U.S. Environmental

Protection Agency

New England Region

Boston, Massachusetts

A Stochastic Population Model Incorporating PCB Effects for Wood Frogs (*Rana sylvatica*) Breeding in Vernal Pools Associated with the Housatonic River

Pittsfield to Lenoxdale, Massachusetts

DCN: 07-0123

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A Stochastic Population Model Incorporating PCB Effects for Wood Frogs (*Rana sylvatica*) Breeding in Vernal Pools Associated with the Housatonic River Pittsfield to Lenoxdale, Massachusetts

July 2003

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1. INTRODUCTION

The U.S. Environmental Protection Agency (USEPA) is conducting an Ecological Risk Assessment (ERA) for the portion of the Housatonic River and its floodplain beginning at the confluence of the East and West Branches of the River in Pittsfield, Massachusetts, and continuing downstream. The Primary Study Area (PSA) for these investigations is the area between the confluence and Woods Pond Dam in Lenoxdale.

Breeding amphibians use portions of the River and temporary and permanent pools, called vernal pools, in the floodplain for courtship and egg laying. These areas then support larval amphibians for periods ranging from several weeks to more than a year, resulting in the exposure of developing amphibians to sediment and water contaminated by polychlorinated biphenyls (PCBs) and other contaminants of concern. Wood frogs (*Rana sylvatica*) are the most abundant frog breeding in the vernal pools within the PSA (approximately 83% of counts of all breeding adult amphibians) and spotted salamanders (*Ambystoma maculatum*) are the most common salamanders (approximately 4% of counts of all breeding adult amphibians) (Woodlot Alternatives 2002, Section III, Chapter 4; Woodlot Alternatives 2003).

Previous studies within the Housatonic River PSA have demonstrated that PCBs can have harmful effects on developing amphibians, including direct mortality and internal and external malformations (FEL 2002). A stochastic population model was developed to determine whether these effects on individual wood frogs influence the dynamics of the wood frog population within the Housatonic River PSA.

This report presents the results of the effort to model wood frog populations within the PSA. A description of the study area encompassed by the model, as well as the amphibian community within the PSA, can be found in previous reports prepared by Woodlot Alternatives (2002, 2003).

2. METHODS AND MODEL PARAMETERIZATION

2.1 DEFINITION OF POPULATION

Sixty-six temporary (i.e., vernal) and permanent pools have been mapped in the Housatonic River PSA (Woodlot Alternatives 2002). Not all, however, are suitable as wood frog breeding habitat. Based on field surveys conducted in the PSA since 1998 (Woodlot Alternatives 2002), field studies of specific pools within the PSA (Woodlot Alternatives 2003), and field collections for laboratory-based studies (FEL 2002), 27 vernal pools within the floodplain of the PSA were identified as suitable wood frog breeding habitat.

The wood frog breeding population within the PSA was defined as those frogs breeding within the 27 vernal pools described above. For the purposes of the model, a closed population was assumed (i.e., no immigration or emigration). Although it is possible that a small number of wood frogs could enter or leave the PSA, wood frogs are not known to migrate long distances and they show fidelity to their natal pools (Berven and Grudzien 1990). It is reasonable to assume, therefore, that the population is closed for the purposes of this model.

2.2 MODELING APPROACH

A dynamic population model projecting wood frog population trends ten years into the future, and computing the risk of population decline (Ginzburg *et al.* 1982), was constructed using vital rate information from the literature (Berven 1990) and initial abundances derived from studies of vernal pools in the PSA (Woodlot Alternatives 2002, 2003). The model was age- and sex-structured and employed yearly time steps between age classes (Caswell 2001). In addition, both demographic and environmental stochasticity were incorporated (Burgman *et al.* 1993, Chapter 4), as was density dependence. The model also considered the spatial location of pools and allowed migration between them as a function of distance based upon dispersal relationships described by Berven and Grudzien (1990).

The impact of total PCBs (tPCBs) on the wood frog population was assessed by comparing population projections from a base population model (i.e., a wood frog population in the absence of tPCBs), with projections from population models that included the effect of tPCBs on population vital rates (see FEL 2002). Two projection comparisons were performed based on simulations of (1) a non-declining base population, and (2) a declining base population. All models were constructed using RAMAS Metapop (Akçakaya 2002).

Population projections from five parameterizations of the model were analyzed for each of the two projection comparisons (i.e., non-declining and declining base populations). The first parameterization was a base model of population change over ten years in the absence of tPCB contamination. The other four parameterizations included the effect of tPCBs on initial population size and vital rates, each incorporating a slightly different combination of assumptions regarding the impact of tPCBs on fertility and mortality. These four parameterizations comprised combinations of low and high estimates of the proportion of malformed frogs that subsequently die or become reproductively incapacitated. The impact of tPCBs on initial population size and vital rates used in these parameterization were derived from vernal pool studies conducted in the PSA by Woodlot Alternatives (2002, 2003), from studies conducted by Fort Environmental Labs (FEL 2002), and from a literature study of the effect of tPCBs on amphibians (Glennemeier and Begnoche 2002).

2.3 POPULATION MODELS

2.3.1 Projection 1 (Non-Declining Base Population) Population Matrix and Vital Rates

2.3.1.1 Projection Matrix

Four age classes were modeled in one-year steps for females and males, respectively, assuming a post-breeding census. Age Class 0 spanned the period from egg to just less than one year of age, Age Class 1 spanned the period from 1 year to just less than two years, etc.; no frogs were modeled as living past the age of 3. Table 1 shows the Leslie matrix used in the base model.

TABLE 1

BASE POPULATION MODEL LESLIE MATRIX FOR NON-DECLINING BASE POPULATION PROJECTION[1]

			From							
			Females				Males			
			Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
To	Females	Age 0	0.048	49.02	21.5	0	0	0	0	
		Age 1	0.02	0	0	0	0	0	0	0
		Age 2	0	0.29	0	0	0	0	0	0
		Age 3	0	0	0.13	0	0	0	0	0
	Males	Age 0	0.048	49.02	21.5	0	0	0	0	0
		Age 1	0	0	0	0	0.02	0	0	0
		Age 2	0	0	0	0	0	0.29	0	0
		Age 3	0	0	0		0	0	0.13	0

For projection 1, fertility and survivorship for wood frogs were derived from one of the seasonal ponds in Maryland studied by Berven (1990). That study reported six yearly life tables for two ponds calculated from data collected between 1976 and 1980. Fertility and survivorship from the pond with the most years of data were averaged across years to produce the figures in the Leslie matrix in Table 1[2]. Standard deviations from these averages were used to model environmental stochasticity (see Section 2.3.1.2).

[1] In the Leslie matrix shown in Table 1, the numbers in the "Age 0" rows represent fertility in terms of average number of eggs produced in each age class that survive to be censused. The numbers in the matrix on the sub-diagonal are the proportion of wood frogs surviving from the previous age class (see Akçakaya 2002).

[2] Berven (1990) reports survivorship (l_x) as the number surviving from birth to the beginning of each age class. This figure was transformed to produce the proportion surviving from the previous to the current age class by dividing l_x by l_{x-1} for each age class.

2.3.1.2 Stochasticity

Demographic stochasticity was incorporated in all vital rates. Environmental stochasticity was assumed to be distributed lognormally, and incorporated in vital rates using standard deviations around vital rates measured over 4 years at the pond studied by Berven (1990) (see Table 2). Vital rates were independent from year to year, but were assumed to be perfectly correlated within a single year.

TABLE 2

VITAL RATE STANDARD DEVIATIONS FOR NON-DECLINING BASE POPULATION PROJECTION

			From							
			Females				Males			
			Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
To	Females	Age 0	0.058	44.138	9.207	0	0	0	0	
		Age 1	0.012	0	0	0	0	0	0	0
		Age 2	0	0.22	0	0	0	0	0	0
		Age 3	0	0	0.07	0	0	0	0	0
	Males	Age 0	0.058	44.138	9.207	0	0	0	0	0
		Age 1	0	0	0	0	0.012	0	0	0
		Age 2	0	0	0	0	0	0.22	0	0
		Age 3	0	0	0		0	0	0.07	0

2.3.2 Projection 2 (Declining Base Population) Population Matrix and Vital Rates

2.3.2.1 Projection Matrix

In this projection comparison, life table data from both of Berven's (1990) study pools were combined, resulting in a model population undergoing moderately rapid decline. Fertility and survivorship from the ponds were averaged across years and ponds to produce the figures in the Leslie matrix for this base model (Table 3).

TABLE 3

BASE POPULATION MODEL LESLIE MATRIX FOR DECLINING BASE POPULATION PROJECTION

			From							
			Females				Males			
			Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
To	Females	Age 0	0.035	44.0	19.1	0	0	0	0	
		Age 1	0.01	0	0	0	0	0	0	0
		Age 2	0	0.26	0	0	0	0	0	0
		Age 3	0	0	0.11	0	0	0	0	0
	Males	Age 0	0.035	44.0	19.1	0	0	0	0	0
		Age 1	0	0	0	0	0.01	0	0	0
		Age 2	0	0	0	0	0	0.26	0	0
		Age 3	0	0	0		0	0	0.11	0

2.3.2.2 Stochasticity

Demographic stochasticity was also incorporated in all vital rates for the declining base population projection and environmental stochasticity was assumed to be distributed lognormally. Because data from two ponds were used, the standard deviations (Table 4) include both temporal and spatial variability. To avoid overestimating the temporal variability input needed for the population model, however, the standard deviations were adjusted so that the coefficients of variation match those calculated for the projection 1 model, which included only temporal variability. Vital rates were independent from year to year, but were assumed to be perfectly correlated within a single year.

TABLE 4

VITAL RATE STANDARD DEVIATIONS FOR NON-DECLINING BASE POPULATION PROJECTION

			From							
			Females				Males			
			Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
To	Females	Age 0	0.043	39.619	8.179	0	0	0	0	
		Age 1	0.008	0	0	0	0	0	0	0
		Age 2	0	0.202	0	0	0	0	0	0
		Age 3	0	0	0.061	0	0	0	0	0
	Males	Age 0	0.043	39.619	8.179	0	0	0	0	0
		Age 1	0	0	0	0	0.008	0	0	0
		Age 2	0	0	0	0	0	0.202	0	0
		Age 3	0	0	0		0	0	0.061	0

2.3.3 Population Size and Initial Abundances

2.3.3.1 Base Model Initial Abundance

The initial number of adults was derived from data collected in 1999 at four vernal pools in the PSA (Woodlot Alternatives 2003) (see Table 5).

TABLE 5

BREEDING ADULT WOOD FROG DENSITIES IN FOUR VERNAL POOLS OF THE PSA IN RELATION TO SPATIALLY WEIGHTED SEDIMENT tPCB CONCENTRATION

Pool	Pool Volume (m^3)	SPATWGT Mean tPCBs	Adult Males	Adult Females	Total Adults	Male Density (per m^3)	Female Density (per m^3)
8-VP-1	72	24.56	104	112	216	1.44	1.56
8-VP-2	824	54.98	91	73	164	0.11	0.09
38-VP-2	202	32.31	318	245	563	1.57	1.21
46-VP-5	68	1.36	151	119	270	2.22	1.75

The data in Table 5 suggest a negatively linear relationship between spatially weighted tPCBs and the density of breeding adults entering the vernal pool. For the base model parameterization, therefore, the relationship between male and female density and tPCBs was controlled with linear regression (Figures 1 and 2).

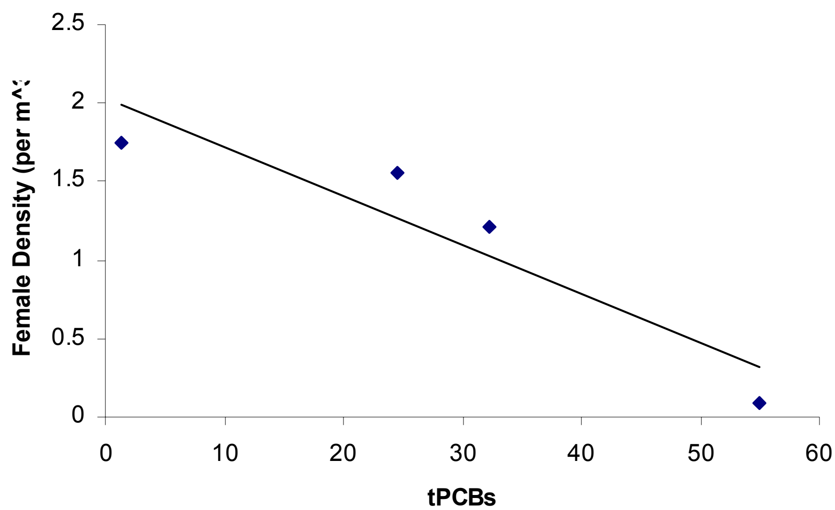

Figure 1. Relationship between spatially weighted tPCBs and breeding adult female wood frog density (R^2=0.86, d.f.=3, F=12.4505, p=0.072; y = 2.03 – 0.03x).

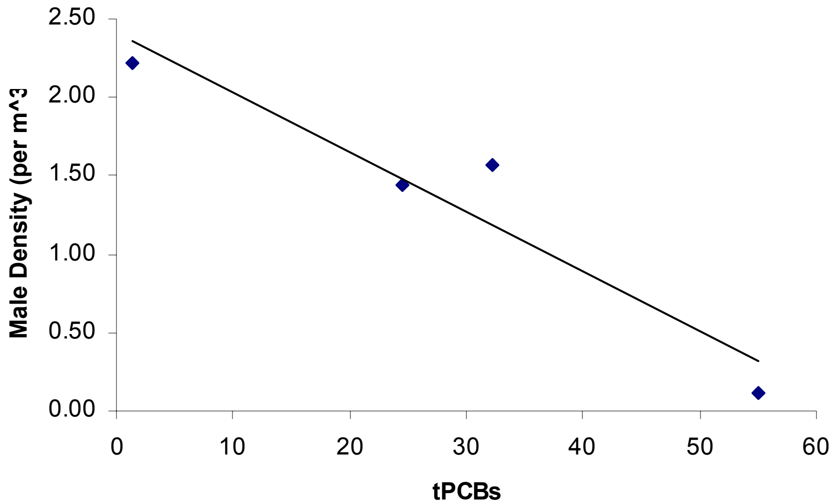

Figure 2. Relationship between spatially weighted tPCBs and breeding adult male wood frog density (R^2=0.91, d.f.=3, F=19.5995, p=0.047; y = 2.4 – 0.04x).

Initial adult populations were calculated for the 27 pools corrected for the effect of tPCBs on population size (i.e., the regression equation was used to predict total adults given pool volume and assuming tPCBs=0) (see Table 6).

TABLE 6

INITIAL ADULT WOOD FROG POPULATION SIZES FOR BASE MODEL

Pool Name	SPATWGT Mean tPCBs	Volume (cubic meters)	Number adult females (assuming tPCB = 0)	Number adult males (assuming tPCB = 0)
23b-VP-1	0.21	127	257	306
23b-VP-2	0.3	111	223	265
46-VP-5	1.36	67	136	162
46-VP-1	0.76	1,897	3,826	4,554
19-VP-7	0.82	55	111	133
8-VP-4	0.95	447	902	1,074
12-VP-1	1.72	208	419	499
23a-VP-1	3.04	457	922	1,098
40-VP-1	3.69	874	1,762	2,097
27b-VP-2	4.18	470	947	1,127
18-VP-2	4.9	1,516	3,057	3,638
66a-VP-1	5.31	32	65	78
18-VP-1	9.03	512	1,032	1,229
27b-VP-3	10.05	76	153	182
27-VP-1	10.21	2,351	4,741	5,643
38-VP-3	13.49	67	135	161
42-VP-3	20.12	186	374	446
49a-VP-1	24.34	15	31	36
8-VP-1	24.56	72	146	174
38a-VP-1	25.77	20	41	49
38-VP-1	28.54	620	1,250	1,488
19-VP-1	30.67	265	533	635
8-VP-5	31.86	52	104	124
38-VP-2	32.31	202	407	485
26-VP-1	38.81	52	106	126
39-VP-1	42.96	5,091	10,266	12,219
8-VP-2	54.98	824	1,662	1,978

The initial number of eggs in the base model was derived from data collected in 2003 at ten vernal pools in the PSA by Woodlot Alternatives in 2003 (M. Thompson, pers. comm.) (see Table 7). As with adult density, these data suggest a negatively linear relationship between the number of egg masses in a pool and the spatially weighted mean sediment tPCB concentration for the pool.

TABLE 7

2003 WOOD FROG EGG MASS COUNTS IN TEN VERNAL POOLS OF THE HOUSATONIC RIVER PSA

Pool	Egg Mass Count	Pool Volume (m^3)	SPATWGT Mean tPCBs
23b-VP-1	250	127	0.21
23b-VP-2	0	111	0.3
46-VP-5	120	68	1.36
46-VP-1	400	1897	0.76
18-VP-1	40	512	1.72
18-VP-2	350	1515	4.9
8-VP-1	31	72	24.56
38-VP-1	82	620	28.54
38-VP-2	134	202	32.31
8-VP-2	0	824	54.98

A multiple linear regression using the data from Table 7 was used to predict egg mass count as a function of pool volume and tPCBs (R^2=0.66, d.f.=9, F=6.8133, p=0.023). The resulting relationship – *Egg Mass Count = 97.11 + 0.15 x Pool Volume – 3.10 × tPCBs*, where tPCBs was set to zero for each pond – was used to predict initial egg mass counts for the 27 pools in the absence of tPCBs (Table 8).

TABLE 8

INITIAL EGG MASS COUNTS FOR BASE MODEL CALCULATED BASED ON SPATIALLY WEIGHTED tPCBs AND VERNAL POOL VOLUME

Pool Name	SPATWGT Mean tPCBs	Volume (cubic meters)	Egg Mass Count (assuming tPCB = 0)	Number of Eggs (assuming 981 Eggs/mass[3])
23b-VP-1	0.21	127	115.74	113,545
23b-VP-2	0.3	111	113.2	111,082
46-VP-5	1.36	67	106.8	104,729
46-VP-1	0.76	1,897	381.2	374,003
19-VP-7	0.82	55	104.9	102,941
8-VP-4	0.95	447	163.8	160,650
12-VP-1	1.72	208	127.8	125,401
23a-VP-1	3.04	457	165.3	162,125
40-VP-1	3.69	874	227.7	223,395
27b-VP-2	4.18	470	167.1	163,926
18-VP-2	4.9	1,516	324.0	317,885
66a-VP-1	5.31	32	101.5	99,593
18-VP-1	9.03	512	173.5	170,157
27b-VP-3	10.05	76	108.0	105,943
27-VP-1	10.21	2,351	449.3	440,795
38-VP-3	13.49	67	106.7	104,699
42-VP-3	20.12	186	124.5	122,130
49a-VP-1	24.34	15	98.9	97,046
8-VP-1	24.56	72	107.5	105,462
38a-VP-1	25.77	20	99.7	97,799
38-VP-1	28.54	620	189.7	186,048
19-VP-1	30.67	265	136.3	133,737
8-VP-5	31.86	52	104.4	102,430
38-VP-2	32.31	202	127.0	124,551
26-VP-1	38.81	52	104.5	102,526
39-VP-1	42.96	5,091	860.3	843,988
8-VP-2	54.98	824	220.3	216,088

[3] The average number of eggs per egg mass in the PSA was derived from data reported by Fort Environmental Laboratories (FEL 2002).

The age structure of the initial population in each pool for the base model is provided in Table 9. A 1:1 sex ratio was assumed for the first age class[4], while the initial number of adult males and females were derived from the observed sex-specific relationships between pool volume and number of adults. The total number of adults was distributed among age classes to approximate the numbers expected assuming the population exhibits a stable age distribution.

[4] Age class 0 includes eggs, larva, and metamorphs less than one year of age. While a female-skewed sex ratio was demonstrated by Fort Environmental Labs for metamorphs collected from vernal pools in the PSA during Phase III of their study, they represent a small fraction (<0.01%) of Age Class 0 individuals. No data on the sex ratio of eggs or larva was available.

TABLE 9

INITIAL AGE CLASS STRUCTURE FOR BASE MODEL POPULATION

	Females				Males			
Pool Name	**Age 0**	**Age 1**	**Age 2**	**Age 3**	**Age 0**	**Age 1**	**Age 2**	**Age 3**
12-VP-1	62701	304	101	14	62701	362	120	17
18-VP-1	85079	749	248	35	85079	891	296	42
18-VP-2	158942	2216	736	104	158942	2638	876	124
19-VP-1	66869	387	128	18	66869	460	153	22
19-VP-7	51471	81	27	4	51471	96	32	5
23a-VP-1	81062	669	222	31	81062	796	264	37
23b-VP-1	56772	186	62	9	56772	222	73	10
23b-VP-2	55541	162	54	8	55541	192	64	9
26-VP-1	51263	77	25	4	51263	91	30	4
27b-VP-2	81963	686	228	32	81963	817	272	39
27b-VP-3	52971	111	37	5	52971	132	44	6
27-VP-1	220398	3438	1142	162	220398	4091	1359	193
38a-VP-1	48900	30	10	1	48900	35	12	2
38-VP-1	93024	906	301	43	93024	1079	358	51
38-VP-2	62275	295	98	14	62275	352	117	17
38-VP-3	52349	98	33	5	52349	117	39	6
39-VP-1	421994	7443	2472	351	421994	8859	2943	418
40-VP-1	111697	1278	424	60	111697	1521	505	72
42-VP-3	61065	271	90	13	61065	323	107	15
46-VP-1	187002	2774	921	131	187002	3302	1097	155
46-VP-5	52364	98	33	5	52364	117	39	6
49a-VP-1	48523	22	7	1	48523	26	9	1
66a-VP-1	49796	47	16	2	49796	56	19	3
8-VP-1	52731	106	35	5	52731	126	42	6
8-VP-2	108044	1204	400	57	108044	1434	476	68
8-VP-4	80325	654	217	31	80325	778	258	37
8-VP-5	51215	76	25	4	51215	90	30	4

2.3.3.2 tPCB-impacted Models Initial Abundance

For the base model, initial abundances were calculated by controlling for the effect of tPCBs on number of egg masses and on adult density observed in studies of vernal pools in the PSA (Woodlot Alternatives 2003). The effect used is shown in Figures 1 and 2. For each of the four tPCB-impacted parameterizations of the projection 1 model, initial population size was recalculated to include the observed effect of tPCBs (see Table 10).

TABLE 10

INITIAL AGE CLASS STRUCTURE FOR PCB-IMPACTED MODEL POPULATION

Pool Name	SPATWGT Mean tPCBs	Females				Males			
		Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
23b-VP-1	0.21	56408	186	62	9	56408	221	73	10
23b-VP-2	0.3	55427	161	54	8	55427	191	64	9
46-VP-5	1.36	51503	97	32	5	51503	116	38	6
46-VP-1	0.76	187371	2738	909	129	187371	3260	1083	153
19-VP-7	0.82	50031	80	26	4	50031	95	31	4
8-VP-4	0.95	78971	645	214	31	78971	766	254	36
12-VP-1	1.72	60332	295	98	14	60332	351	117	17
23a-VP-1	3.04	77009	637	211	30	77009	756	251	35
40-VP-1	3.69	106929	1204	400	57	106929	1427	474	67
27b-VP-2	4.18	76028	640	213	30	76028	760	253	36
18-VP-2	4.9	152546	2055	683	97	152546	2423	804	114
66a-VP-1	5.31	41693	44	14	2	41693	51	17	2
18-VP-1	9.03	71613	646	214	30	71613	757	251	36
27b-VP-3	10.05	37769	94	31	4	37769	110	36	5
27-VP-1	10.21	206501	2898	963	136	206501	3395	1128	160
38-VP-3	13.49	31883	78	26	4	31883	91	30	4
42-VP-3	20.12	30902	188	63	9	30902	215	71	10
49a-VP-1	24.34	11772	14	5	1	11772	16	5	1
8-VP-1	24.56	15696	66	22	3	15696	74	25	4
38a-VP-1	25.77	9810	18	6	1	9810	20	7	1
38-VP-1	28.54	50031	512	170	24	50031	566	188	27
19-VP-1	30.67	20601	205	68	10	20601	225	75	11
8-VP-5	31.86	2943	39	13	2	2943	42	14	2
38-VP-2	32.31	13244	149	50	7	13244	162	54	8
26-VP-1	38.81	0	32	10	1	0	32	11	2
39-VP-1	42.96	360518	2584	858	122	360518	2516	836	119
8-VP-2	54.98	25506	197	66	9	25506	120	40	6

2.3.3.3 Density Dependence

Berven (1990) notes that larval population densities have been observed to fluctuate up to two orders of magnitude from minimum to maximum and adults up to one order of magnitude. Some of these fluctuations are potentially related to density dependent effects. For all simulations, therefore, a carrying capacity ceiling was calculated at ten times the initial population size of each pool and populations were not allowed to grow beyond this ceiling. This ceiling brackets the highest observed population fluctuations.

2.3.4 Environmental Correlation

Correlation coefficients of 0.5 were assumed between all pools when calculating year-to-year demographic stochasticity due to environmental fluctuation. This is a relatively strong correlation intended to simulate ponds experiencing very similar, but not identical, environmental changes from year to year.

2.3.5 Dispersal

The metapopulation models constructed for the population projection simulations were geographically explicit. Distances between ponds were calculated, and the dispersal equation reported for wood frogs by Berven and Grudzien (1990) was used to calculate the proportion of frogs dispersing from each pond that immigrate to each other pond. The equation used was negative exponential in form, and was given by

$$\mathbf{y = 0.4392 \times 10}^{-0.000560x},$$

where x is distance (in meters) and y is the proportion of frogs dispersing that distance. Berven and Grudzien (1990) also report that, on average, 18.54% of wood frogs disperse in their first year, with no difference in dispersal rates between males and females. This percentage was used as the proportion dispersing from each pool in the simulation (Table 11).

TABLE 11

WOOD FROG DISPERSAL MATRIX[5]

	12-VP-1	18-VP-1	18-VP-2	19-VP-1	19-VP-7	23a-VP-1	23b-VP-1	23b-VP-2	26-VP-1	27b-VP-2	27b-VP-3	27-VP-1	38a-VP-1	38-VP-1	38-VP-2	38-VP-3	39-VP-1	40-VP-1	42-VP-3	46-VP-1	46-VP-5	49a-VP-1	66a-VP-1	8-VP-1	8-VP-2	8-VP-4
12-VP-1	0.0000	0.0253	0.0250	0.0181	0.0150	0.0044	0.0039	0.0038	0.0034	0.0052	0.0057	0.0038	0.0005	0.0005	0.0005	0.0005	0.0006	0.0004	0.0003	0.0002	0.0001	0.0001	0.0001	0.0097	0.0128	0.0113
18-VP-1	0.0304	0.0000	0.0347	0.0213	0.0207	0.0056	0.0046	0.0045	0.0038	0.0059	0.0064	0.0042	0.0006	0.0006	0.0006	0.0006	0.0007	0.0005	0.0004	0.0002	0.0002	0.0001	0.0001	0.0115	0.0160	0.0134
18-VP-2	0.0296	0.0342	0.0000	0.0198	0.0199	0.0053	0.0043	0.0042	0.0035	0.0055	0.0059	0.0039	0.0005	0.0006	0.0005	0.0005	0.0007	0.0005	0.0004	0.0002	0.0002	0.0001	0.0001	0.0124	0.0173	0.0144
19-VP-1	0.0216	0.0212	0.0200	0.0000	0.0251	0.0090	0.0079	0.0077	0.0066	0.0103	0.0111	0.0073	0.0009	0.0011	0.0010	0.0009	0.0013	0.0009	0.0007	0.0003	0.0003	0.0002	0.0001	0.0069	0.0099	0.0080
19-VP-7	0.0174	0.0200	0.0196	0.0245	0.0000	0.0099	0.0076	0.0073	0.0059	0.0090	0.0096	0.0065	0.0009	0.0011	0.0010	0.0009	0.0012	0.0009	0.0007	0.0003	0.0003	0.0002	0.0001	0.0086	0.0123	0.0096
23a-VP-1	0.0053	0.0055	0.0053	0.0090	0.0102	0.0000	0.0195	0.0182	0.0151	0.0152	0.0147	0.0147	0.0034	0.0038	0.0037	0.0034	0.0044	0.0034	0.0028	0.0012	0.0011	0.0008	0.0004	0.0025	0.0035	0.0027
23b-VP-1	0.0058	0.0057	0.0054	0.0098	0.0097	0.0242	0.0000	0.0278	0.0221	0.0217	0.0207	0.0224	0.0036	0.0040	0.0037	0.0036	0.0048	0.0033	0.0026	0.0012	0.0010	0.0008	0.0004	0.0022	0.0031	0.0024
23b-VP-2	0.0057	0.0056	0.0053	0.0097	0.0094	0.0227	0.0281	0.0000	0.0233	0.0222	0.0212	0.0238	0.0037	0.0041	0.0038	0.0036	0.0049	0.0033	0.0026	0.0012	0.0010	0.0008	0.0004	0.0021	0.0030	0.0024
26-VP-1	0.0045	0.0042	0.0040	0.0073	0.0067	0.0167	0.0197	0.0206	0.0000	0.0177	0.0172	0.0269	0.0046	0.0052	0.0047	0.0046	0.0064	0.0038	0.0031	0.0014	0.0012	0.0010	0.0006	0.0015	0.0022	0.0017
27b-VP-2	0.0076	0.0072	0.0068	0.0126	0.0114	0.0186	0.0213	0.0217	0.0196	0.0000	0.0290	0.0217	0.0028	0.0031	0.0028	0.0027	0.0038	0.0024	0.0019	0.0009	0.0007	0.0006	0.0003	0.0026	0.0037	0.0029
27b-VP-3	0.0081	0.0076	0.0071	0.0133	0.0118	0.0175	0.0199	0.0201	0.0185	0.0283	0.0000	0.0206	0.0026	0.0029	0.0026	0.0026	0.0036	0.0022	0.0018	0.0008	0.0007	0.0006	0.0003	0.0027	0.0038	0.0030
27-VP-1	0.0053	0.0049	0.0046	0.0086	0.0078	0.0172	0.0211	0.0222	0.0284	0.0207	0.0202	0.0000	0.0039	0.0044	0.0040	0.0039	0.0055	0.0033	0.0027	0.0012	0.0010	0.0008	0.0005	0.0018	0.0025	0.0020
38a-VP-1	0.0006	0.0006	0.0006	0.0010	0.0010	0.0037	0.0031	0.0031	0.0045	0.0024	0.0023	0.0036	0.0000	0.0301	0.0284	0.0318	0.0293	0.0224	0.0202	0.0096	0.0082	0.0073	0.0042	0.0002	0.0003	0.0003
38-VP-1	0.0007	0.0007	0.0006	0.0012	0.0012	0.0042	0.0035	0.0035	0.0051	0.0027	0.0026	0.0041	0.0303	0.0000	0.0290	0.0303	0.0300	0.0219	0.0190	0.0088	0.0075	0.0065	0.0038	0.0003	0.0004	0.0003
38-VP-2	0.0006	0.0006	0.0006	0.0010	0.0011	0.0039	0.0032	0.0032	0.0045	0.0025	0.0024	0.0036	0.0281	0.0285	0.0000	0.0295	0.0250	0.0263	0.0225	0.0102	0.0087	0.0073	0.0041	0.0003	0.0004	0.0003
38-VP-3	0.0006	0.0006	0.0006	0.0010	0.0011	0.0037	0.0032	0.0032	0.0045	0.0024	0.0024	0.0036	0.0323	0.0306	0.0304	0.0000	0.0280	0.0236	0.0210	0.0098	0.0083	0.0073	0.0042	0.0003	0.0004	0.0003
39-VP-1	0.0007	0.0007	0.0007	0.0012	0.0012	0.0042	0.0037	0.0038	0.0056	0.0030	0.0029	0.0045	0.0261	0.0265	0.0226	0.0246	0.0000	0.0171	0.0152	0.0074	0.0062	0.0058	0.0034	0.0003	0.0004	0.0003
40-VP-1	0.0004	0.0004	0.0004	0.0007	0.0008	0.0029	0.0022	0.0022	0.0029	0.0017	0.0016	0.0024	0.0175	0.0170	0.0208	0.0182	0.0150	0.0000	0.0358	0.0157	0.0135	0.0103	0.0057	0.0002	0.0003	0.0002
42-VP-3	0.0003	0.0003	0.0003	0.0005	0.0005	0.0020	0.0015	0.0015	0.0020	0.0011	0.0011	0.0016	0.0134	0.0125	0.0151	0.0137	0.0114	0.0304	0.0000	0.0228	0.0196	0.0148	0.0082	0.0001	0.0002	0.0002
46-VP-1	0.0001	0.0001	0.0001	0.0001	0.0002	0.0006	0.0004	0.0004	0.0006	0.0003	0.0003	0.0004	0.0040	0.0036	0.0043	0.0040	0.0034	0.0083	0.0142	0.0000	0.0703	0.0485	0.0276	0.0000	0.0001	0.0000
46-VP-5	0.0001	0.0001	0.0001	0.0001	0.0001	0.0004	0.0003	0.0003	0.0004	0.0002	0.0002	0.0003	0.0031	0.0028	0.0033	0.0031	0.0026	0.0065	0.0111	0.0639	0.0000	0.0547	0.0329	0.0000	0.0000	0.0000
49a-VP-1	0.0000	0.0000	0.0000	0.0000	0.0001	0.0002	0.0001	0.0001	0.0002	0.0001	0.0001	0.0002	0.0016	0.0014	0.0016	0.0016	0.0014	0.0029	0.0049	0.0254	0.0315	0.0000	0.0877	0.0000	0.0000	0.0000
66a-VP-1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0002	0.0002	0.0002	0.0002	0.0003	0.0005	0.0027	0.0036	0.0166	0.0000	0.0000	0.0000	0.0000
8-VP-1	0.0078	0.0077	0.0084	0.0047	0.0059	0.0017	0.0012	0.0011	0.0009	0.0014	0.0015	0.0010	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0001	0.0000	0.0000	0.0000	0.0268	0.0340
8-VP-2	0.0123	0.0128	0.0140	0.0080	0.0101	0.0028	0.0020	0.0019	0.0016	0.0024	0.0026	0.0017	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0001	0.0001	0.0001	0.0000	0.0322	0.0000	0.0355
8-VP-4	0.0107	0.0105	0.0115	0.0063	0.0078	0.0022	0.0016	0.0015	0.0012	0.0019	0.0020	0.0013	0.0002	0.0002	0.0002	0.0002	0.0003	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000	0.0401	0.0349	0.0000
8-VP-5	0.0092	0.0090	0.0099	0.0055	0.0068	0.0019	0.0014	0.0013	0.0011	0.0016	0.0017	0.0012	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001	0.0000	0.0000	0.0468	0.0310	0.0402
	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854	0.1854

[5] Dispersal occurs from the pond named in the column titles to the pond named in the row titles, and columns sum to 0.1854, which is the proportion of frogs dispersing from each pond. Only Age Class 0 individuals were allowed to disperse, which is in keeping with observations from the literature (Berven and Grudzien 1990) indicating that migrating individuals disperse once during their lifetime, prior to their first breeding.

2.4 IMPACT OF tPCBs ON VITAL RATES

2.4.1 Larval Survival

A study of wood frogs collected from the PSA conducted at Fort Environmental Labs (FEL 2002) revealed a relationship between larval wood frog mortality and the spatially weighted concentration of tPCBs in vernal pool sediment (Table 12).

TABLE 12

LARVAL WOOD FROG MORTALITY IN RELATION TO SPATIALLY WEIGHTED MEAN tPCB CONCENTRATIONS IN VERNAL POOL SEDIMENT

Pool Name	SPATWGT Mean tPCBs	End Mean % Mortality
23b-VP-1	0.21	89
23b-VP-2	0.3	83
46-VP-5	1.36	36
46-VP-1	0.8	87
18-VP-2	4.9	98
8-VP-1	24.6	67
38-VP-1	28.5	26
38-VP-2	32.3	52
WML-1	0	77
WML-2	0	87
WML-3	0	75

The percent mortality data in Table 12 was arcsin transformed and a linear regression was performed to determine the relationship between spatially weighted tPCBs and larval mortality (see Figure 3).

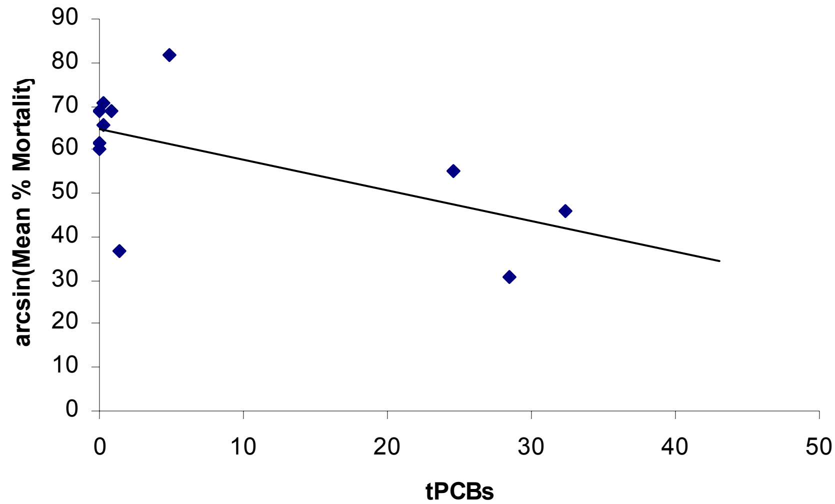

Figure 3. Relationship between spatially weighted tPCBs and larval wood frog mortality (R^2=0.39, d.f.=9, F=5.0163, p=0.0555; y = 64.57 – 0.80x).

This relationship was used to predict the relative decrease in larval mortality associated with increased tPCBs in the 27 vernal pools (see Table 13).

TABLE 13

RELATIONSHIP BETWEEN SPATIALLY WEIGHTED tPCBs IN VERNAL POOL SEDIMENT AND LARVAL WOOD FROG MORTALITY RATES

Pool Name	SPATWGT Mean tPCBs	Mean larval mortality (tPCB=0)	Mean larval mortality given pond-specific tPCBs	Decreased mean mortality / 100	Increased survival proportion due to tPCBs
23b-VP-1	0.21	81.36	81.13	0.00	1.00
23b-VP-2	0.3	81.36	81.03	0.00	1.00
46-VP-5	1.36	81.36	80.58	0.01	1.01
46-VP-1	0.76	81.36	80.53	0.01	1.01
19-VP-7	0.82	81.36	80.47	0.01	1.01
8-VP-4	0.95	81.36	80.33	0.01	1.01
12-VP-1	1.72	81.36	79.48	0.02	1.02
23a-VP-1	3.04	81.36	77.99	0.03	1.03
40-VP-1	3.69	81.36	77.24	0.04	1.04
27b-VP-2	4.18	81.36	76.67	0.05	1.05
18-VP-2	4.9	81.36	75.83	0.06	1.06
66a-VP-1	5.31	81.36	75.34	0.06	1.06
18-VP-1	9.03	81.36	70.79	0.11	1.11
27b-VP-3	10.05	81.36	69.51	0.12	1.12
27-VP-1	10.21	81.36	69.30	0.12	1.12
38-VP-3	13.49	81.36	65.06	0.16	1.16
42-VP-3	20.12	81.36	56.14	0.25	1.25
49a-VP-1	24.34	81.36	50.33	0.31	1.31
8-VP-1	24.56	81.36	50.03	0.31	1.31
38a-VP-1	25.77	81.36	48.36	0.33	1.33
38-VP-1	28.54	81.36	44.55	0.37	1.37
19-VP-1	30.67	81.36	41.65	0.40	1.40
8-VP-5	31.86	81.36	40.03	0.41	1.41
38-VP-2	32.31	81.36	39.43	0.42	1.42
26-VP-1	38.81	81.36	30.88	0.50	1.50
39-VP-1	42.96	81.36	25.73	0.56	1.56
8-VP-2	54.98	81.36	12.83	0.69	1.69

2.4.2 Metamorph Malformation Rates

Additional research conducted by Fort Environmental Labs included collecting wood frog metamorphs from ten vernal pools in the PSA and reporting the percent malformed for each sex (FEL 2002) (see Table 14).

TABLE 14

MALFORMATION RATES IN RECENTLY METAMORPHED WOOD FROGS IN RELATION TO SPATIALLY WEIGHTED tPCB CONCENTRATIONS IN VERNAL POOL SEDIMENT

Pool Name	SPATWGT Mean tPCBs	% Malformed Male Metamorph	% Malformed Female Metamorph	% Total Malformed Metamorph
WML-1	0	0	0	0
WML-3	0	0	5.9	2.9
23b-VP-1	0.21	3.9	5.9	4.9
23b-VP-2	0.3	5	6.5	5.9
46-VP-5	1.36	3	12.3	9.2
46-VP-1	0.8	8.2	8.9	8.6
18-VP-2	4.9	13.8	32.8	26.9
8-VP-1	24.6	0	66.7	66.7
38-VP-1	28.5	20	46.3	41
38-VP-2	32.3	42.1	53.8	51.5

These data were arcsin transformed and regression relationships for females and males were derived (Figure 4).

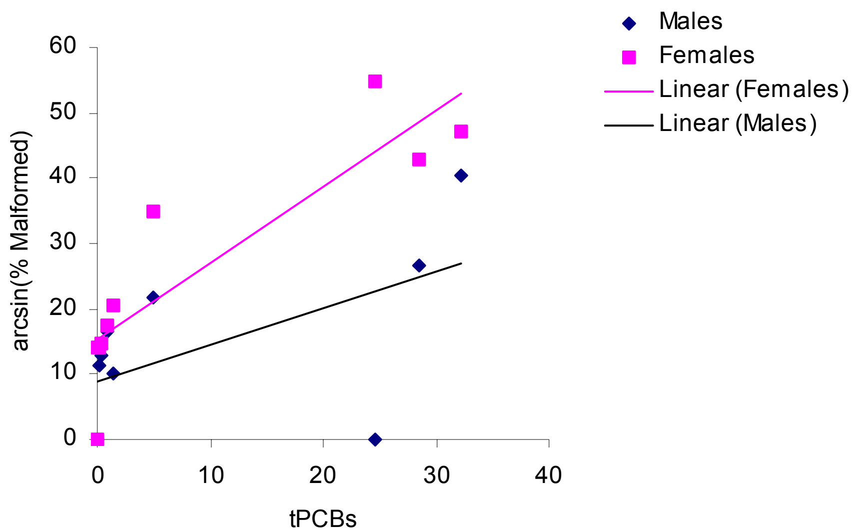

Figure 4. Relationship between spatially weighted tPCBs and the arcsin transform of the percent of metamorphs malformed (Females: R^2=0.75, d.f.=8, F=21.4220, p=0.0024; y = 15.04 + 1.03x; Males: R^2=0.72, d.f.=8, F=18.4281, p=0.0036; y = 9.16 + 0.84x).

The predicted percent malformed at each of the 27 vernal ponds as a function of tPCBs using the relationships from the figure above are shown in the table below.

TABLE 15

PREDICTED MALFORMATION RATES IN WOOD FROGS IN RELATION TO SPATIALLY WEIGHTED tPCB CONCENTRATIONS IN VERNAL POOL SEDIMENT

Pool Name	SPATWGT Mean tPCBs	Predicted % female malformed	Predicted % male malformed	Predicted total % malformed
23b-VP-1	0.21	7.1	2.7	5.5
23b-VP-2	0.3	7.1	2.7	5.5
46-VP-5	1.36	7.5	2.9	5.9
46-VP-1	0.76	7.6	2.9	5.9
19-VP-7	0.82	7.6	2.9	6.0
8-VP-4	0.95	7.8	3.0	6.1
12-VP-1	1.72	8.5	3.4	6.7
23a-VP-1	3.04	9.9	4.1	8.0
40-VP-1	3.69	10.6	4.5	8.6
27b-VP-2	4.18	11.1	4.8	9.1
18-VP-2	4.9	11.9	5.3	9.8
66a-VP-1	5.31	12.4	5.6	10.3
18-VP-1	9.03	17.1	8.3	14.6
27b-VP-3	10.05	18.5	9.2	15.9
27-VP-1	10.21	18.7	9.3	16.1
38-VP-3	13.49	23.4	12.3	20.5
42-VP-3	20.12	34.1	19.4	30.7
49a-VP-1	24.34	41.4	24.5	37.7
8-VP-1	24.56	41.7	24.7	38.1
38a-VP-1	25.77	43.9	26.3	40.2
38-VP-1	28.54	48.8	29.9	45.0
19-VP-1	30.67	52.6	32.8	48.8
8-VP-5	31.86	54.7	34.5	50.9

To determine the effect of malformation on mortality, several sources were consulted. Glennemeier and Begnoche (2002) report increased mortality rates between 20 and 60% due to malformation caused by laboratory exposure of two species of frogs (*R. pipiens* and *R. utricularia*) to comparable levels of PCBs. Fort Environmental Labs estimates rates between 70 and 100% mortality among Housatonic *R. sylvatica* given the severity of malformations (D. Fort, pers. comm.) Based upon this information, simulations were run with models parameterized so that 50% of malformed one-year-old frogs died, and with models parameterized so that 100% of malformed one-year-old frogs died. These values are intended to bracket the uncertainty regarding the mortality rate of malformed frogs.

2.4.3 Metamorph Gonadal Abnormality Rates

Fort Environmental Labs tallied the number of malformed frogs from their study that exhibited gonadal abnormalities (FEL 2002) (see Table 16). Fifty-seven percent of malformed female metamorphs were observed to have gonadal abnormalities.

TABLE 16

GONADAL MALFORMATION RATES IN WOOD FROGS IN THE HOUSATONIC RIVER PSA

	Male	Female	Total
Abnormal	24	124	148
Gonadal Abnormality	11	71	82
Proportion	0.46	0.57	0.55

There are no direct data, however, regarding the proportion of gonadal abnormalities leading to reproductive impairment. Fort Environmental Labs estimates 70 to 100% of females with gonadal abnormalities are sterile, based upon the observed severity of the abnormalities (D. Fort, pers. comm.). Based upon this information, simulations were run with models parameterized so that 50% of females with gonadal abnormalities were sterile, and with models parameterized so that 100% of females with gonadal abnormalities were sterile. These values are intended to bracket the uncertainty regarding the sterility rate of female frogs with gonadal abnormalities.

2.4.4 Summary of tPCB Impacts on Vital Rates

Impacts of tPCBs on vital rates are incorporated into the various impacted parameterizations as proportions by which fertility and mortality are increased or decreased. The proportion by which fertility is impacted is presented in the table below. Separate values are shown for the assumption that 50% and 100% of gonadally abnormal females are sterile, respectively. These values are factors by which fecundity values in the Leslie matrix are multiplied for each pond (Table 17).

TABLE 17

FECUNDITY MULTIPLIERS FOR MODEL PARAMETERS BASED ON THE RELATIONSHIP BETWEEN SPATIALLY WEIGHTED tPCBs AND GONADAL MALFORMATION RATES

Pool Name	SPATWGT Mean tPCBs	Fecundity multiplier (50% of gonadal malformations lead to sterility)	Fecundity multiplier (100% of gonadal malformations lead to sterility)
23b-VP-1	0.21	0.98	0.96
23b-VP-2	0.3	0.98	0.959
46-VP-5	1.36	0.978	0.957
46-VP-1	0.76	0.978	0.957
19-VP-7	0.82	0.978	0.956
8-VP-4	0.95	0.978	0.956
12-VP-1	1.72	0.976	0.951
23a-VP-1	3.04	0.972	0.944
40-VP-1	3.69	0.97	0.94
27b-VP-2	4.18	0.968	0.936
18-VP-2	4.9	0.966	0.932
66a-VP-1	5.31	0.965	0.929
18-VP-1	9.03	0.951	0.902
27b-VP-3	10.05	0.947	0.894
27-VP-1	10.21	0.946	0.893
38-VP-3	13.49	0.933	0.866
42-VP-3	20.12	0.902	0.805
49a-VP-1	24.34	0.882	0.763
8-VP-1	24.56	0.88	0.761
38a-VP-1	25.77	0.874	0.749
38-VP-1	28.54	0.86	0.721
19-VP-1	30.67	0.849	0.699
8-VP-5	31.86	0.843	0.687
38-VP-2	32.31	0.841	0.682
26-VP-1	38.81	0.809	0.618
39-VP-1	42.96	0.79	0.579
8-VP-2	54.98	0.743	0.486

Table 18 shows the pool-specific multipliers modifying the impact of tPCBs on mortality. Impacts are age class- and sex-specific, and half of all malformed frogs are assumed to die. Note that mortality in the zero age class decreases as tPCBs increase, as observed in the Fort Environmental Labs study (FEL 2002), and that mortality due to malformation occurs in age class 1.

TABLE 18

AGE CLASS- AND SEX-SPECIFIC MULTIPLIERS FOR MODEL PARAMETERS BASED ON THE RELATIONSHIP BETWEEN tPCBs AND MORTALITY ASSUMING THAT HALF OF THE MALFORMED FROGS DIE

Pool Name	SPATWGT Mean tPCBs	Female				Male			
		Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
23b-VP-1	0.21	1	0.96	1	1	1	0.99	1	1
23b-VP-2	0.3	1	0.96	1	1	1	0.99	1	1
46-VP-5	1.36	1.01	0.96	1	1	1.01	0.99	1	1
46-VP-1	0.76	1.01	0.96	1	1	1.01	0.99	1	1
19-VP-7	0.82	1.01	0.96	1	1	1.01	0.99	1	1
8-VP-4	0.95	1.01	0.96	1	1	1.01	0.98	1	1
12-VP-1	1.72	1.02	0.96	1	1	1.02	0.98	1	1
23a-VP-1	3.04	1.03	0.95	1	1	1.03	0.98	1	1
40-VP-1	3.69	1.04	0.95	1	1	1.04	0.98	1	1
27b-VP-2	4.18	1.05	0.94	1	1	1.05	0.98	1	1
18-VP-2	4.9	1.06	0.94	1	1	1.06	0.97	1	1
66a-VP-1	5.31	1.06	0.94	1	1	1.06	0.97	1	1
18-VP-1	9.03	1.11	0.91	1	1	1.11	0.96	1	1
27b-VP-3	10.05	1.12	0.91	1	1	1.12	0.95	1	1
27-VP-1	10.21	1.12	0.91	1	1	1.12	0.95	1	1
38-VP-3	13.49	1.16	0.88	1	1	1.16	0.94	1	1
42-VP-3	20.12	1.25	0.83	1	1	1.25	0.9	1	1
49a-VP-1	24.34	1.31	0.79	1	1	1.31	0.88	1	1
8-VP-1	24.56	1.31	0.79	1	1	1.31	0.88	1	1
38a-VP-1	25.77	1.33	0.78	1	1	1.33	0.87	1	1
38-VP-1	28.54	1.37	0.76	1	1	1.37	0.85	1	1
19-VP-1	30.67	1.4	0.74	1	1	1.4	0.84	1	1
8-VP-5	31.86	1.41	0.73	1	1	1.41	0.83	1	1
38-VP-2	32.31	1.42	0.72	1	1	1.42	0.82	1	1
26-VP-1	38.81	1.5	0.67	1	1	1.5	0.78	1	1
39-VP-1	42.96	1.56	0.63	1	1	1.56	0.75	1	1
8-VP-2	54.98	1.69	0.55	1	1	1.69	0.66	1	1

Table 19 shows the mortality multipliers used for simulations assuming that 100% of malformed metamorphs die (i.e., otherwise it is identical to Table 18).

TABLE 19

AGE CLASS- AND SEX-SPECIFIC MULTIPLIERS FOR MODEL PARAMETERS BASED ON THE RELATIONSHIP BETWEEN tPCBs AND MORTALITY ASSUMING THAT ALL MALFORMED FROGS DIE

Pool Name	SPATWGT Mean tPCBs	Female				Male			
		Age 0	Age 1	Age 2	Age 3	Age 0	Age 1	Age 2	Age 3
23b-VP-1	0.21	1	0.93	1	1	1	0.97	1	1
23b-VP-2	0.3	1	0.93	1	1	1	0.97	1	1
46-VP-5	1.36	1.01	0.92	1	1	1.01	0.97	1	1
46-VP-1	0.76	1.01	0.92	1	1	1.01	0.97	1	1
19-VP-7	0.82	1.01	0.92	1	1	1.01	0.97	1	1
8-VP-4	0.95	1.01	0.92	1	1	1.01	0.97	1	1
12-VP-1	1.72	1.02	0.91	1	1	1.02	0.97	1	1
23a-VP-1	3.04	1.03	0.9	1	1	1.03	0.96	1	1
40-VP-1	3.69	1.04	0.89	1	1	1.04	0.95	1	1
27b-VP-2	4.18	1.05	0.89	1	1	1.05	0.95	1	1
18-VP-2	4.9	1.06	0.88	1	1	1.06	0.95	1	1
66a-VP-1	5.31	1.06	0.88	1	1	1.06	0.94	1	1
18-VP-1	9.03	1.11	0.83	1	1	1.11	0.92	1	1
27b-VP-3	10.05	1.12	0.82	1	1	1.12	0.91	1	1
27-VP-1	10.21	1.12	0.81	1	1	1.12	0.91	1	1
38-VP-3	13.49	1.16	0.77	1	1	1.16	0.88	1	1
42-VP-3	20.12	1.25	0.66	1	1	1.25	0.81	1	1
49a-VP-1	24.34	1.31	0.59	1	1	1.31	0.76	1	1
8-VP-1	24.56	1.31	0.58	1	1	1.31	0.75	1	1
38a-VP-1	25.77	1.33	0.56	1	1	1.33	0.74	1	1
38-VP-1	28.54	1.37	0.51	1	1	1.37	0.7	1	1
19-VP-1	30.67	1.4	0.47	1	1	1.4	0.67	1	1
8-VP-5	31.86	1.41	0.45	1	1	1.41	0.66	1	1

3. MODELING RESULTS AND DISCUSSION

The wood frog population in the PSA was projected over a ten-year period in one-year time steps based on 1,000 replications of each projection. Two population projections were run, each with four combinations of assumptions regarding the impact of malformation on fertility and mortality, respectively. The first projection uses the life-table data from Berven (1990) for a single pond monitored over four years as a base model. The resulting population projection matrix results in a stable or moderately declining population size over the ten years of the simulation. This base model was compared to the following four impacted projections (1) impact 1: 100% of gonadally abnormal metamorphs sterile, 50% of malformed metamorphs die; (2) impact 2: 100% of gonadally abnormal metamorphs sterile, 100% of malformed metamorphs die; (3) impact 3: 50% of gonadally abnormal metamorphs sterile, 50% of malformed metamorphs die; and (4) impact 4: 50% of gonadally abnormal metamorphs sterile, 100% of malformed metamorphs die. The results of the first projection are shown in Figure 5 below.

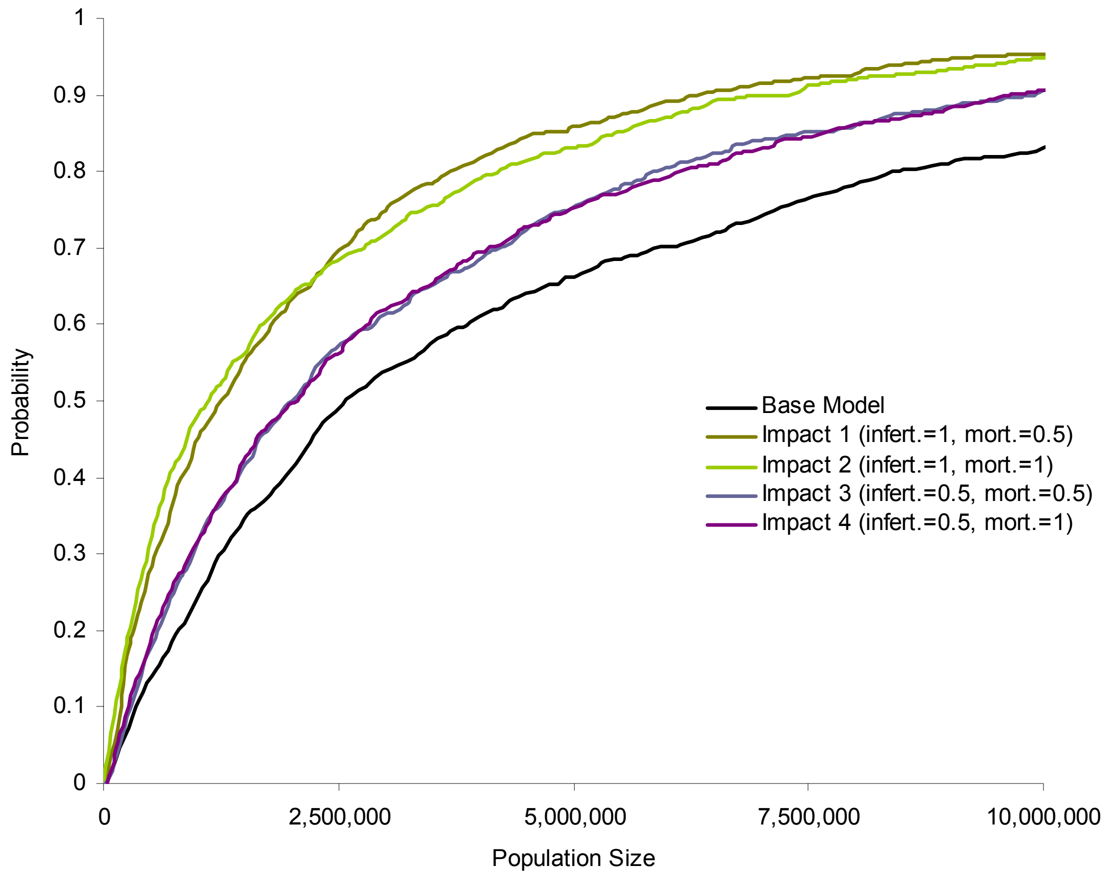

Figure 5. Comparison of Base Model and PCB-Impacted Wood Frog Population Projections Assuming a Stable Population (Note that population sizes include eggs, since the census is taken just after breeding). The estimated initial population size for the 27 pools in the PSA is approximately 3.8 million.

The lines graphed in the figures represent the means of the 1,000 simulations. In Figure 5, the lines indicate the probability that the population will fall at or below the population size on the x-axis. Higher probabilities of falling below a specified population size (towards the top left of the graph) imply higher probability of extinction. All four impact scenarios show a significantly increased risk of population decline compared to the unimpacted base model. Impacts naturally group by the severity of the effect of gonadal abnormalities on fertility. When only 50% of the females with gonadal abnormalities are sterile, the probability of the population size falling below 6.1 to 6.2 million (including eggs) is increased by 10 to 11%. When gonadal abnormalities are assumed most severe, the probability of the population dropping below 1 to 1.8 million increases by 22 to 24%. Note that the current population size estimated from PSA data was about 3.8 million. With no impact, the probability of falling below the current population size at the end of ten years was estimated by the base model to be about 65%. With the impact of tPCBs, the probability of falling below the current population size increases to between 67 and 80% (maximum differences and p-values associated with Kolmolgorov-Smirnov (KS) statistical tests between the base model and the various impacted models are shown in Table 20).

TABLE 20

MAXIMUM DIFFERENCES AND KS TESTS OF SIGNIFICANCE COMPARING FOUR PCB IMPACT SCENARIOS FOR MODELED STABLE WOOD FROG POPULATIONS

	Maximum difference (D)	p-value
Impact 1	0.223	0.0000
Impact 2	0.241	0.0000
Impact 3	0.109	0.0000
Impact 4	0.097	0.0002

The second projection used as a base model the life-table data from Berven (1990) for two ponds with environmental stochasticity adjusted to remove spatial variation while maintaining temporal variation. The resulting population projection matrix resulted in a declining population size over the ten years of the simulation. This base model was compared to the four impacted projections (see Figure 6).

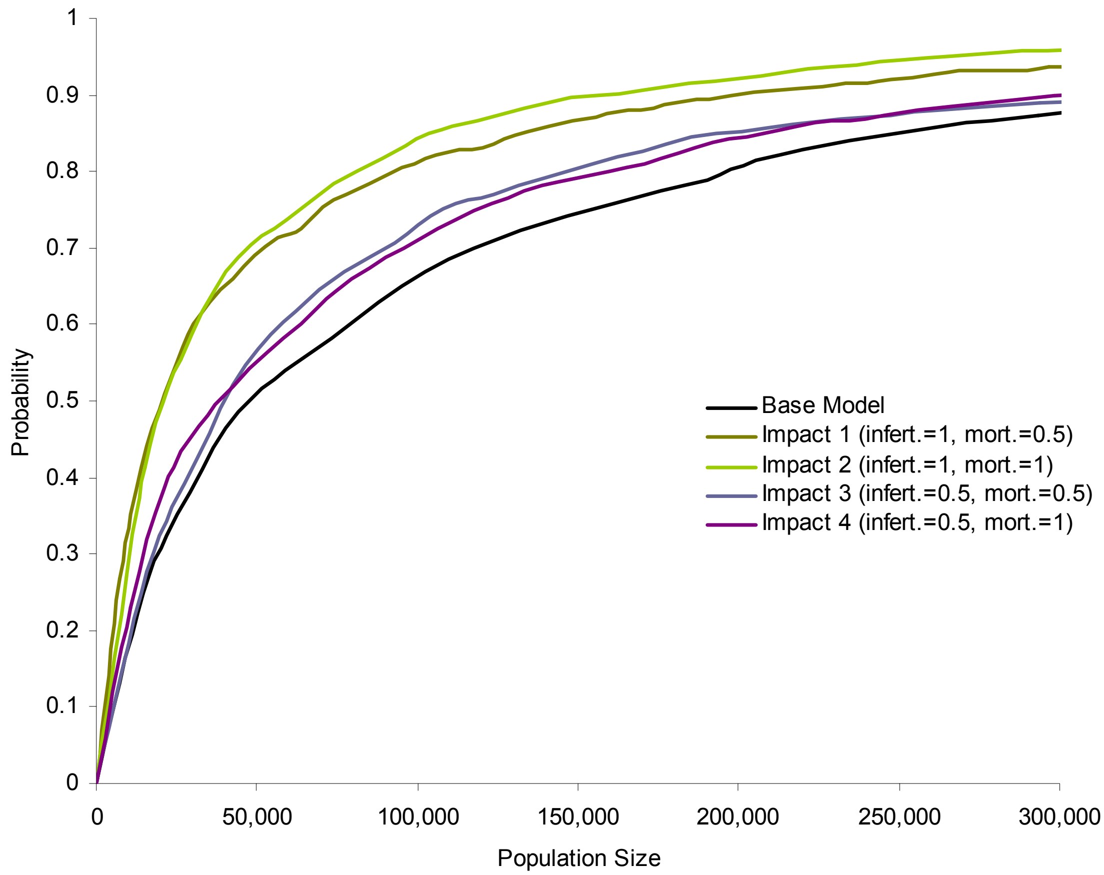

Figure 6. Comparison of Base Model and PCB-Impacted Wood Frog Population Projections Assuming a Declining Population (Note that population sizes include eggs, since the census is taken just after breeding).

Given the declining base model, the population projection indicates a 99.8% chance that the population will be smaller than it is now (i.e., smaller than 3.8 million) at the end of 10 years (not shown in Figure 6). The probability that the population will be 1/100th of its current size (about 38,000 on the graph) with no tPCB impact is about 45%. The effect of tPCB impacts is to increase this probability to as much as about 65%. Maximum differences and KS tests of significance are shown in the table below.

TABLE 21

MAXIMUM DIFFERENCES AND KS TESTS OF SIGNIFICANCE COMPARING FOUR PCB IMPACT SCENARIOS FOR MODELED DECLINING WOOD FROG POPULATIONS

	Maximum difference (D)	p-value
Impact 1	0.219	0.0000
Impact 2	0.209	0.0000
Impact 3	0.077	0.0053
Impact 4	0.078	0.0046

Another series of simulations was run using the same two projections and parameterizations to assess the amount of time before the population faces quasi-extinction (Ginzburg *et al.* 1982). The quasi-extinction threshold was set to a 95% or greater population decline from present levels. Figure 7 shows the results for projection 1. The risk of a 95% population decline is less than about 30% over the next ten years in all parameterizations. However, the actual risk varies considerably depending on the impact of tPCBs on population vital rates. In all cases, tPCBs decrease the time to extinction. The median time to extinction is decreased by between 2 and 14 years, depending on the specific parameterization.

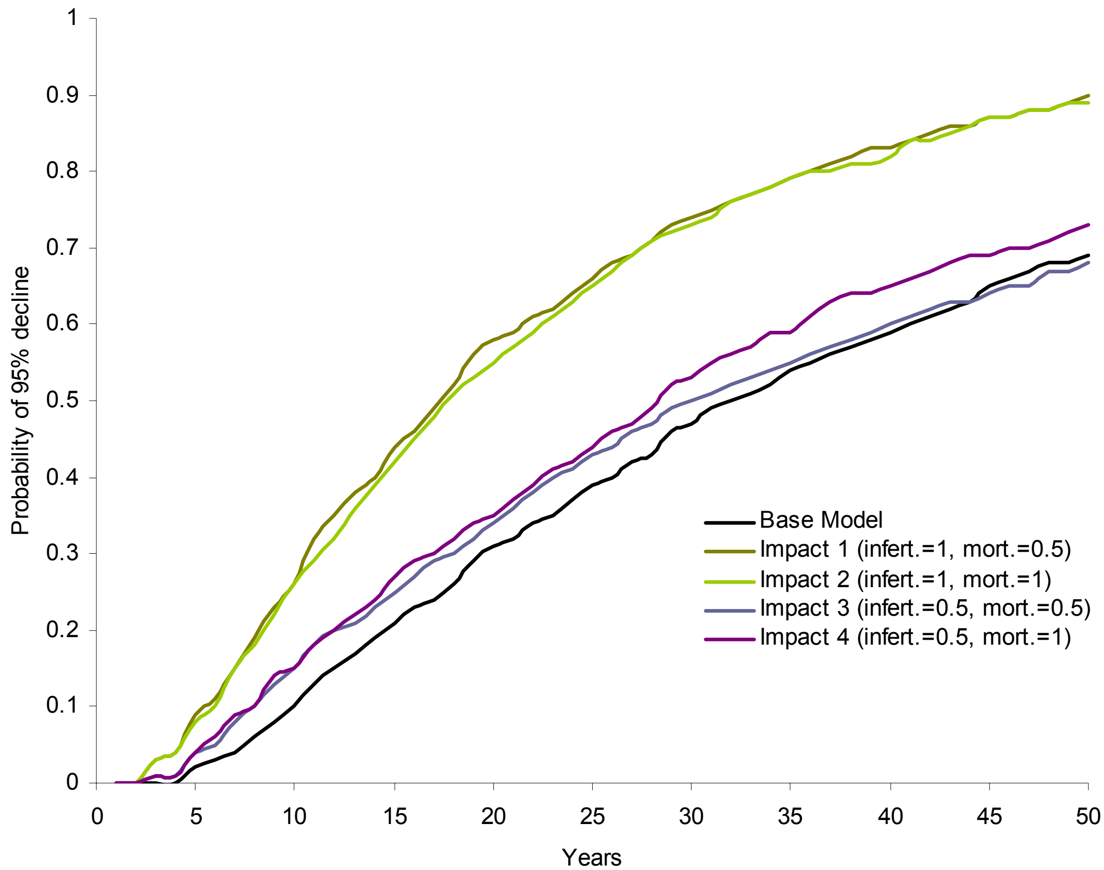

Figure 7. Time (in years) for the Population to Decline by 95%. Comparison of Base Model and PCB-Impacted Wood Frog Population Projections Assuming a Stable Population.

Figure 8 shows the results of the quasi-extinction study for projection 2, where the base population is already modeled as declining. The risk of a 95% population decline over the next ten years is more than 80% in all parameterizations. In all cases, tPCBs decrease the time to extinction. The median time to extinction is decreased by between 0.4 and 1.2 years, depending on the specific parameterization. Note that the model assumes the 27-pool population in the PSA is closed to immigration from the outside. This assumption allows for near certain population extinction over the 20 years. Were immigration to the PSA modeled, times to extinction would be lengthened.

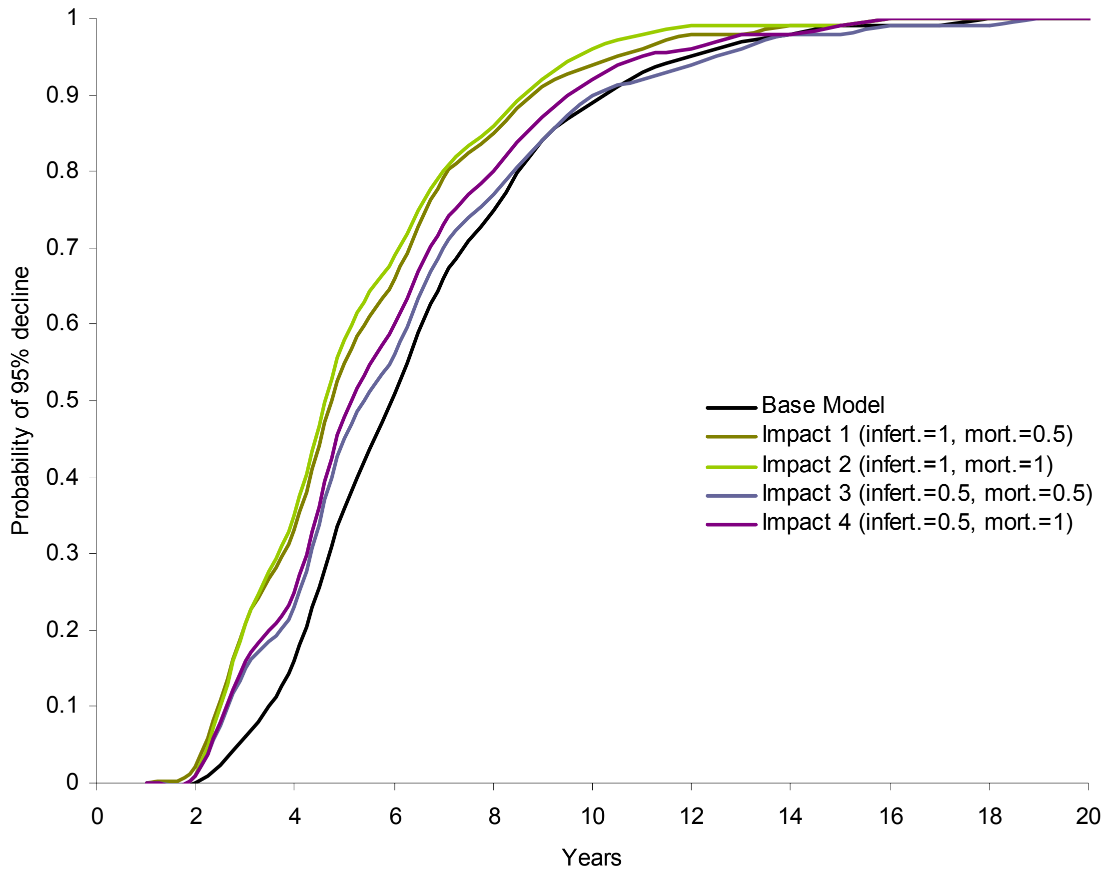

Figure 8. Time (in years) for the Population to Decline by 95%. Comparison of Base Model and PCB-Impacted Wood Frog Population Projections Assuming a Declining Population.

Figure 9 shows the percent by which the population in the PSA can be expected to decline over the next ten years for projection 1. The probability of a 75% reduction in abundance is just over 30% for the base model and higher for the two parameterization assuming that 100% of gonadal abnormalities lead to sterility. Note that because of the impact of tPCBs on the initial populations, the initial population size used for impacted parameterizations is smaller than that used for the base model. As a result, the percents by which the two parameterization assuming that 50% of gonadal abnormalities lead to sterility and the base model decline are similar, even though the absolute reduction in population size is greater for the impacted parameterizations.

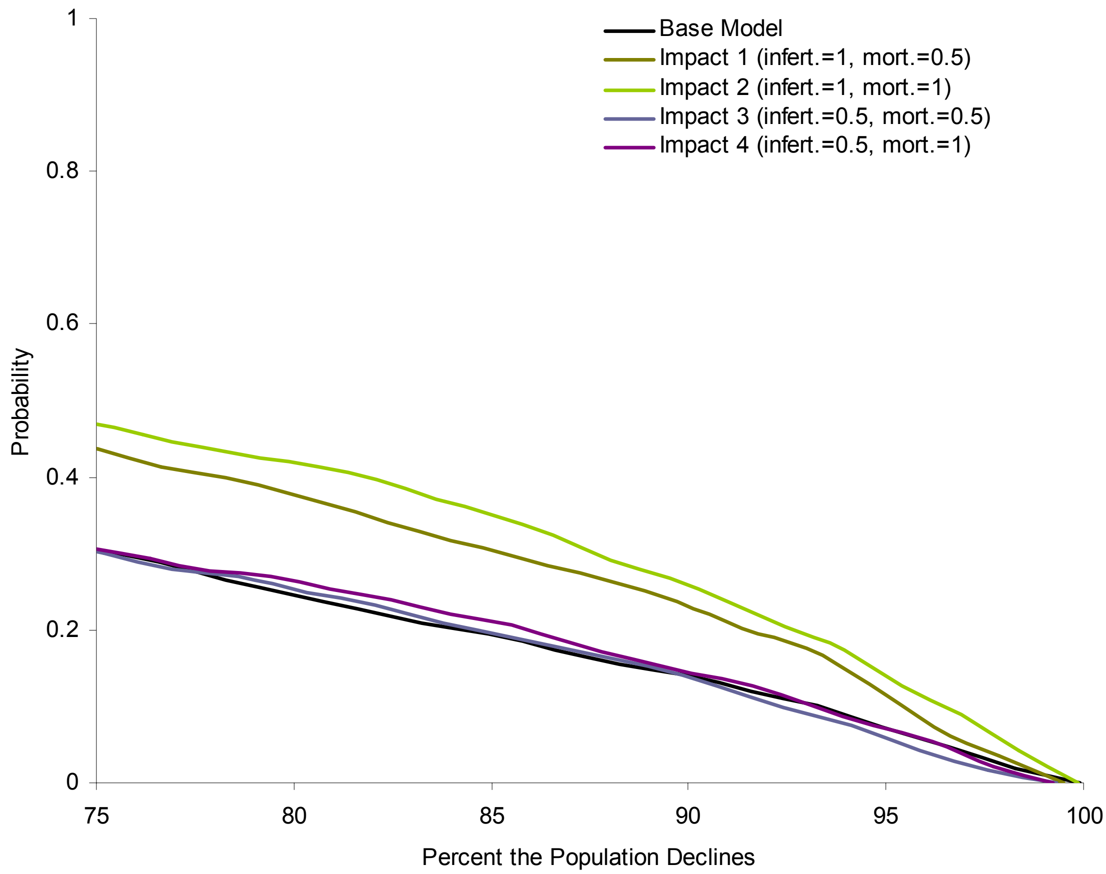

Figure 9. Percent by which the Population Declines over the Next Ten Years. Comparison of Base Model and PCB-Impacted Wood Frog Population Projections Assuming a Stable Population.

Figure 10 shows the percent by which the population in the PSA can be expected to decline over the next ten years for projection 2. With the declining base population, there is a near certainty of 75% decrease in abundance by the end of ten years. The parameterizations with the higher fertility impact are more likely to decline by greater percentages, while the parameterizations with the lower fertility impact are likely to decline by a percentage comparable to the base model. Because the impacted parameterizations start the ten years with an initial population size smaller than the base population, the absolute abundance at the end of ten years is less for all impacted parameterizations, however.

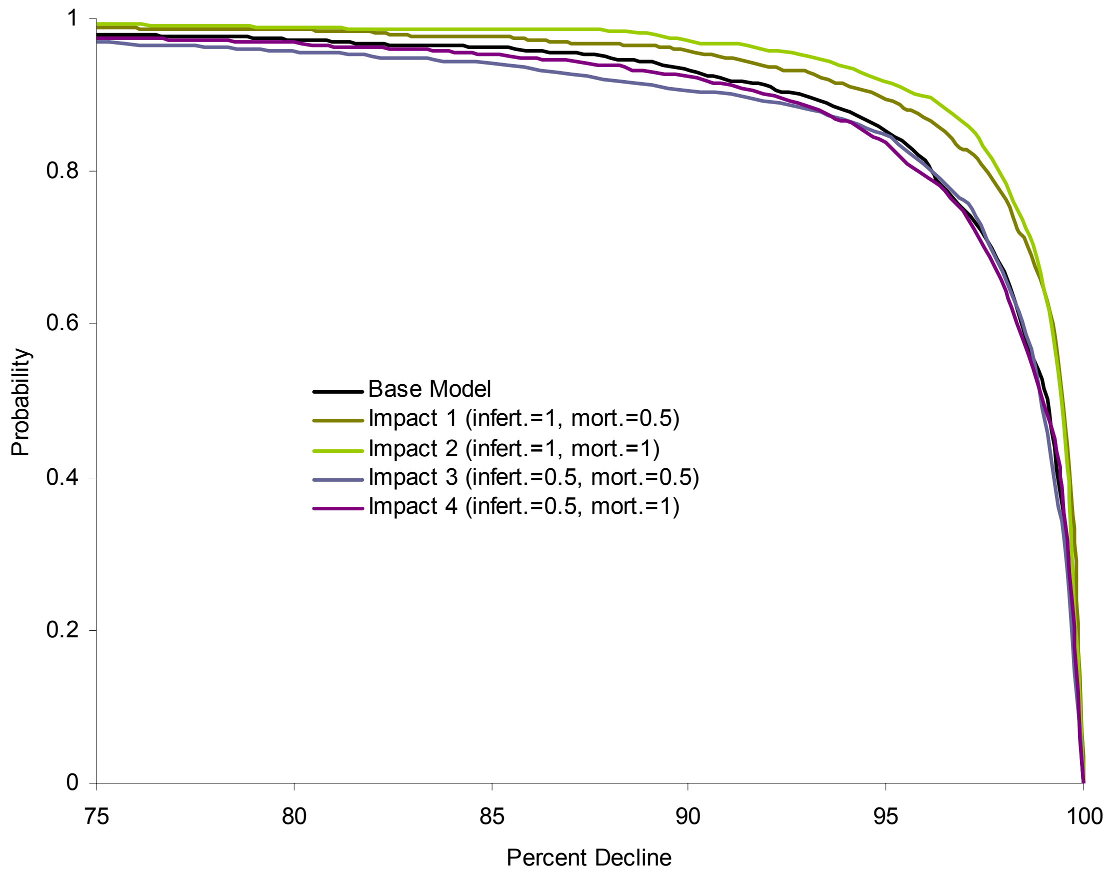

Figure 10. Percent by which the Population Declines over the Next Ten Years. Comparison of Base Model and PCB-Impacted Wood Frog Population Projections Assuming a Declining Population.

Expected minimum abundance at the end of ten years, average local extinction duration over ten years, and the expected median time to metapopulation extinction are summarized in Table 22. The expected minimum abundance (in millions of individuals, including eggs and larva), show the minimum over ten years. For projection 1, the impact of tPCBs reduces the minimum population size by at least half a million individuals and by as much as 850,000 individuals. A similar impact is seen with projection 2.

Average local extinction duration is the average time (in years) that individual vernal pools remain empty after a local extinction. In projection 1, no local extinctions are expected to occur;

however, in projection 2, where the base population is already declining, tPCB impacts increase the average maximum local extinction duration by up to one additional year.

Median time to extinction (in years) is the median number of years by which population abundance decreases by 95%. In projection 1, the base model exhibits a 32.2-year median. tPCB impacts decrease this median by between 2.2 and 14.8 years, depending on the parameterization. In projection 2, the base median time to extinction is 5.9 years, and tPCBs are seen to reduce the median.

TABLE 22

EXPECTED MINIMUM ABUNDANCE AT THE END OF TEN YEARS, AVERAGE LOCAL EXTINCTION DURATION OVER TEN YEARS, AND THE EXPECTED MEDIAN TIME TO METAPOPULATION EXTINCTION

	Base Model	Impact 1	Impact 2	Impact 3	Impact 4	Difference from base [min., max.]
Projection 1						
Expected minimum abundance (10^6 individuals)	1.64	0.79	0.81	1.10	1.04	[0.54, 0.85]
Average local extinction duration (years)	0	0	0	0	0	[0, 0]
Median time to extinction (years)	32.2	17.4	17.6	30.0	28.5	[2.2, 14.8]
Projection 2						
Expected minimum abundance (10^6 individuals)	0.13	0.06	0.06	0.10	0.10	[0.03, 0.07]
Average maximum local extinction duration (years)	1.11	2.11	1.52	1.11	1.22	[0, 1]
Median time to extinction (years)	5.9	4.8	4.7	5.5	5.2	[0.4, 1.2]

These results indicate an impact of tPCBs on wood frog population growth and abundance. tPCBs hasten population decline, reduce population numbers, and increase the likelihood of extinction. Data collected in the PSA provide field evidence supporting the population-level effects of tPCBs seen in the simulations. The relationship between sediment tPCB concentrations and adult male and female density shown in Figures 1 and 2 indicate that increased tPCB concentration leads to decreased density – particularly for adult females. It is notable that, even given the extremely small sample sizes, the negative relationships seen in the figures approach or are at the 0.05 level of statistical significance. Similarly, the relationship between tPCB concentration and number of egg masses counted per pool in the PSA shown in Table 7 is supportive of the population-level impacts seen in the simulations.

3.1 ASSUMPTIONS

Table 23 presents a summary of choices and assumptions made to produce the population model described above. Each assumption is marked with "O", indicating the assumption is likely to be optimistic and may understate the effect of PCBs on population decline, with "C", indicating the assumption is probably conservative and may overstate the effect of PCBs on population decline, or with "?", indicating that it is unclear whether the assumption is optimistic or conservative.

TABLE 23

ASSUMPTIONS MADE IN CONSTRUCTING WOOD FROG POPULATION MODELS FOR THE HOUSATONIC RIVER PSA

?	Age-structured model with yearly time step
?	Density-dependent model with ceiling carrying capacity
C	Vital rates cross-correlated by 0.5 within each time step
O	Omitted effect of PCBs on sex ratios
?	Time horizon of 10 years (terminal risk)
?	Housatonic data used to determine initial abundances
?	Data from Maryland population used to determine vital rates
?	Data from Virginia population used to determine dispersal
O	Assumed males could breed with up to 10 females
O	Modeled laboratory-observed effect showing tPCBs increase larval survival
?	Assumed gonadal abnormalities can cause sterility of 50-100%
?	Assumed malformation can cause death of 50-100%
C	Assumed no four year olds survive or breed
?	Assumed only zero year olds disperse
?	Corrected standard deviations of vital rates for declining population to remove spatial variability

4. LITERATURE CITED

Akçakaya, H.R. 2002 *RAMAS Metapop: Viability Analysis for Stage-structured Metapopulations* (Version 4.0). Applied Biomathematics, Setauket, New York.

Berven, K.A. 1990 Factors affecting population fluctuations in larval and adult stages of the wood frog (*Rana sylvatica*). *Ecology* 71(4)1599-1608.

Berven, K.A. and T.A. Grudzien 1990 Dispersal in the wood frog (*Rana sylvatica*): Implications for genetic population structure. *Evolution* 44(8):2047-2056.

Burgman, M.A., S. Ferson, and H.R. Akçakaya 1993 *Risk Assessment in Conservation Biology.* Chapman and Hall: London.

Caswell, H. 2001 *Matrix Population Models: Construction, Analysis, and Interpretation.* Sinauer Associates, Inc.: Sunderland, MA.

FEL (Fort Environmental Laboratories, Inc.) 2002 *Final Report – Frog Reproduction and Development Study. 2000 Rana sylvatica Vernal Pool Study.* Study protocol no.: WESR01-RSTS03-1. Prepared by Fort Environmental Laboratories, Inc., Stillwater, OK.

Ginzburg, L.R. and S. Ferson 1992 Assessing the effect of compensation on the risk of population decline and extinction. Chapter 19 in Smith, C.L. (ed.), *Estuarine Research in the 1980's: The Hudson River Environmental Society Seventh Symposium on Hudson River Ecology.* State University of New York Press: Albany. Pp. 392-403.

Ginzburg, L.R., L.B. Slobodkin, K. Johnson, and A.G. Bindman 1982 Quasiextinction probabilities as a measure of impact on population growth. *Risk Analysis* 2:171-181.

Glennemeier, K.A. and L.J. Begnoche 2002 Impact of organochlorine contamination on amphibian populations in Southwestern Michigan. *Journal of Herpetology* 36(2):233-244.

Woodlot Alternatives, Inc. 2002 Ecological Characterization of the Housatonic River. Prepared for U.S. Environmental Protection Agency.

Woodlot Alternatives, Inc. 2003 Amphibian Reproductive Success Within Vernal Pools Associated with the Housatonic River, Pittsfield to Lenoxdale, Massachusetts. Prepared for U.S. Environmental Protection Agency.