Fork Willamette below Cottage Grove Reservoir -RM 29.5	11278	10/07/2002	12/12/2002	03/19/2003	06/18/2003	0.966	0.450	4.48	2.43	4.37
Cottage Grove Reservoir on Coast Fork Willamette -RM 29.7	13750	10/07/2002	12/12/2002	03/19/2003	06/18/2003	1.730	0.450	6.80	2.64	4.00
Coast Fork Willamette above Cottage Grove Reservoir- RM 32.5	29614	10/07/2002	12/12/2002	03/19/2003	06/18/2003	3.990	2.220	6.72	4.07	4.31
Dennis Creek at Mouth (Trib to Sarroutte Crk, to CFW RM 39.9)	29047	10/07/2002	12/12/2002	03/19/2003	06/18/2003	6.130	2.650	9.94	6.88	12.90

Page 1

Water Quality Data											
SITE NAME -RIVER MILE				METHYL MERCURY (ng/L)							
	ter 3	Quarter 4		Quarter 1		Quarter 2		Quarter 3		Quarter 4	
MAINSTEM WILLAMETTE AND TRIBS	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved	Total	Dissolved
Willamette River at SP&S Bridge (Portland) -RM 7	0.748	0.64	0.25	0.0642	0.0727	0.0439	< 0.0278	0.0535	0.0299	0.707	0.0335
Clackamas River at Riverside Park -RM 24.8	0.674	0.61	0.28	0.0949	0.0591	0.0477	< 0.0278	0.0338	0.0295	0.61	0.0413
Willamette River at Rogers Landing (Newberg) -RM 50.1	0.653	0.6	0.32	0.0882	0.0741	0.1010	< 0.0278	0.0396	<0.0228	0.1240	0.0593
Willamette River at Wheatland Ferry -RM 71.9	0.586	0.91	0.41	0.0918	0.0799	0.1260	< 0.0278	0.0738	<0.0228	0.1110	0.0338
Santiam River at Jefferson -RM109	0.568	0.48	0.31	0.0678	0.0638	0.0576	< 0.0278	<0.0228	<0.0228	0.0457	<0.0228
Willamette River at Willamette Park (Corvallis) -RM 132.9	0.61	0.63	0.38	0.0864	0.0831	0.0707	0.0626	0.0428	<0.0228	0.078	0.064
Willamette River at Greenway Bridge (Eugene) -RM 180	1.100	0.75	0.200	0.0898	0.0718	0.0728	0.0316	0.0487	0.0313	0.0675	0.0541
MIDDLE FORK WILLAMETTE											
Middle Fork Willamette River at Jasper	1.040	0.490	0.220	0.0562	0.0638	0.0804	0.0604	0.0329	0.0331	0.0427	0.054
Middle Fork Willamette River above Hills Crk. Res. -RM 52.9	0.514	0.506	0.270	0.0443	0.0525	0.0335	< 0.0278	<0.0228	<0.0228	0.0284	0.0287
COAST FORK WILLAMETTE AND TRIBS											
Row River below Dorena Reservoir (Trib to CFW RM 20.8)	1.69	1.56	0.97	0.1360	0.0694	0.0902	0.0306	0.0502	0.0306	0.0383	0.0376
Dorena Reservoir on Row River (Trib to CFW RM 20.8)	1.53	0.72	0.56	0.0545	0.0715	0.0745	0.0413	0.0428	0.0305	0.0408	0.041
Row River above Dorena Reservoir (Trib to CFW RM 20.8)	1.50	0.70	0.61	0.0637	0.0754	0.0278	< 0.0278	0.0316	0.0342	0.0751	0.0556
Brice Creek at RM 0.7 (Trib to Row RM 21.1, to CFW 20.8)	0.953	0.70	0.61	0.0493	0.0595	< 0.0278	< 0.0278	0.0309	0.024	<0.0228	0.0241
Laying Creek at Mouth (Trib to Row RM 21.1, to CFW 20.8)	1.15	0.57	0.5	0.0440	0.0675	0.0946	< 0.0278	0.0423	0.0314	<0.0228	0.0619
Coast Fork Willamette below Cottage Grove Reservoir -RM 29.5	2.39	2.99	1.92	0.1740	0.1100	0.183	0.117	0.0587	0.0298	0.122	0.0818
Cottage Grove Reservoir on Coast Fork Willamette -RM 29.7	1.68	1.43	1.13	0.1600	0.0954	0.2210	0.0966	0.0679	0.028	0.1300	0.0623
Coast Fork Willamette above Cottage Grove Reservoir- RM 32.5	2.44	3.51	1.90	0.2570	0.1720	0.211	0.181	0.0683	0.053	0.252	0.182
Dennis Creek at Mouth (Trib to Sarroutte Crk, to CFW RM 39.9)	5.44	18.50	2.95	0.0742	0.0783	0.1010	0.0970	0.0830	0.0527	0.1130	0.1090

Fish Data

Site	LASAR Number	Sample Date	Species	Length(mm)	Weight(g)	Hg(mg/kg-wet)
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	515	2500	1.67
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	470	1750	2.23
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	450	1500	1.15
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	429	1250	1.94
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	420	1200	1.82
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	405	1000	1.85
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	395	1000	2.54
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	390	1100	1.13
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	336	525	1.06
Cottage Grove Reservoir	13750	8/14/2003	Large Mouth Bass	260	200	0.899
Dorena Reservoir	13769	7/14/2003	Small Mouth Bass	371	700	0.429
Dorena Reservoir	13769	7/15/2003	Large Mouth Bass	481	1800	0.785
Dorena Reservoir	13769	7/10/2003	Large Mouth Bass	475	1700	0.568
Dorena Reservoir	13769	7/12/2003	Large Mouth Bass	455	1500	0.616
Dorena Reservoir	13769	7/9/2003	Large Mouth Bass	451	1450	0.667
Dorena Reservoir	13769	7/13/2003	Large Mouth Bass	445	1450	0.767
Dorena Reservoir	13769	7/17/2003	Large Mouth Bass	444	1450	0.557
Dorena Reservoir	13769	7/11/2003	Large Mouth Bass	432	1150	0.719
Dorena Reservoir	13769	7/8/2003	Large Mouth Bass	429	1400	0.588
Dorena Reservoir	13769	7/16/2003	Large Mouth Bass	393	1000	0.657
Willamette River at Roger Landing	26339	7/15/2003	Small Mouth Bass	390	800	0.585
Willamette River at Roger Landing	26339	9/2/2003	Small Mouth Bass	326	450	0.314
Willamette River at Roger Landing	26339	7/14/2003	Small Mouth Bass	282	350	0.172
Willamette River at Roger Landing	26339	9/2/2003	Small Mouth Bass	270	325	0.239
Willamette River at Roger Landing	26339	7/15/2003	Small Mouth Bass	240	180	0.194
Willamette River at Roger Landing	26339	7/14/2003	Northern Pike Minnow	403	500	1.14
Willamette River at Roger Landing	26339	7/14/2003	Northern Pike Minnow	383	510	0.925
Willamette River at Roger Landing	26339	7/14/2003	Northern Pike Minnow	375	460	0.673
Willamette River at Roger Landing	26339	7/14/2003	Northern Pike Minnow	349	340	0.961
Willamette River at Roger Landing	26339	7/15/2003	Northern Pike Minnow	340	310	1.04
Willamette River at Roger Landing	26339	7/15/2003	Northern Pike Minnow	333	290	0.489
Willamette River at Roger Landing	26339	7/14/2003	Northern Pike Minnow	332	340	1.06
Willamette River at Roger Landing	26339	7/15/2003	Northern Pike Minnow	325	280	0.552
Willamette River at Roger Landing	26339	7/15/2003	Northern Pike Minnow	320	250	0.339
Willamette River at Roger Landing	26339	7/14/2003	Northern Pike Minnow	313	275	0.246
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	493	1250	0.391
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	479	1100	0.366
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	478	1050	0.270
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	466	975	0.368
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	465	950	0.263

Site	LASAR Number	Sample Date	Species	Length(mm)	Weight(g)	Hg(mg/kg-wet)
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	456	850	0.300
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	440	820	0.552
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	435	800	0.0896
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	421	750	0.166
Willamette River at Roger Landing	26339	7/14/2003	Largescale Sucker	402	690	0.185
Willamette River at Roger Landing	26339	7/14/2003	Large Mouth Bass	439	1250	0.688
Willamette River at Roger Landing	26339	7/15/2003	Large Mouth Bass	439	1250	0.665
Willamette River at Roger Landing	26339	9/2/2003	Large Mouth Bass	317	525	0.201
Willamette River at Roger Landing	26339	9/2/2003	Large Mouth Bass	281	350	0.176
Willamette River at Roger Landing	26339	7/15/2003	Large Mouth Bass	260	260	0.283
Willamette River at Roger Landing	26339	9/2/2003	Large Mouth Bass	256	260	0.135
Willamette River at SP&S RR Bridge	10332	7/16/2003	Small Mouth Bass	300	360	0.187
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	477	1000	0.111
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	465	1000	0.142
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	435	750	0.308
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	415	700	0.237
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	410	600	0.16
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	395	600	0.167
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	390	550	0.304
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	380	500	0.0857
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	340	375	0.0487
Willamette River at SP&S RR Bridge	10332	7/16/2003	Largescale Sucker	320	290	0.0246
Willamette River at Wheatland Ferry	10344	8/11/2003	Small Mouth Bass	373	700	0.485
Willamette River at Wheatland Ferry	10344	9/2/2003	Small Mouth Bass	293	370	0.2
Willamette River at Wheatland Ferry	10344	8/11/2003	Small Mouth Bass	240	200	0.102
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	530	1250	0.942
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	505	1200	0.799
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	490	1000	0.642
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	440	750	0.706
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	415	750	0.753
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	394	500	0.828
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	365	375	1.31
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	350	350	0.807
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	336	290	0.477
Willamette River at Wheatland Ferry	10344	8/11/2003	Northern Pike Minnow	335	260	0.993
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	505	1150	0.399
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	500	1000	0.419
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	480	1000	0.202
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	450	750	0.113
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	440	1000	0.237
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	430	650	0.171

Site	LASAR Number	Sample Date	Species	Length(mm)	Weight(g)	Hg(mg/kg-wet)
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	420	700	0.229
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	415	700	0.224
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	400	700	0.188
Willamette River at Wheatland Ferry	10344	8/11/2003	Largescale Sucker	400	600	0.105
Willamette River at Wheatland Ferry	10344	9/2/2003	Large Mouth Bass	452	1700	0.645
Willamette River at Wheatland Ferry	10344	8/11/2003	Large Mouth Bass	335	700	0.569
Willamette River at Wheatland Ferry	10344	8/11/2003	Large Mouth Bass	285	425	0.156
Willamette River at Wheatland Ferry	10344	9/2/2003	Large Mouth Bass	273	330	0.237
Willamette River at Wheatland Ferry	10344	8/11/2003	Large Mouth Bass	255	245	0.105
Willamette River at Wheatland Ferry	10344	8/11/2003	Large Mouth Bass	235	200	0.0954
Willamette River at Wheatland Ferry	10344	8/11/2003	Large Mouth Bass	206	150	0.0962
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Small Mouth Bass	444	1200	0.761
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Small Mouth Bass	364	680	0.288
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Small Mouth Bass	344	580	0.251
Willamette River at Willamette Park, Corvallis	29043	8/20/2003	Small Mouth Bass	253	260	0.0582
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Small Mouth Bass	240	220	0.122
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Small Mouth Bass	205	140	0.111
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	602	1800	0.963
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	429	730	0.379
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	390	550	0.534
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	375	390	0.919
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	373	500	0.393
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	370	460	0.232
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	349	360	0.477
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	345	340	0.811
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	340	300	0.893
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Northern Pike Minnow	330	310	0.355
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	544	1325	0.232
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	539	1525	0.192
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	522	1300	0.353
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	511	1325	0.234
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	480	975	0.0631
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	475	930	0.18
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	475	1000	0.0588
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	473	1050	0.347
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	430	820	0.091
Willamette River at Willamette Park, Corvallis	29043	8/13/2003	Largescale Sucker	424	740	0.0515
Willamette River at Willamette Park, Corvallis	29043	8/20/2003	Large Mouth Bass	302	450	0.134
Willamette River at Willamette Park, Corvallis	29043	8/20/2003	Large Mouth Bass	282	375	0.224
Willamette River at Willamette Park, Corvallis	29043	8/20/2003	Large Mouth Bass	255	290	0.254
Willamette River at Willamette Park, Corvallis	29043	8/20/2003	Large Mouth Bass	231	200	0.135

Site	LASAR Number	Sample Date	Species	Length(mm)	Weight(g)	Hg(mg/kg-wet)
Willamette River at Willamette Park, Portland	10827	8/12/2003	Small Mouth Bass	278	300	0.147
Willamette River at Willamette Park, Portland	10827	8/12/2003	Small Mouth Bass	275	300	0.206
Willamette River at Willamette Park, Portland	10827	7/17/2003	Small Mouth Bass	266	250	0.211
Willamette River at Willamette Park, Portland	10827	7/17/2003	Small Mouth Bass	260	230	0.162
Willamette River at Willamette Park, Portland	10827	7/17/2003	Small Mouth Bass	254	240	0.194
Willamette River at Willamette Park, Portland	10827	8/12/2003	Small Mouth Bass	254	200	0.24
Willamette River at Willamette Park, Portland	10827	7/17/2003	Small Mouth Bass	253	230	0.150
Willamette River at Willamette Park, Portland	10827	8/12/2003	Small Mouth Bass	243	200	0.211
Willamette River at Willamette Park, Portland	10827	8/12/2003	Small Mouth Bass	236	175	0.121
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Small Mouth Bass	290	375	0.142
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Small Mouth Bass	275	375	0.121
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	489	1000	1.62
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	445	910	1.03
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	440	860	1.02
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	416	610	0.825
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	349	390	0.527
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	340	320	0.483
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	337	340	0.393
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	321	275	0.417
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	319	320	0.288
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Northern Pike Minnow	305	250	0.249
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	517	1250	0.307
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	490	1000	0.155
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	484	1150	0.124
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	476	900	0.154
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	475	1100	0.135
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	475	1100	0.0356
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	465	1000	0.0725
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	465	975	0.053
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	456	1000	0.0533
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Largescale Sucker	436	1000	0.0743
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	425	1300	0.945
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	405	1200	1.59
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	270	300	0.229
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	245	225	0.229
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	235	200	0.23
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	235	175	0.31
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	225	200	0.199
Willamette River u/s of McKenzie ,d/s Beltline	12784	7/30/2003	Large Mouth Bass	215	125	0.156

Sediment Data

SITE NAME	LASAR	SAMPLE DATE	TOTAL MERCURY (mg/Kg) dry	TOTAL METHYL MERCURY (ng/g) dry	TOTAL SOLIDS (%)	MASS (%) DRY WEIGHT	TOTAL ORGANIC CARBON (mg/Kg) dry	SEDIMENT pH (SU) Initial	Final
MAINSTEM WILLAMETTE AND TRIBS									
Willamette River at SP&S Bridge (Portland)	10332	08/26/2002	0.168	0.545	40.5	41.8	21000	7.3	7.3
Clackamas River at Riverside Park	29045	09/11/2002	< 0.02	0.367	65.2	51.1	3800	6.6	6.6
Willamette River at Rogers Landing (Newberg)	26339	08/27/2002	0.042	0.670	49.3	50.9	11000	7.0	6.9
Willamette River at Wheatland Ferry	10344	09/11/2002	0.561	0.105	47.7	66.4	5400	6.7	6.4
Santiam River at Jefferson	10775	09/06/2002	< 0.02	0.580	45.5	50.9	6800	7.1	7.0
Willamette River at Willamette Park (Corvallis)	29043	09/04/2002	< 0.02	0.259	58.3	58.2	3700	7.2	7.0
Willamette River at Greenway Bridge (Eugene)	29044	09/06/2002	< 0.02	0.115	74.4	72.9	2500	6.4	6.4
MIDDLE FORK WILLAMETTE									
Middle Fork Willamette River u/s Springfield DW Wellfield	29232	08/15/2002	< 0.02	0.0859	67.4	66.7	2100	7.2	6.9
Middle Fork Willamette River above Hills Crk. Res.	27986	08/14/2002	< 0.02	0.0668	77.2	81.6	490	7.2	7.4
COAST FORK WILLAMETTE AND TRIBS									
Row River below Dorena Reservoir (Trib to CFW RM 20.8)	10991	08/20/2002	0.0262	0.190	73.8	77.8	2900	7.2	
Dorena Reservoir on Row River (Trib to CFW RM 20.8)	13769	08/27/2002	0.17	1.03	27.1	28.1	31000	7.1	7.1
Row River above Dorena Reservoir (Trib to CFW RM 20.8)	10993	08/20/2002	0.385	< 0.0576	74.7	74.7	870	7.3	7.3
Brice Creek at RM 0.7 (Trib to Row RM 21.1, to CFW 20.8)	29048	08/20/2002	0.0388	0.133	74.1	74.7	1100	6.8	7.0
Layng Creek at Mouth (Trib to Row RM 21.1, to CFW 20.8)	29049	08/15/2002	0.036	0.234	74.3	76.5	2700	7.0	7.1
Coast Fork Willamette below Cottage Grove Reservoir	11278	09/03/2002	0.173	< 0.0576	74.5	75.5	1900	7.0	6.8
Cottage Grove Reservoir on Coast Fork Willamette	13750	08/27/2002	0.887	1.16	35.0	36.0	19000	7.4	7.3
Coast Fork Willamette above Cottage Grove Reservoir	29614	09/03/2002	0.451	1.22	67.2	64.7	3200	7.0	6.7
Dennis Creek at Mouth (Trib to Sarroutte Crk, to CFW RM 39.9)	29047	08/15/2002	0.902	1.07	65.7	75.5	6400	7.4	7.8

Sediment Data

SITE NAME	REDOX (mV)	WET SOIL MASS (g)	ARTI-FACTS (g)	SAND Total=nominal 100% (%)	SILT & CLAY	SAND MEDIUM Total=nominal 100% (%)	SAND VERY FINE (%)
MAINSTEM WILLAMETTE AND TRIBS							
Willamette River at SP&S Bridge (Portland)	-110	19.07	< 0.1	6.9	93.1	5.6	81.6
Clackamas River at Riverside Park	112	48.98	0.2737	84.5	15.5	60.5	3.1
Willamette River at Rogers Landing (Newberg)	-47	20.84	< 0.1	63.7	36.3	26.3	24.7
Willamette River at Wheatland Ferry	147	50.44	0.0159	91.9	8.1	32.5	15.9
Santiam River at Jefferson	-20	48.42	0.0166	83.7	16.3	13.6	39.7
Willamette River at Willamette Park (Corvallis)	178	48.08	< 0.1	90.0	10.0	27.1	16.6
Willamette River at Greenway Bridge (Eugene)	108	47.72	< 0.1	95.9	4.1	36.1	3.6
MIDDLE FORK WILLAMETTE							
Middle Fork Willamette River u/s Springfield DW Wellfield	118	47.06	< 0.1	97.8	2.2	69	1.1
Middle Fork Willamette River above Hills Crk. Res.	219	48.04	< 0.1	97.3	2.7	10.7	0.4
COAST FORK WILLAMETTE AND TRIBS							
Row River below Dorena Reservoir (Trib to CFW RM 20.8)	262	48.98	0.4	90.6	9.4	2.9	0.7
Dorena Reservoir on Row River (Trib to CFW RM 20.8)	-64	26.41	< 0.1	3.1	96.9	17.0	42.7
Row River above Dorena Reservoir (Trib to CFW RM 20.8)	297	49.21	0.31	99.0	1.0	18.6	0.5
Brice Creek at RM 0.7 (Trib to Row RM 21.1, to CFW 20.8)	179	49.66	0.1822	98.6	1.4	6.3	0.2
Layng Creek at Mouth (Trib to Row RM 21.1, to CFW 20.8)	289	46.94	0.2612	95.8	4.2	5.7	1.3
Coast Fork Willamette below Cottage Grove Reservoir	30	49.60	< 0.1	94.9	5.1	9.9	1.1
Cottage Grove Reservoir on Coast Fork Willamette	-68	27.42	< 0.1	1.3	98.7	13.3	40.9
Coast Fork Willamette above Cottage Grove Reservoir	83	49.48	0.1260	82.9	17.1	55.7	1.3
Dennis Creek at Mouth (Trib to Sarroutte Crk, to CFW RM 39.9)	312	48.22	< 0.1	91.6	8.4	20.7	3.4