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Assessing Effects of PCB Exposure on American Mink (*Mustela vison*) Abundance in Portland Harbor

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ABSTRACT

This article presents an integrated analysis using a Monte Carlo exposure model, dose–response effects model and habitat, and population dynamics models, all of which allow us to quantitatively estimate the effects of polychlorinated biphenyl (PCB) exposure on American mink (*Mustela vison*) abundance at the Portland Harbor Superfund Site (Site), and the associated uncertainties. The Site extends from river mile 1.9 of the Lower Willamette River, near its confluence with the Columbia River, to river mile 11.8, just downstream of downtown Portland, Oregon. The potential effects of PCBs on the American mink population were evaluated in the Baseline Ecological Risk Assessment (BERA) due to the historical presence of mink in the area and because mink are known to be highly sensitive to the effects of PCBs. Hazard quotients (HQs) calculated in the BERA indicated that PCB concentrations measured in Portland Harbor fish were above levels known to cause reproductive effects in mink. Further analysis was needed to evaluate the potential magnitude of effects on the Site mink population. The integrated analysis presented herein demonstrates that if an effect of PCB exposure is a less than 30% reduction in kit production, then PCB remediation is not expected to have any effect on mink abundance. This is a Site-specific conclusion that depends on the quality, abundance, and distribution of mink habitat in Portland Harbor. The PCB dose associated with a 30% reduction in kit production was calculated as 101 μg/kg bw/d (90% CI = 69–146 μg/kg bw/d). The mink PCB dose estimates from the Portland Harbor BERA indicate that if mink are present, their baseline exposure levels probably exceed 101 μg/kg bw/d. Therefore, some level of reduction in PCB exposure could be beneficial to the species if the study area provides sufficient habitat to support a mink population. This analysis demonstrates that risk analysis for population-level assessment endpoints benefits from analyses beyond those that calculate exposure and predict organism-level effects. Evaluation of population-level impacts provides risk managers with a richer perspective within which to evaluate the environmental protectiveness and cost-effectiveness of feasibility study alternatives across a range of potential remediation goals. *Integr Environ Assess Manag* 2014;10:60–68. © 2013 SETAC

Keywords: *Mustela vison* PCBs Population-level ecological risk assessment Portland Harbor Probabilistic risk assessment Uncertainty analysis

INTRODUCTION

The Portland Harbor Superfund Site extends from river mile 1.9 of the Lower Willamette River, near its confluence with the Columbia River, to river mile 11.8, just downstream from downtown Portland, OR. The potential effects of PCBs on the American mink population were evaluated in a Baseline Ecological Risk Assessment (BERA) due to the historical presence of mink in the area and their known sensitivity to the effects of PCBs (Windward 2011).

In the BERA, risks were estimated by comparing 95% upper confidence limit (UCL) dietary exposure estimates to a mink reproduction lowest observed adverse effect level (LOAEL) to calculate hazard quotients (HQs). Calculated HQs indicated that mink exposed to PCB concentrations measured in Portland Harbor fish might experience reduced reproductive success. What cannot be discerned from the HQs, though, is the degree to which the predicted PCB exposures exceeding the LOAEL might affect mink population attributes, such as abundance in Portland Harbor.

Further analysis of potential population effects beyond those presented in the BERA were conducted, because mink PCB risk estimates were among the most important receptor-contaminant of potential ecological concern (COPC) pairs for defining remediation goals (RGs) and areas of concern (AOCs) in the Feasibility Study (FS). This article presents analyses of how PCB exposure would affect mink abundance. It includes quantitative uncertainty analyses. This particular assessment is hypothetical in the sense that it does not attempt to account for exogenous compensatory mechanisms such as in-migration, or depensatory mechanisms such as increased vulnerability to predation due to reduced growth.

We examined 4 important determinants of PCB effects on mink abundance:

1. Exposure
   A probabilistic exposure model was developed to predict the range and associated probabilities of doses of PCBs in the diet of mink in the site, given the variability and uncertainty associated with the parameters used to model exposure.
2. Dose–response
   A probabilistic dose–response model was developed to predict the degree of reproductive impairment in individual

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mink exposed to PCBs in the site, and to provide confidence bounds on these predictions.

3. Habitat use
   A habitat model was developed to characterize the opportunities for mink to occupy the site.
4. Population dynamics
   A population dynamics model characterizing how modeled individual female mink interact with one another and the available habitat was developed to estimate the carrying capacity of the site (i.e., mink abundance in the absence of PCB exposure).

For the rest of this document, the habitat model and population dynamics model are grouped together as the 2 components of a spatially explicit population model.

METHODS

Probabilistic exposure model

A probabilistic analysis of mink PCB exposure was conducted by adapting a model that was originally developed to estimate mink exposure to PCBs in the Clinch River, TN (Moore et al. 1999). In the Portland Harbor application of the model, direct air, and water exposure pathways were excluded because their contribution to total exposure was judged to be too small to significantly affect results. Also, prey fractions were defined using a 2-tier structure wherein prey were first divided into 3 groups (fish, crayfish, and terrestrial), then prey fractions were defined within the fish group. The purpose of the 2-tiered structure was to make it easier to use the different types of data sources available for the 3 groups. The model then took the form of Equation 1:

$$IR = MR \times \left[f_{fish} \times \sum_{i=1}^{n} \left(\frac{C_i \times P_i}{AE_{fish} \times GE_{fish}} \right) + f_{cf} \times \frac{C_{cf}}{AE_{cf} \times GE_{cf}} + f_{terr} \times \frac{C_{terr}}{AE_{terr} \times GE_{terr}} \right], \quad (1)$$

where IR = PCB ingestion rate (μg/kg bw/d); MR = metabolic rate of wild female mink (kcal/kg bw/d); f_{fish} = fraction of the mink's diet comprised of fish; C_i = average PCB concentration in fish species i (μg/kg); P_i = proportion of fish species i in the fish fraction of the mink's diet (unitless); AE_{fish} = food assimilation efficiency for fish species i (unitless); GE_{fish} = gross energy of fish species i (kcal/g); i = fish species index variable; n = number of fish species in the mink diet; f_{cf} = fraction of the mink's diet comprised of crayfish; C_{cf} = estimated average PCB concentration in crayfish (μg/kg); AE_{cf} = food assimilation efficiency for crayfish (unitless); GE_{cf} = gross energy of crayfish (kcal/g); f_{terr} = fraction of the mink's diet comprised of terrestrial species; C_{terr} = average PCB concentration in terrestrial species (μg/kg); AE_{terr} = food assimilation efficiency for terrestrial species (unitless); and GE_{terr} = gross energy of terrestrial species (kcal/g).

We were interested in predicting ingestion rate (IR) as a function of fish and crayfish tissue concentrations (the C_i terms), so the C_i terms were the inputs. The other parameters in the model were treated as coefficients (i.e., variables that influenced the relationship between the inputs and output). Site-specific data were used for C_i, and C_{cf}. Conservative point estimates were used for each 1-mile exposure area (Supplemental Table 1). C_i and C_f were especially conservative because the composite samples used to determine them included some fish larger than might be consumed by mink. These concentrations were established in the BERA, and the influence of uncertainty in these values on risk estimates was not of interest for this analysis.

Site-specific data on terrestrial prey concentrations were not available so were estimated by applying PCB bioaccumulation factors for small mammals from the Kalamazoo River Superfund site (Blankenship et al. 2005) to PCB soil data from the Willamette River Basin (USEPA 2007). The resulting modeled results suggest that PCB concentrations in terrestrial prey are orders of magnitude lower than measured PCB concentrations in any of the aquatic prey from Portland Harbor. The terrestrial exposure term is important in estimating IR because the fraction f_{terr} of the mink's diet that is comprised of terrestrial prey is effectively clean.

The fractions of different fish in the mink's diet were assumed to be directly proportional to prey availability. Thus, P_i values were based on site-specific fish abundance survey data and were assumed to be the same throughout Portland Harbor (Supplemental Table 2). All other terms in the exposure model were initially parameterized using distributions presented in Moore et al. (1999).

A Spearman rank correlation coefficient sensitivity analysis was used to identify which of the coefficient uncertainties had an important influence on predicted mink PCB exposure levels. The coefficients MR, f_{fish}, f_{terr}, GE_{fish}, and P_{carp} had correlation coefficients of ($\pm$) 0.2 or greater, whereas the other coefficients had lower correlations with IR. The initial distributions for these 5 important model coefficients were further investigated and refined. The final model coefficient distributions used in the probabilistic exposure analysis are presented in Supplemental Table 2.

Distributions of the fractions of fish, crayfish, and terrestrial prey (f_{fish}, f_{cf}, and f_{terr}) were estimated from literature-reported values (Hamilton 1940; Sealander 1943; Korschgen 1958; Alexander 1977; Burgess and Bider 1980), and a correlation matrix was developed to describe the interdependencies (Supplemental Table 2). Monte Carlo samples were drawn from the distributions considering the correlation matrix. Resulting prey fractions were summed, and the sampled values were normalized to the total. Monte Carlo iterations with normalized f_{fish}, f_{cf}, or f_{terr} values that fell outside the originally defined distribution for the coefficient were filtered from the IR probability distributions.

Dose–response model

A dose–response model, with confidence intervals, was developed to estimate the reduction in production of mink kits due to maternal dietary exposure to total PCBs. An existing model and data set (Fuchsman et al. 2007) was adapted for use in the current analysis. Data from studies that reported elevated PCB concentrations in controls (Platonow and Karstad 1973; Jensen et al. 1977) were excluded. Three other studies (Aulerich and Ringer 1977; Brunström et al. 2001; Kakela et al. 2002) were also excluded based on lesser differences in how controls differed from PCB-dosed mink. A log-logistic model (Equation 2) was fit to the data.

$$y = P_o + \frac{1 - P_o}{1 + \exp(-(a + b \times \ln(x)))} \quad (2)$$

where x = PCB dose (μg/kg bw/d); y = surviving kits per mated female (%control); P_o = upper asymptote for

Table 1. Study area habitats classified as acceptable for mink

Land cover type	Definition
Suitable habitat	
Wooded wetland	NWI vegetated wetland area and >25% tree canopy in photo
Forested	Upland >25% tree canopy and <30% constructed materials
Herbaceous wetland	NWI vegetated wetland area and >20% vegetation cover in photo or clear wetland characteristics in an aerial photo within NWI area
Woody shore	Riverbank with >25% tree canopy within 50 m of the shoreline
Grassy and/or herbaceous shore	Riverbank with >30% cover of emergent or upland nonwoody vegetation and <20% cover of woody vegetation within 50 m of the shoreline
Beach and/or unconsolidated shore	Unvegetated mud, sand, gravel, or rock riverbank within 50 m of the shoreline, connecting the river with areas of vegetated habitat
Urban scrub/shrub/grass	>20% woody shrub, bramble, or tall herbaceous vegetation, >25% grass or short herbaceous vegetation, and <25% tree cover; surrounded by developed property and/or landscaped or used for parking
Urban wooded	Tree canopy >25% of cover and understory >25% vegetated; surrounded by developed property/used for parking and/or landscaped rather than natural vegetation
Pasture/crops	Crops or fields in agricultural area
Urban rough grass/ herbaceous	>20% cover of rough grass and/or short herbaceous vegetation and <20% taller vegetation in developed area
Nonhabitat	
Lawn	Maintained short grass turf with <25% taller vegetation
Developed	>30% paved, built, or other constructed materials
In-river (<13 feet)	Inside the river study area polygon bounded by the 13 foot NAVD88 contour
Artificial pond	Manmade pond with no aquatic vegetation

surviving kits per mated female (%control); and a and b = regression coefficients.

P_o was set equal to 100% of control as per Fuchsman et al. (2007), which means that we assumed that kit survival rates greater than control were not due to PCB exposure. The model's goodness of fit was evaluated using r^2 and residual standard error (RSE). The fitted values for the regression coefficients were identical to those reported by Fuchsman et al. (2007), $a = 6.795$ and $b = 1.327$. Goodness of fit ($r^2 = 0.54$, RSE = 32.0; $n = 46$) was only slightly different than that reported by Fuchsman et al. (2007) ($r^2 = 0.46$, RSE = 32.6; $n = 59$), indicating the Fuchsman et al. (2007) model was insensitive to the removal of excluded studies. Confidence intervals around the model prediction were developed by bootstrapping (Figure 1). Bootstrapping involved randomly sampling, with replacement, $n = 46$ dose–response pairs from

Table 2. Mink spatially explicit population model parameter values

	Scenario		
Model parameter	**Worst case**	**Mid-range[a]**	**Best case**
Average female kit production (unitless)	1.5[b]	2.5	3.5[c]
Probability of mortality (%)	70[c]	50	30[c]
Dispersal distance (km)	10[b]	105	200[c]
Habitat diameter (km)[d]	6[e]	6[e]	6[e]
Habitat requirement (ha)	31[c]	19.5	8[c]

[a]The mid-range scenario is the average of the worst-case and best-case scenarios.
[b]Bonesi et al. (2007). Females only, which was assumed to be 50% of total kit production.
[c]MacDonald and Rushton (2003).
[d]The habitat diameter is set at the maximum observed American mink habitat diameter (MacDonald and Strachan 1999) for all scenarios because the size of a mink home range is assumed to be a direct result of the quality of available habitat, not a characteristic intrinsic to American mink that requires estimation independent of the habitat requirement.
[e]MacDonald and Strachan (1999).

the screened Fuchsman data set, fitting the log-logistic model, and estimating every fifth percentile response from the fitted model for 1392 bootstrap iterations.

The dose–response equation for the mean percent reduction in kit production was combined with the probabilistic exposure model. At this stage, then, the model predicted mean percent reduction in kit production (with uncertainty bounds) from the estimated total PCB dose from prey items consumed by mink.

Spatially explicit population model

Next, a spatially explicit mink population model was developed to explore the difference in the abundance of mink in the Portland Harbor study area with and without PCB exposure over a 40-year time period. This model was adapted from a model described by MacDonald and Rushton (2003). As described above, it consists of 2 components: a habitat model and a population dynamics model. The habitat model was developed from empirical data on the Portland Harbor shoreline landscape. The population dynamics model simulates individual (mink) life histories and dispersal within the Portland Harbor landscape.

Habitat model

Portland Harbor habitat was classified as either suitable only for mink dispersal or suitable for mink dispersal, foraging, and breeding. MacDonald and Rushton (2003) used a logistic regression analysis of data from the River Thames, England (MacDonald et al. 1998) to classify suitable mink foraging and breeding habitat. They found that deciduous woodland, rough grassland, and marsh within 200 meters of the water were suitable for foraging and breeding. This is consistent with the US Fish and Wildlife Service's mink habitat suitability index model, which classifies suitable habitat according to tree and shrub cover within both 100 meters and 3 meters of water's edge (Allen 1986).

Portland Harbor land cover was classified into 10 types using ortho-rectified aerial photographs in ArcGIS 9.03 (Table 1). Coarse resolution work was done with a 10 ft-resolution orthophoto (Metro Data Resource Center 2006), and more detailed editing with 1 m-resolution orthophotos (USDA FSA 2005). Current conditions were confirmed by viewing 1 ft-resolution Google satellite maps (Google Earth 2009), and the map layer edited where appropriate using permanent structures such as roads to reconcile the locations. The site was divided into a grid of 202 cells and the amount of suitable habitat within each cell was determined from the GIS. Cells measured 300 meters along the riverbank and extended 200 meters upland from the bank (Figure 3).

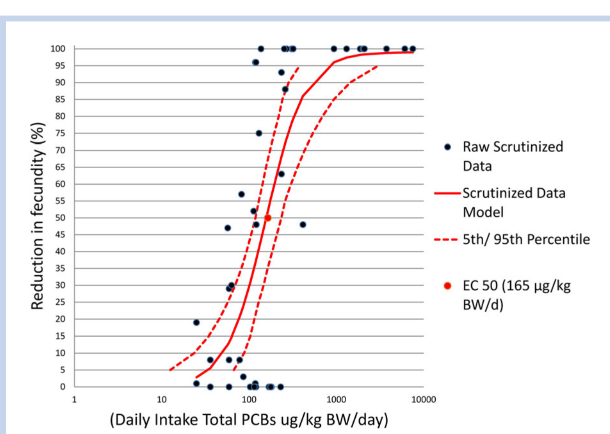

Figure 1. Mink-PCBs percent reduction in surviving offspring as a function of dietary dose (with 95% confidence limits).

Population dynamics model

The population dynamics model was coupled with the habitat model to simulate dispersal, reproduction, and mortality of individual female mink on the site over a simulated 40-year time span with and without PCB exposure. Male mink have larger overlapping home ranges during the breeding season (Allen 1986) and mate-finding was assumed to not limit reproduction. The model was written using the agent-based modeling program Repast-Symphony. Agent-based modeling tracks the movement and fate of individuals (in this case mink) and interaction among individuals based on decision criteria defined by the modeler. The model is stage structured, modeling juvenile and adult life histories separately. The model progresses in a step-wise manner. Each year, yearling females become adults and explore the landscape to form a territory. If sufficient unoccupied habitat is acquired, they reproduce, and their survival is modeled. The survival of each juvenile is then modeled independently. At the end of each year, the locations and number of juvenile and adult mink are recorded. A schematic of the model is presented in Figure 2. Each component is described below.

Initial conditions

Each model run was initiated by the introduction of 11 adult female mink to pre-assigned cells, distributed throughout the site. The same cells were populated at the beginning of each model run to reduce variability within the model.

Habitat acquisition

Each week in the model year (i.e., 52 times per year), dispersing individual mink moved to an adjacent cell and acquired the available habitat until a sufficient amount of habitat was acquired to establish a territory. In practice, mink were able to search all available contiguous habitat within 11 or 12 weeks. The amount of habitat required to establish a territory varied for different scenarios, based on the range reported in MacDonald and Rushton (2003). Because all mink described in the model are female and mink display intrasexual exclusivity and intersexual overlap, the territories within the model were nonoverlapping. Once territories were acquired, adult mink were assumed to hold them until they died, whereupon the cell became available to new individuals.

The movement pattern of the mink was determined by the connectivity between cells defined within the GIS landscape (Figure 3). The home range was required to be contiguous based on this system of connectivity. The maximum length along the river corridor within which a home range could be established was 6 km, the largest home range diameter reported from field observations (MacDonald and Strachan 1999). If the habitat acquired within 1 year was insufficient to establish a territory, it was assumed that the mink could not be supported by the available resources and therefore died (MacDonald and Rushton 2003). If sufficient habitat was acquired, a territory was established and the mink reproduced.

Reproduction

Reproduction occurred in surviving adult mink at the end of each year. The number of kits produced by each adult mink was

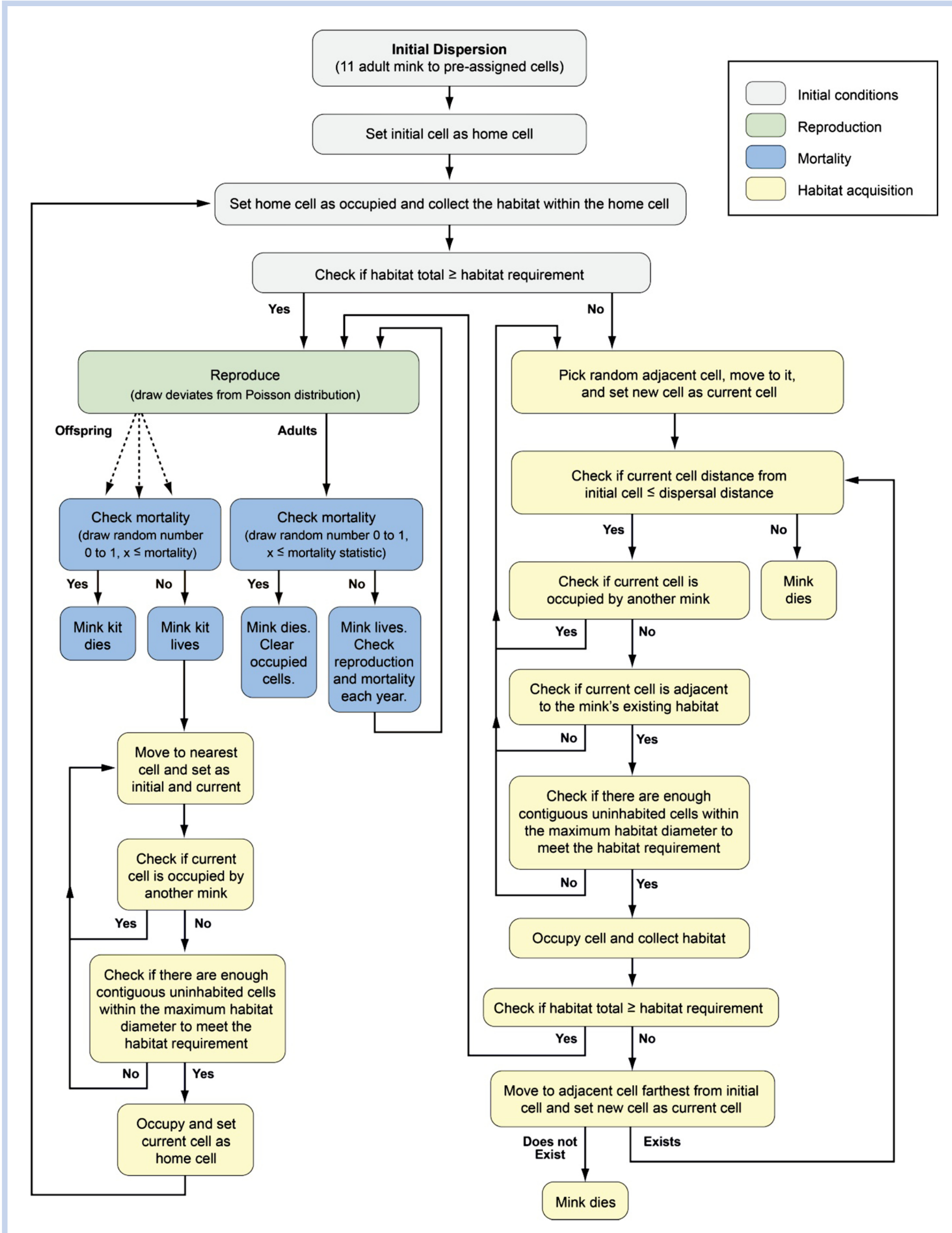

Figure 2. Schematic diagram of spatially explicit mink population model.

determined by drawing a random integer from a Poisson distribution with the mean based on the average female kit production value. The average female kit production value was determined from brood sizes reported in the literature, assuming females made up half of each brood (Gerell 1971; as cited in Bonesi et al. 2007). The specific mean values varied for different scenarios, as described below.

Mortality

Mortality not resulting from habitat constraints occurred in juvenile mink following birth and in adult mink following reproduction. Mortality in individual mink was determined by generating a random number between 0 and 1. If the number was less than or equal to the probability of mortality, the mink died and any cells occupied by this mink were cleared and available for occupation by other mink. No distinction was made in the model between the probability of mortality for adult or for juvenile mink. The average mortality value was varied for different scenarios, as described below, based on the range of values reported by MacDonald and Rushton (2003).

Following the mortality check, surviving juvenile mink dispersed throughout the GIS landscape. The distance that they were able to disperse from their birthplace varied for different scenarios, as described below, based on dispersal distances reported in MacDonald and Rushton (2003) and Bonesi et al. (2007). In practice, dispersal distance had minimal effect on the model, because the site is small relative to mink's dispersal ability. At the end of 1 year, juvenile mink became adults and were capable of reproducing.

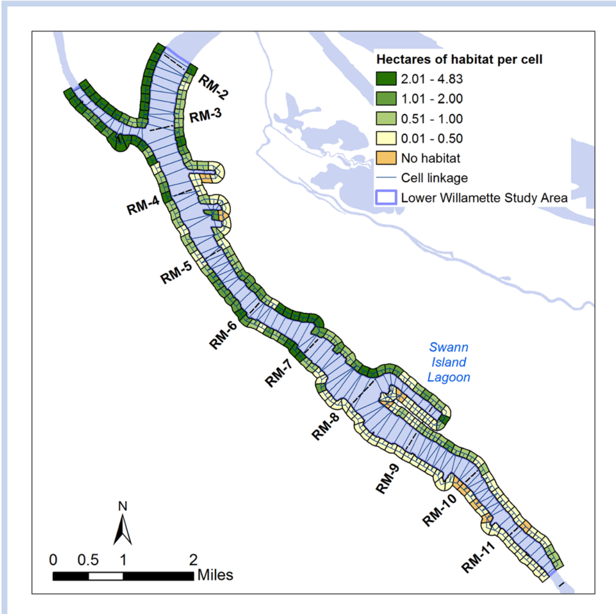

Figure 3. Site mink habitat density and connectivity network.

To explore uncertainty due to variability in the parameter values, the population model was run 100 times each for 3 scenarios. Evaluating scenarios, rather than using a full probabilistic analysis, was consistent with the approach used by MacDonald and Rushton (2003) and minimized programming effort. The scenarios represented best, worst, and mid-range parameter values selected from the range of literature values as to their likelihood to support a mink population within the site (Table 2). Results were recorded as the average number of female mink in the study area over all model runs. The cells occupied at the end of each year by adult mink were also tracked to determine spatial patterns within the population.

PCB effects were incorporated into the model by adjusting average female kit production values. Average female kit production was multiplied by 1, minus the percent reduction in kit production output from the dose–response model for a given PCB dose, and rounded to the nearest integer. Reductions in kit production corresponded to the mean, upper, and lower 95% confidence bounds of the Site-wide PCB exposure estimates. Additionally, the percent reduction in kit production at which the study area population began to decrease was estimated by incrementally increasing percent reductions in kit production. The PCB concentration likely to cause this magnitude of effect was then interpolated from the dose–response model.

RESULTS AND DISCUSSION

Probabilistic exposure analysis

The probabilistic exposure analysis demonstrates that a broad range of mink PCB exposures is plausible given the concentrations of PCBs in study area fish and the variability and uncertainty associated with the exposure model parameters. Estimated mean dietary doses ranged from 217 to 417 μg total PCBs/kg bw/d across the different exposure areas. The study area wide, mean dose (and 95% confidence limits) were 260 (71–550) μg total PCBs/kg bw/d. Use of conservative point estimates for prey PCB concentrations likely resulted in somewhat elevated estimates of exposure.

The parameter values used in the exposure model are mostly from the general literature on mink and so encompass a broader range than may be applicable to mink that occur in and around the Lower Willamette River. For example, the fraction of mammals versus fish in the diet has a large influence on the predicted dose. Based on studies from fish-bearing water bodies in North America, the fraction of fish in mink's diet ranges from 8% for a stream in Quebec to 85% for a river in Michigan (USEPA 1993). It is likely that a smaller range is reasonable for Lower Willamette River mink; however, it is uncertain which data from the general literature best apply to the study area.

Dose–response analysis

The dose–response model incorporates effects data reported in a large number of studies and indicates the degree to which kit production is likely to be reduced for a given PCB dose, as well as uncertainty bounds. This provides critical information necessary to quantify the risks to mink. The range of percent reduction in kit production considering uncertainty in both the exposure and effects models was evaluated by plotting probabilistic exposure distributions on the dose–response model with 95% CIs. Figure 4 shows the exposure uncertainty distributions for the areas with lowest and highest doses, plotted along with the dose–response curve. Figure 4 is read as follows:

- Read the response of interest (i.e., cumulative probability of exposure) off the right vertical axis
- Project left horizontally to the exposure distribution for the reach of interest
- From the intersection with the exposure distribution, project down to the *x*-axis to find the associated dose
- Project vertically to the mean, lower confidence limit, or upper confidence limit of the dose–response curve
- Project horizontally to the left vertical axis to determine the percent reduction in kit production

The combined exposure and dose–response predictions indicate a broad range of uncertainty in the expected level of reduced kit production in study area mink (Figure 4). The kit production predictions for the exposure areas with the highest and lowest exposures illustrate the range of predicted effects for all exposure areas. The 5th to 95th percentiles of the exposure for the reach with the lowest exposures correspond to effects from less than 5% to greater than 95% reduction in kit production in mink at the 95% confidence limits of the dose–response curve. The 5th to 95th percentiles of exposure for the reach with the highest exposures correspond to effects encompassing from 35% to 100% reduction in kit production in mink at the 95% confidence limits of the dose–response curve. Although this indicates a substantial reduction in kit production, this information is insufficient to determine the potential effect on mink abundance. To understand the effect on mink abundance, it is necessary to consider the interrelationships between Portland Harbor habitat, mink behavior, and kit production.

Spatially explicit population analysis

The spatially explicit population model provides the link between reduction in kit production and mink abundance. Population modeling results indicate that the study area might or might not offer sufficient suitable mink habitat to support any mink, even in the absence of any PCB effect on kit

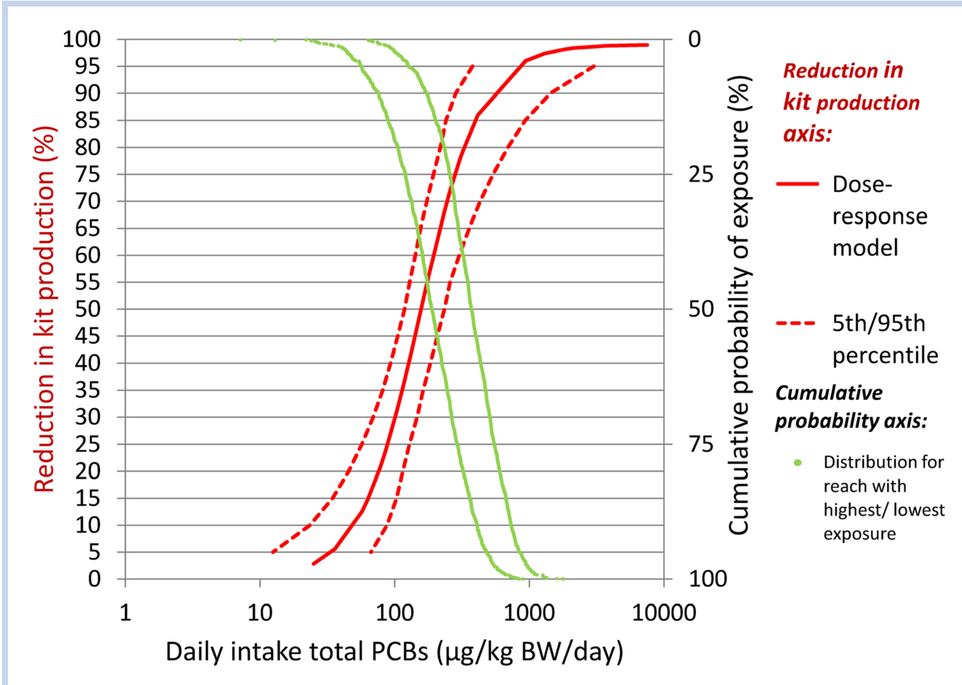

Figure 4. Mink total PCB dietary dose cumulative distribution function for reaches with highest and lowest exposure concentrations plotted with the mink total PCB dose–response model.

production. These projections are consistent with a recent United States Fish and Wildlife Service (USFWS) survey of the lower 15 miles of the Willamette River (the study area bookended by a 3-mile reach through downtown Portland, OR at the upstream end and a 2-mile reach through agricultural, light industrial and wetland preserve lands at the downstream end). The USFWS survey found that the lower 15 mile reach of the Willamette River is unlikely to support a self-sustaining mink population due to habitat constraints, though it might support some individuals (USFWS 2011).

Population dynamics over the course of the 40-year model runs corresponded closely with habitat density on the landscape such that areas with high habitat density (e.g., Sauvie Island at RM 2 west) were consistently occupied, whereas, occupation of areas with lower habitat density (e.g., RM 9 west) fluctuated. When the model was run using mid-range and worst-case parameter sets, increased mortality and larger habitat requirements resulted in only areas with high habitat density supporting mink. PCB effects magnified these spatial patterns. Qualitatively, this indicates that the mink population is less vulnerable to PCB effects when habitat quality, abundance and connectivity are improved and other non-PCB stressors affecting mink survival are decreased.

The number of mink in the study area fluctuated over the first 10 years (the model's initial transient period) then stabilized. Therefore, scenarios were compared as the average number of female mink per year over all runs from year 11 to 40. Given the worst-case parameter assumptions, the study area was not able to support any mink (even in the absence of PCBs). Given the best-case parameter assumptions, in the absence of PCBs, the study area was predicted to support from 16 to 35 female mink with an average population of 23. Given the mid-range parameter assumptions, in the absence of PCBs, the study area was predicted to support from 4 to 13 female mink with an average population of 7.7.

Because the best-case parameter assumptions resulted in unrealistically high population estimates for the study area (e.g., as per the 2011 USFWS survey findings), and worst-case parameter assumptions always resulted in no mink, mid-range parameter assumptions were used to estimate the effects of PCBs on the mink population. The projected effect of PCBs on abundance, as determined by incrementally increasing percent reduction in kit production, is presented on Figure 5. Figure 5 is read as follows:

- Read the response of interest (% reduction in kit production) off of the left vertical axis
- Project horizontally right to the dose–response curve (either the mean dose–response curve [solid red], the lower confidence limit [the dashed red line to the left], or the upper confidence limit [the dashed red line to the right])
- From the intersection with the dose–response curve, project down to the x-axis to find the associated dose
- Go back to the intersection with the dose–response curve; project vertically up or down to the abundance curve (solid black; dashed left = lower confidence limit; dashed right = upper confidence limit)
- From the intersection with the abundance curve, project horizontally to the abundance axis (the right vertical axis)

Our analysis found that if mink throughout the study area were exposed to the mean baseline dose estimate of 260 μg/kg bw/d, the mean projected response would be a 65% reduction in kit production. Given a 65% reduction in kit production, the population model predicts the average mink population would be reduced to 4 adult females. If mink throughout the study area were exposed to the 95th percentile baseline dose estimate of 550 μg/kg bw/d (i.e., a reasonable worst-case exposure), the mean projected response would be a 90% reduction in kit production. Based on the population model, the study area

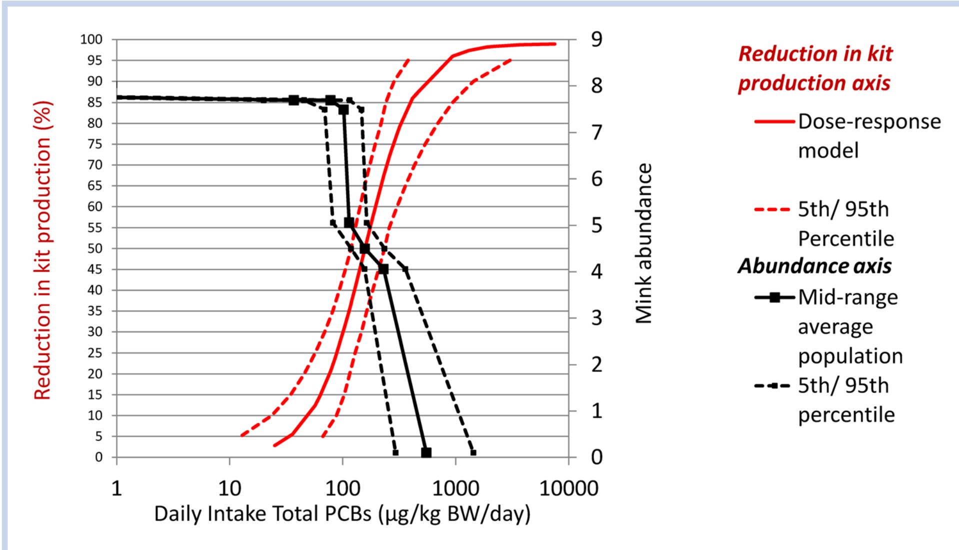

Figure 5. Study area mink abundance estimates plotted with dose–response model.

would not be expected to support mink (i.e., projected abundance = 0) if kit production were reduced by 90%.

Incremental increases in percent reduction in kit production showed that reductions in kit production of up to approximately 30% did not substantially affect mink abundance (Figure 5). The 30% response corresponds to a dose of 101 µg/kg bw/d, with a 90% confidence interval of 69 to 146 µg/kg bw/d. Doses associated with greater than 30% response are projected to reduce abundance.

CONCLUSION

Examining exposure, dose–response, habitat and population dynamics together allowed us to quantitatively estimate the effect of PCB exposure on mink abundance at the site, and the associated uncertainties. This provided important information for the FS alternatives analysis. It provides risk managers a more ecologically relevant perspective for evaluating the protectiveness and cost-effectiveness of FS alternatives than what would be possible based on a risk assessment relying on HQs. The analysis demonstrates that remediating sediment to achieve exposure levels at or below the LOAEL TRV (37 µg/kg bw/d) probably is not necessary to protect the mink population. Based on data reported in Restum et al. (1998), 37 µg/kg bw/d corresponds to an 8% reduction in surviving kits per mated female, and a 6% reduction in kit production as predicted by the dose–response model (Figure 1). If the effect of PCB exposure is less than 30% reduction in kit production, then PCB remediation is not expected to have any effect on mink abundance. The PCB dose associated with a 30% reduction in kit production is 101 µg/kg bw/d (90% CI = 69–146 µg/kg bw/d). The mink-PCB dose estimates from the Portland Harbor BERA indicate that if mink are present, then their baseline exposure levels probably exceed 101 µg/kg bw/d. Therefore, some level of reduction in PCB exposure could be beneficial if the study area provides sufficient habitat to support a mink population. The projected vulnerability of a Portland Harbor mink population to PCB effects is sensitive to uncertainty about habitat quality, abundance, and connectivity.

This article demonstrates that risk analysis for population-level assessment endpoints benefits from analyses beyond the calculation of HQs. The integrated analyses of exposure, effects, habitat, and population dynamics presented here was possible for mink due to the abundant literature on their sensitivity to PCBs, which allowed for the development of the dose–response model. Additionally, an abundance of literature on American mink population dynamics and habitat requirements is available due to research in Europe on the eradication of American mink, which are an introduced pest there.

The application of this approach to other receptors at other sites would be straightforward when an increased understanding of the implications of risk predictions is desired. Species-habitat relationship (e.g., USFWS habitat suitability index models) and population demographics data are readily available from the literature for many species. Dose–response data for other receptors is less available for other species and contaminants, though interspecies extrapolation is a persistent source of uncertainty in ecological risk assessments (Forbes et al. 2001; Buckler et al. 2005; Solomon et al. 2008).

The individual-based population model was useful for Portland Harbor because it allowed for an evaluation of PCB effects on population dynamics within the context of the relatively small area and marginal habitat afforded by the site. Realistically, Portland Harbor is surrounded by habitat of higher quality, and any mink in Portland Harbor are a component of a much larger population (USFWS 2011). Nonetheless, this analysis allowed for an evaluation of potential PCB effects on this hypothetical population. By going beyond models that evaluate hypothetical exposure and organismal effects to quantify the population-level ramifications of those effects, this study gives risk managers a richer perspective for evaluating environmental protectiveness and the cost-effectiveness of remedial goals.

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SUPPLEMENTAL DATA

Table S1. Total PCB Concentrations (mg/kg WW) in Mink Prey for each 1-Mile Exposure Area

Table S2. Exposure Model Input and Coefficient Distributions Used in the Probabilistic Exposure Analysis

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