PART 5

LM FOOD CHAIN

Chapter 4. Description of Data, Constants, and Other Information Necessary to Run Model

5.4.1 Chemical Properties of PCB Contaminants

Polychlorinated biphenyls (PCBs) have been recognized as significant environmental contaminants since 1966 (Mullin *et al.*, 1984). Their impact is particularly evident in the Great Lakes basin (Neidermeyer and Hickey, 1976; Hesselberg *et al.*, 1990; Oliver *et al.*, 1989; Eisenreich *et al.*, 1989). In this modeling project, 40 PCB congeners or co-eluters were targeted for simulation of their individual bioaccumulation by fish in the lake. Most of the PCB congeners were selected for their abundance and bioaccumulative tendency in the lake ecosystem. Other PCB congeners were included to make the targeted PCB group cover the full range of PCB hydrophobicity, and thus, a better representative subset of all existing 209 PCB congeners.

Hydrophobicity of a PCB congener is measured by its octanol-water partition coefficient (K_{ow}) which is the most important chemical property governing bioaccumulation of the congener in organisms. Another important chemical property involved in modeling PCB contaminants is the organic carbon partition coefficient (K_{oc}) whose value can often be correlated to that of K_{ow}. In this work, the following empirical relationship (Eadie *et al.*, 1990) was used:

$$\log K_{oc} = 1.94 + 0.72 \log K_{ow} \qquad (5.4.1)$$

The targeted PCB congeners or co-eluter congeners are listed in Table 5.4.1 with their octanol-water partition coefficients K_{ow}. The values of K_{ow} are those of Hawker and Connell (1988). The molecular weight (MW) for each PCB congener is also listed for additional reference.

5.4.2 Site-Specific Data

5.4.2.1 Fish Food Web Structures

The structure of a food web shows how individual organisms in the food web are related to each other through feeding interactions. This dietary information is necessary for establishing appropriate linkages among individual submodels of a food web model and is important to the accurate simulation of chemical bioaccumulation in the food web.

The fish food webs of interest are those of two top predators in Lake Michigan, lake trout and coho salmon. These two species were selected for their important economic value. It is desirable to have a better understanding of the present and future concentrations of PCB contaminants in these two fish populations with the help of model simulations.

5.4.2.1.1 Lake Trout Food Web

It is believed that the lake trout in Lake Michigan are represented by three subpopulations at Sturgeon Bay, Sheboygan Reef, and Saugatuck (Figure 5.4.1). Movements of lake trout in Lake Michigan are believed to be considerably restricted in range (Brown *et al.*, 1981). Each of the lake trout subpopulations has a site-specific food web structure.

Table 5.4.1. Targeted PCB Congeners and Their K_{ow}

Congener	IUPAC	Homolog	Molecular Weight	log K_{ow}
	0	0	154	4.09
4	3	1	188	4.69
2,3	5	2	223	4.97
2,4'	8	2	223	5.07
3,4	12	2	223	5.22
3,4'	13	2	223	5.29
4,4'	15	2	223	5.3
2,4',4	17	3	257	5.25
2,2',3	16	3	257	5.16
2,4',6	32	3	257	5.44
2,2',5	18	3	257	5.24
2,3',5	26	3	257	5.66
2,4,4'	28	3	257	5.67
2,4',5	31	3	257	5.67
2',3,4	33	3	257	5.6
3,4,4'	37	3	257	5.83
2,2',3,4'	42	4	292	5.76
2,2',3,5'	44	4	292	5.75
2,2'4,5'	49	4	292	5.85
2,2',5,5'	52	4	292	5.84
2,3,3',4'	56	4	292	6.11
2,3,4,4'	60	4	292	6.11
2,3',4,4'	66	4	292	6.2
2,3',4',5	70	4	292	6.2
2',3,4,5	76	4	292	6.13
2,4,4',5	74	4	292	6.2
3,3',4,4'	77	4	292	6.36
2,3,3',4',6	110	5	326	6.48
3,4,4',5	81	4	292	6.36
2,2',3,4,5'	87	5	326	6.29
2,2',3,3',6	84	5	326	6.04
2,2',3,5,5'	92	5	326	6.35
2,2',3,4,6'	89	5	326	6.07
2,2',3,4,4'	85	5	326	6.3
2,2',4,4',5	99	5	326	6.39
2,2',4,5,5'	101	5	326	6.38
2,3',4,4',5	118	5	326	6.74
2',3,4,4',5	123	5	326	6.74
2,2',3,4',5',6	149	6	361	6.67
2,3,3',4,4'	105	5	326	6.65
2,2',3,3',4,6'	132	6	361	6.58
2,2',4,4',5,5'	153	6	361	6.92
2,2',3,5,5',6	151	6	361	6.64
2,2',3,4,4',5'	138	6	361	6.83
2,3,3',4',5,6	163	6	361	6.99
2,2',3,4',5,5'	146	6	361	6.89
2,2',3,3',4,4',5	170	7	395	7.27

Table 5.4.1. Targeted PCB Congeners and Their K_{ow} (Continued)

Congener	IUPAC	Homolog	Molecular Weight	log K_{ow}
2,3,3',4,4',5,6'	190	7	395	7.46
2,2',3,3',4,5,5'	172	7	395	7.33
2,2',3,3',4,4',6,6'	197	8	430	7.3
2,2',3,4,4',5,5'	180	7	395	7.36
2,2',3,4,4',5,6'	182	7	395	7.2
2,2',3,4',5,5',6	187	7	395	7.17
2,2',3,3',4,4',5,6	195	8	430	7.56
2,2',3,3',4,5,5',6,6'	208	9	464	7.71
2,2',3,3',4,4',5',6	196	8	430	7.65
2,2',3,4,4',5,5',6	203	8	430	7.65
2,2',3,3',4',5,5',6	201	8	430	7.62

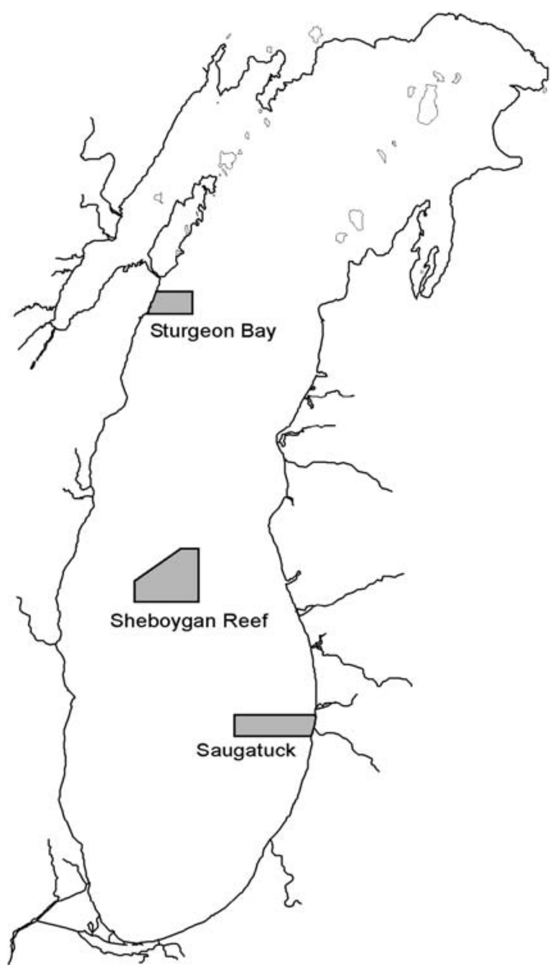

Figure 5.4.1. Biota zones in Lake Michigan.

For each lake trout subpopulation, the food web was constructed using dietary data compiled from field sampling of lake trout and associated forage fish population. Lake trout (*Salvelinus namaycush*) were caught at the three locations during the spring, summer, and fall of 1994 and 1995. They were primarily captured *via* gill netting at depths ranging from 9 to 40 m. A minor portion of trout was captured by bottom trawling. Bottom trawling was used at depths of 10 to 50 m to obtain forage fish. Prey fish included alewife (*Alosa pseudoharengus*), rainbow smelt (*Osmerus mordax*), bloater (*Coregonus hoyi*), slimy sculpin (*Cottus cognatus*), and deepwater sculpin (*Myoxocephalus thompsoni*). The diets of lake trout and forage fish were determined by stomach analysis following a standard operating procedure established for the Lake Michigan Mass Balance Project (LMMBP) (U.S. Environmental Protection Agency, 1997a). For lake trout, the diet components were further classified into age classes.

The organisms in the base of Lake Michigan fish food webs are zooplankton, *Mysis*, and *Diporeia*. Their dietary information was obtained from literature sources. *Mysis* are reported to feed on zooplankton, phytoplankton, and "fresh" detrital material at the sediment surface and suspended in the water column (Beeton and Bowers, 1982; Grossnickle, 1982). Zooplankton are believed to feed on organic-rich particles, mainly phytoplankton in the water column (Peters and Downing, 1984). *Diporeia* are reported to feed on relatively "fresh" detrital material at the sediment surface (Evans *et al*., 1990; Gardner *et al*., 1990; Johnson, 1987; Lydy and Landrum, 1993; Marzolf, 1965; Quigley, 1988; Quigley and Vanderploeg, 1991).

Annual average dietary data for lake trout and its forage populations in the three biota zones of the lake are summarized in Tables 5.4.2a through 5.4.7. These data were used to construct a complete food web structure for each of the three lake trout populations in Lake Michigan.

5.4.2.1.2 Coho Salmon Food Web

The coho salmon in Lake Michigan are believed to move around large portions of the lake during the fish's lifetime (Patriarche, 1980). They were modeled as a single lake-wide population. The dietary information of the coho salmon was compiled from field sampling. Coho salmon (*Oncorhynchus kisutch*) were sampled from angler's catches at various locations of the lake from May to November in 1994 and April to November in 1995.

The diet of coho salmon was determined by stomach analysis following a standard operating procedure established for the LMMBP (Elliott *et al*., 1996; Elliott and Holey, 1998; U.S. Environmental Protection Agency, 1997a). The prey species were further classified into age classes. The results are presented in Table 5.4.8.

Due to their extensive movement, coho salmon in the lake may encounter site-specific forage populations in different regions. This means that a given forage species in the coho salmon diet may belong to different subpopulations. The forage fish may have a location-dependent dietary history. Therefore, the food web structure below the top trophic level can vary with the movement of coho salmon. In order to construct an accurate food web structure for coho salmon in Lake Michigan, information on its migration pattern and food web structures of its forage populations in related locations is needed. The migration pattern of the coho salmon was established based on a general index of fish density, catch-per-unit-of-effort (CPE), in various locations on a monthly basis. In general, the fish aggregate in southern Lake Michigan during spring and travel to the southwestern region of the lake in summer. In the late summer and early autumn, most of the coho salmon are found in the northeastern region of the lake. They move back to the southeastern region during the winter. However, dietary information for forage fish in these locations were not readily available. Therefore, it was not possible to construct a comprehensive food web structure for coho salmon that reflects the seasonal or spatial variation of its forage food webs.

The most complete dietary information for forage fish was that collected from the Sturgeon Bay, Sheboygan Reef, and Saugatuck lake trout biota zones (Tables 5.4.3 through 5.4.7). In this study, these dietary data were used to construct three local food web structures for the coho salmon by linking each of them with the dietary data of the coho salmon as presented in Table 5.4.8.

Table 5.4.2a. Annual Dietary Composition of Lake Trout at Saugatuck (1994-1995)

Lake Trout Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	Slimy Sculpin	Deepwater Sculpin	*Diporeia*	*Mysis*
Age 1	Age 1				20		20	
	Age 2				20			
	Age 3				20			
	Age 4							
	Age 5				20			
Age 2	Age 1	35						
	Age 2	5	20			40		
Age 3	Age 1	10	20		10			
	Age 2		20					
	Age 3		30					
	Age 4				10			
Age 4	Age 2	5	25	10				
	Age 3	10	25					
	Age 4			25				
Age 5	Age 2	5						
	Age 3	10	20			15		
	Age 4	10		40				
Age 6	Age 2	10	5					
	Age 3	20						
	Age 4	10	5	20				
	Age 5							
	Age 6	20		10				
Age 7	Age 3	15						
	Age 4	15		30				
	Age 5	10						
	Age 6			30				
Age 8	Age 3	10						
	Age 4	20		15				
	Age 5			20				
	Age 6	20		10				
	Age 7	5						
Age 9	Age 4	20						
	Age 5			30				
	Age 6	20		10				
	Age 7	20						
Age 10	Age 2		10					
	Age 3	10						
	Age 4	15	15	10				
	Age 5			10				
	Age 6	30						

Table 5.4.2a. Annual Dietary Composition of Lake Trout at Saugatuck (1994-1995) (Continued)

Lake Trout Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	Slimy Sculpin	Deepwater Sculpin	*Diporeia*	*Mysis*
Age 11	Age 3	10						
	Age 4			30				
	Age 5			25				
	Age 6	10						
	Age 7			25				
Age 12	Age 1		5					
	Age 2							
	Age 3	10						
	Age 4							
	Age 5	20		15				
	Age 6		10	30				
	Age 7	10						

Table 5.4.2b. Annual Dietary Composition of Lake Trout at Sheboygan Reef (1994-1995)

Lake Trout Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	Slimy Sculpin	Deepwater Sculpin	*Diporeia*	*Mysis*
Age 1	Age 1	85					15	
Age 2	Age 1	80				10	5	5
Age 3	Age 1	55						
	Age 2							45
Age 4	Age 1	20						
	Age 2	20				10		20
	Age 3	10						
	Age 4			10				
	Age 5			10				
Age 5	Age 1	20						
	Age 2	15						10
	Age 3	15						
	Age 4	10		20				
	Age 5							
	Age 6			10				
Age 6	Age 2	30		10				
	Age 3	20						
	Age 4	10						
	Age 5	10		20				

Table 5.4.2b. Annual Dietary Composition of Lake Trout at Sheboygan Reef (1994-1995) (Continued)

Lake Trout Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	Slimy Sculpin	Deepwater Sculpin	*Diporeia*	*Mysis*
Age 7	Age 2	35						
	Age 3	25						
	Age 4	10		15				
	Age 5	15						
Age 8	Age 2	20						
	Age 3	5						
	Age 4	20		20				
	Age 5	15		20				
Age 9	Age 2	10						
	Age 3	15						
	Age 4	30						
	Age 5	20		10				
	Age 6			15				
Age 10	Age 2	5						
	Age 3	20						
	Age 4			15				
	Age 5	40		10				
	Age 6			10				
Age 11	Age 2	5						
	Age 3							
	Age 4	20		15				
	Age 5			20				
	Age 6	20		20				
Age 12	Age 2	10						
	Age 3	10						
	Age 4	15						
	Age 5	10		20				
	Age 6	10						
	Age 7			25				

Table 5.4.2c. Annual Dietary Composition of Lake Trout at Sturgeon Bay (1994-1995)

Lake Trout Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	Slimy Sculpin	Deepwater Sculpin	*Diporeia*	*Mysis*
Age 1	Age 1	85					15	
Age 2	Age 1	80				10	5	5
Age 3	Age 1	45	5					
	Age 2	10	5		10			
	Age 3		5		20			
Age 4	Age 1	30						
	Age 2		20					
	Age 3	10	30					
	Age 4	10						
Age 5	Age 1	30						
	Age 2		15					
	Age 3	15	15					
	Age 4	10	15					
Age 6	Age 1	10	5					
	Age 2							
	Age 3	20	10					
	Age 4							
	Age 5							
	Age 6	30		10				
	Age 7	15						
Age 7	Age 2	30	5					
	Age 3	20	5					
	Age 4	20						
	Age 5	10						
	Age 6							
	Age 7	10						
Age 8	Age 2	10	15					
	Age 3	20						
	Age 4	25						
	Age 5		5					
	Age 6	10		10				
	Age 7	5						
Age 9	Age 3	10	10					
	Age 4	30						
	Age 5		10	10				
	Age 6	20						
	Age 7	10						

Table 5.4.2c. Annual Dietary Composition of Lake Trout at Sturgeon Bay (1994-1995) (Continued)

Lake Trout Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	Slimy Sculpin	Deepwater Sculpin	*Diporeia*	*Mysis*
Age 10	Age 2		5					
	Age 3	15	5					
	Age 4	20						
	Age 5	25	5	5				
	Age 6							
	Age 7	20						
Age 11	Age 2		5					
	Age 3	15						
	Age 4	20						
	Age 5	35	5					
	Age 6							
	Age 7	20						
Age 12	Age 2	15						
	Age 3	25						
	Age 4	10						
	Age 5	25		25				

Table 5.4.3. Dietary Composition of Alewife in Lake Michigan (1994-1995)

	Prey	Saugatuck (0 - < 75 m)	Sturgeon Bay (0 - ~ 100 m)	Sheboygan Reef (50 - 75 m)
Small: Fish Length < 120 mm				
Age 1-2	*Diporeia*	10	45	40
	Mysis			
	Zooplankton	90	55	60
Large: Fish Length > 120 mm				
Age 3-7	*Diporeia*	10	75	20
	Mysis			50
	Zooplankton	90	25	30

Table 5.4.4. Dietary Composition of Bloater in Lake Michigan (1994-1995)

	Prey	Saugatuck (0 - < 75 m)	Sturgeon Bay (0 - ~ 100 m)	Sheboygan Reef (50 - 75 m)
Small: Fish Length <= 160 mm				
Age 1-3	*Diporeia*	80	100	35
	Mysis	20		35
	Zooplankton			30
Large: Fish Length (g) > 160 mm				
Age 4-7	*Diporeia*	75	70	25
	Mysis	25	30	75
	Zooplankton			

Table 5.4.5. Dietary Composition of Rainbow Smelt in Lake Michigan (1994-1995)

	Prey	Saugatuck (0 - < 75 m)	Sturgeon Bay (0 - ~ 100 m)	Sheboygan Reef (50 - 75 m)
All Ages	*Diporeia*		10	
	Mysis	65	90	60
	Zooplankton	35		40

Table 5.4.6. Dietary Composition of Slimy Sculpin in Lake Michigan (1994-1995)

	Prey	Saugatuck (0 - < 75 m)	Sturgeon Bay (0 - ~ 100 m)	Sheboygan Reef (50 - 75 m)
All Ages	*Diporeia*	90	80	90
	Mysis	10	20	10

Table 5.4.7. Dietary Composition of Deepwater Sculpin in Lake Michigan (1994-1995)

	Prey	Saugatuck (0 - < 75 m)	Sturgeon Bay (0 - ~ 100 m)	Sheboygan Reef (50 - 75 m)
All Ages	*Diporeia*	70	45	80
	Mysis	30	55	20

Table 5.4.8. Dietary Composition of Coho Salmon in Lake Michigan (1994-1995)

Coho Salmon Age	Forage Fish Age	Alewife	Rainbow Smelt	Bloater	*Diporeia*	*Mysis*
Age 1	Age 1	40	10	10		
	Age 2	40				
Age 2	Age 1	25				
	Age 2	10				
	Age 3	20	5			
	Age 4	20				
	Age 5	10				
	Age 6					
	Age 7	10				

5.4.2.2 Fish Growth Rates

At a given body weight, W, fish growth rate, G, can be written as:

$$G = (dw/dt)/W \tag{5.4.2}$$

where

(dw/dt) = the derivative of fish weight W with respect to fish age t

With a set of weight-age data of a fish available, the average value for the fish growth rate for a given period of time can then be estimated by the following equation:

$$G = ln(W_1 / W_o)/(t_1 - t_o) \tag{5.4.3}$$

where

W_1 = fish weight (g) at age t_1 (day)

W_o = fish weight (g) at age t_0 (day)

G = fish average growth rate during age t_0 to t_1

The weight-age data for fish species in the food webs were obtained from field sampling conducted in 1994-1995 by the Great Lakes National Program Office (GLNPO) for the LMMBP. The methods of fish collection are described in Section 4.2.1. Each fish was weighed to the nearest gram. The lake trout and coho salmon were aged based on either decoding the information on a coded-wire tag (if found) or enumeration of annuli on scales in conjunction with use of fin clip information. More details on the fish aging procedure can be found in Lake Michigan Mass Balance Study Methods Compendium (U.S.

Environmental Protection Agency, 1997a) and Madenjian *et al*. (1998a, 1999). Forage fish were aged based on lengths and weights taken from the literature, and compared to the length and weight data collected for each of the fish species in this study.

A general relationship between age and weight for each fish was established through regression of the large amount of field data. The age-weight relationships for the lake trout in three biota zones, the migratory coho salmon, and their forage fish populations are presented in Tables 5.4.9a through 5.4.9c. Age-weight relationships for forage fish exhibit no regional variation, and a lake-wide average was obtained for each forage species. The results in Tables 5.4.9a, 5.4.9b, and 5.4.9c were used to estimate fish growth rates in the food web models.

The weight-age relationship for *Mysis* was estimated based on information from literature sources (Brafield and Llewellyn, 1962; Pothoven *et al*., 2000). The results are presented in Table 5.4.9d.

A constant value of 0.10 (1/day) was adapted as the average growth rate for zooplankton in the lake (Connolly *et al*., 1992).

5.4.2.3 Energy Density of Food Web Components

In a bioenergetics-based food web model, energy balance is the basis for estimating chemical fluxes between fish and its prey species. It is, therefore, important to have a good knowledge of the energy content of the fish and its prey items.

Energy densities, D, of all fish species in this study were estimated based on lipid and protein fractions in individual organisms (Lucas, 1996).

$$D = 35.5\, f_L + 20.08\, f_{pr} \tag{5.4.4}$$

The terms f_L and f_{pr} are lipid and protein fractions in the fish body, respectively. The energy equivalents of lipid components (kJ/g) is 35.5, and the energy equivalents of protein components (kJ/g) is 20.08. The standard value of energy equivalent for protein is 23.4 kJ/g-protein (Cho *et al*., 1982). It was adjusted to a lower value of 20.08 kJ/g-protein because after digestion, a portion of energy in the assimilated protein is lost by nitrogenous excretion and is not available for further respiration. Energy contributions from other body components of a fish, such as carbohydrates, are negligible (Diana, 1995).

Fish lipid content was analyzed by extracting homogenized fish composite with 100 mL of 90/10 (v:v) petroleum ether/ethyl acetate. The extract was then evaporated and the residue was weighed as extractable lipid. Detailed procedures for fish lipid separation and determination are available in the Lake Michigan Mass Balance Study Methods Compendium (U.S. Environmental Protection Agency, 1997b) and Madenjian *et al* (2000). The values of protein fraction in the lake trout, coho salmon, and the other fish were compiled from or estimated based on various literature sources (Flath and Diana, 1985; Foltz and Norden, 1977; Gardner *et al*., 1985; Rottiers and Tucker, 1982; Schindler *et al*., 1971; Vijverberg and Frank, 1976). The lipid and protein fractions used for estimating energy content for all organisms in this study are compiled in Tables 5.4.10a through 5.4.10h.

5.4.2.4 Exposure Conditions

Environmental conditions to which fish are exposed play an important part in determining chemical exchange fluxes between a fish and its environment. Among the model parameters which characterize the environmental conditions for food webs, contaminant levels in water and sediment have direct influence on the contaminant level in exposed fish food webs, and temperature and oxygen content of the exposure environment regulate the chemical kinetics in fish food webs.

Due to the variation in Lake Michigan water characteristics, the exposure condition is different among fish food webs in different biota zones. To facilitate model calculations for fish food webs at Sturgeon Bay, Sheboygan Reef, and Saugatuck, exposure information for each of these three biota zones was required. Exposure data used are summarized here. All data for the LMMBP are available upon request to the GLNPO.

Table 5.4.9a. Average Weight-Age Relationships for Lake Trout in Lake Michigan (1994-1995)

Age	Sheboygan Reef Weight (g)	Saugatuck Weight (g)	Sturgeon Bay Weight (g)
1	20	90	98
2	128	180	120
3	244	550	350
4	490	1100	800
5	900	2050	1500
6	1378	2850	2700
7	1900	3400	3200
8	2600	4000	3700
9	3400	4500	4400
10	4000	5400	5000
11	4400	6500	5500
12	4700	6900	5600
13	4900	7100	5800
14	5200	7100	6000

Table 5.4.9b. Average Weight-Age Relationships for Coho Salmon in Lake Michigan (1994-1995)

Age	Day	Weight (g)
1	90	30
	122	80
	152	140
	183	220
	214	322
	244	450
	274	620
	304	878
	335	880
	366	885
2	30	890
	60	895
	90	900
	121	1400
	151	1850
	183	2190
	214	2450
	244	2670
	274	2860
	304	3050

Table 5.4.9c. Average Weight-Age Relationships of Forage Fish in Lake Michigan (1994-1995)

Age	Alewife Weight (g)	Bloater Weight (g)	Rainbow Smelt Weight (g)	Slimy Sculpin Weight (g)	Deepwater Sculpin Weight (g)
1	3	3.7	5.3	0.6	0.6
2	15	12	8	1.2	1.8
3	27	26	13	2.2	3.5
4	37	38	19	4.6	7
5	45	50	22	8.4	13
6	50	65	25	10	19
7	53	88	28	10.6	24
8	55	110	30		29
9			32		34
10			34		38
11					40

Table 5.4.9d. Estimated Weight-Age Relationships of *Mysis* in Lake Michigan

Month	Weight (g-wet) Sturgeon Bay	Weight (g-wet) Sheboygan Reef	Weight (g-wet) Saugatuck
0	0.00019	0.00001	0.00001
4	0.00194	0.00061	0.00095
8	0.00893	0.00330	0.00537
12	0.01691	0.00910	0.01706
16	0.03336	0.01860	0.04123

Table 5.4.10a. Average Lipid and Protein Fractions (%) of Lake Trout in Lake Michigan (1994-1995)

Age	Sheboygan Reef	Sturgeon Bay	Saugatuck	Protein %
1	2.3	4.8	2.3	17.37
2	3.66	4.68	3.66	
3	7.9	9.21	7.13	
4	9.36	11.81	9.52	
5	12.48	17.04	14.77	
6	15.56	18.3	18.96	
7	18.6	19.13	21.05	
8	19.36	20.52	18.56	
9	19.34	20.15	19.12	
10	19.1	22.63	20.68	
11	20.73	22.5	22	
12	22.4	20.53	23	
13	20.2	20.9	21.7	
14	20.1	21.4	19.7	
15		22.4	30.6	

Table 5.4.10b. Average Lipid and Protein Fractions (%) of Coho Salmon in Lake Michigan (1994-1995)

Age	Day	Lipid %	Protein %
1	90	5.14	20.00
	122	5.25	
	152	5.37	
	183	5.54	
	214	5.75	
	244	6.01	
	274	6.36	
	304	6.90	
	335	6.90	
	366	6.91	
2	30	6.92	
	60	6.93	
	90	6.94	
	121	7.98	
	151	8.91	
	183	9.61	
	214	10.15	
	244	10.61	
	274	11.00	
	304	11.39	

Table 5.4.10c. Average Lipid and Protein Fractions (%) of Alewife in Lake Michigan (1994-1995)

Age	Sheboygan Reef	Saugatuck	Sturgeon Bay	Protein %
1	7.2	5.5	4	16.7
2	8.5	5.5	6	
3	9	6	6	
4	10.5	7.5	6	
5	11.5	9	6	
6	12	10	6	
7	12.2	11	6	
8	12.5	12	6	

Table 5.4.10d. Average Lipid and Protein Fractions (%) of Bloater in Lake Michigan (1994-1995)

Age	Sheboygan Reef	Saugatuck	Sturgeon Bay	Protein %
1	5	4	5	16.3
2	5.5	4.5	7	
3	8	5.5	8.5	
4	11	6.5	9.5	
5	12	7.5	12.5	
6	12.5	8.5	13.5	
7	13	10.5	14.5	
8	13.5	11	15.5	

Table 5.4.10e. Average Lipid and Protein Fractions (%) of Rainbow Smelt in Lake Michigan (1994-1995)

Age	Sheboygan Reef	Saugatuck	Sturgeon Bay	Protein %
1	4.4	3.5	3	16.9
2	4.4	3.5	3	
3	4.4	3.5	3	
4	4.4	3.5	3	
5	4.4	3.5	3	
6	4.4	3.5	3	
7	4.4	3.5	3	
8	4.4	3.5	3	
9	4.4	3.5	3	
10	4.4	3.5	3	

Table 5.4.10f. Average Lipid and Protein Fractions (%) of Slimy Sculpin in Lake Michigan (1994-1995)

Age	Sheboygan Reef	Saugatuck	Sturgeon Bay	Protein %
1	6.4	3.5	8	15.9
2	6.5	4	8.1	
3	6.6	4.5	8.2	
4	6.8	5	8.3	
5	7.1	5.2	8.4	
6	7.2	5.2	8.5	
7	7.3	5.2	8.5	

Table 5.4.10g. Average Lipid and Protein Fractions (%) of Deepwater Sculpin in Lake Michigan (1994-1995)

Age	Sheboygan Reef	Saugatuck	Sturgeon Bay	Protein %
1	8.8	2	7	14.4
2	8.9	3	7.1	
3	9	4	7.2	
4	9.1	5	7.3	
5	9.4	5.5	7.5	
6	9.7	6	7.7	
7	9.9	7	7.8	
8	10.1	7.2	7.9	
9	10.3	7.2	8	
10	10.5	7.5	8.1	
11	10.6	7.5	8.2	

Table 5.4.10h. Average Lipid and Protein Fractions (%) of Zooplankton, *Mysis,* and *Diporeia* in Lake Michigan (1994-1995)

Species	Sheboygan Reef	Saugatuck	Sturgeon Bay	Protein %
Zooplankton	2.91	2.79	1.57	7.1
Mysis	2.31	1.61	2.9	7
Diporeia	3.21	1.66	4.48	10

5.4.2.4.1 PCB Concentrations in Water

Lake Michigan water and particulate samples were collected at several stations within the Sturgeon Bay, Sheboygan Reef, and Saugatuck biota zones. Information regarding the sampling stations, collection procedures, sample preparation, and methods for PCB analysis are available in detail (U.S. Environmental Protection Agency, 1997a, 1997b). The organic carbon fraction in the suspended particles was also analyzed. The analysis procedures can also be found in the above documents.

No temporal variation of PCB concentrations was found for samples collected during 1994 and 1995. PCB concentrations in suspended particles were organic carbon normalized. There was substantial variation of PCB concentrations in suspended particles among samples collected from different water depths. No substantial vertical variation was found for PCBs in the dissolved form. PCBs in suspended particles were divided into those collected at depth < 20 m and those collected at depth > 20 m. For this study, it was assumed that the fish food webs were exposed to particulate PCB concentrations in the deeper layer. Median values for dissolved PCBs and those associated with suspended particles were used for model calibration. The PCB concentrations in the water column of the three biota zones are given in Table 5.4.11.

5.4.2.4.2 PCB Concentrations in Sediment

Sediment sampling was not specifically conducted within the three biota zones. Sediment PCB concentrations in the three biota zones were

Table 5.4.11. PCB Concentrations in Lake Michigan Water Column (1994-1995)

	Sturgeon Bay		Sheboygan Reef		Saugatuck	
PCB Congeners	**Dissolved (ng/L)**	**Particulate (ng/g-OC)**	**Dissolved (ng/L)**	**Particulate (ng/g-OC)**	**Dissolved (ng/L)**	**Particulate (ng/g-OC)**
3	0	0	0	0	0	0
8+5	0	0	0	0	0	0
12	0.002831	0	0.002265	6.94990	0.003126	0
13	0.001163	0.63374	0.00122	2.09185	0.0009	2.11576
15+17	0.003063	4.02012	0.002608	7.54759	0.004061	11.95844
16	0	1.00157	0	1.56798	0.001473	3.22824
32	0	1.37860	0	1.58024	0	4.22044
18	0.00333	3.57836	0.00377	5.47443	0.004623	10.4442
26	0.000941	0.22132	0.001258	0.37498	0.001582	2.96423
28+31	0.008012	12.42481	0.007067	17.84289	0.009846	55.58153
33	0.004408	2.28478	0.005054	3.43611	0.006045	9.97024
37+42	0.008967	14.5969	0.009517	15.35747	0.008866	16.86476
44	0.003189	5.38999	0.002878	7.30135	0.00581	20.89396
49	0.002259	3.96632	0.002054	6.86181	0.003302	14.05582
52	0.005627	9.48455	0.005518	16.12783	0.008475	35.36909
56+60	0.00134	7.20351	0.001344	13.76338	0.00198	30.47388
66	0.001664	18.39126	0.001893	29.53261	0.002783	63.51781
70+76	0.002179	7.46113	0.0021	16.42939	0.003036	33.74864
74	0.00103	4.18880	0.001039	5.84207	0.001371	14.10166
77+110	0.00291	13.79423	0.002586	28.80211	0.004342	49.83354
81	7.68E-05	1.52913	0	2.09813	0.000147	2.60703
87	0.00227	4.43503	0.002572	8.03297	0.002373	13.37302
92+84	0.005722	15.83466	0.007226	32.15896	0.01356	74.07366
89	0.00068	0.15860	0	0	0	1.59772
85	0.000507	4.76618	0.000569	8.63774	0.000681	13.30061
99	0.006156	25.2633	0.004236	36.02048	0.004228	49.72043
101	0.001328	10.76926	0.00278	17.31631	0.004522	34.31707
118	0.001236	10.49375	0.001156	19.16489	0.001713	35.9058
123+149	0.000705	6.59078	0.000862	13.43283	0.001331	21.52096
132+153+105	0.000724	18.7597	0.000958	31.21532	0.001451	58.52275
151	0	2.11833	0	3.88177	0	6.37438
163+138	0.002134	20.59195	0.002948	37.87159	0.002877	55.57444
146	0.00059	5.19236	0.000583	7.64438	0.000572	9.26933
170+190	4.74E-05	2.54427	7.36E-05	5.30883	0.000131	8.24745
172+197	0	1.03453	0	1.85133	0	2.81659
180	0	1.91204	5.13E-05	5.94020	0	18.31716
187+182	0.002588	4.91753	0.000984	7.07428	0.000683	12.63331
208+195	4.34E-05	0.88921	0	1.91721	0	2.42335
196+203	3.28E-05	1.50532	2.75E-05	3.83510	0	5.10087
201	0.000168	3.05836	7.34E-05	6.59986	0.00018	9.01875

estimated based on samples collected at several nearby stations. These stations were selected for their closeness to a specific biota zone in distance, depth, and sediment characteristics. Because organic carbon normalized sediment PCB data showed limited horizontal variation, the estimate of sediment PCB exposure by using data from nearby stations was appropriate. Information regarding the sampling stations, collection procedures, sample preparation, and methods for PCB analysis are available in detail (U.S. Environmental Protection Agency, 1997a, 1997b). Organic carbon and dry fraction of sediment samples were also analyzed. The analysis procedures can also be found in the above documents.

Sediment data analysis revealed no significant temporal variation in PCB concentrations for samples collected during 1994 and 1995. PCB concentrations in sediment were organic carbon normalized. Median values for PCBs in sediment carbon were used for model calculations. The concentrations of PCBs dissolved in sediment pore water were estimated based on measured PCB data, organic carbon content, dry fraction in the sediment samples, and organic carbon-water partition coefficients for individual PCB congeners. The results of PCB concentrations in the sediment solids and pore water for the three biota zones are given in Table 5.4.12.

5.4.2.4.3 Exposure Temperature

Lake Michigan is a vast water body with a volume of 4,920 km^3. It has a surface area of 57,800 km^2, and its deepest point is 282 m (Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1992). Physical characteristics of the lake vary with region and depth (Environment Canada and U.S. Environmental Protection Agency, 1997). To better reflect this reality, the model was constructed to simulate the exposure environment for each species, rather than as a whole for all species in a food web.

The prevailing annual cycles of exposure temperature for a lake-wide coho salmon population and for three lake trout and their forage populations at Sturgeon Bay, Sheboygan Reef, and Saugatuck were established and are presented in Figures 5.4.2a through 5.4.2c. The results were compiled based on site-specific information, such as annual water temperature profiles (U.S. Environmental Protection Agency, 1995), species optimal temperature and depth at different life stages (Otto *et al*., 1976; Peterson *et al*., 1979; Stewart *et al*., 1983; Wismer and Christie, 1987; Wells, 1968), prey availability (Crowder and Crawford, 1984; Eck and Wells, 1986; Janssen and Brandt, 1980), spawning season (Janssen and Brandt, 1980), and spawn site preference (Jude *et al*., 1986; Rice, 1985). For simplicity, the exposure temperatures for different age groups in certain species were aggregated and average annual temperature cycles were determined for the species. The seasonal variation of surface water temperatures (U.S. Environmental Protection Agency, 1995) in the lake is also presented in the first panel of Figures 5.4.2a - 5.4.2b and Figure 5.4.2c for reference.

5.4.2.4.4 Oxygen Concentration in Water

The oxygen concentration in water that organisms vent through their gill membranes was determined by water temperature. In this study, the dissolved oxygen content in water [O_2] was estimated according to an empirical correlation between oxygen solubility (mg/L) and water temperature (Greenberg *et al*., 1992).

$$\begin{aligned} Ln\,[O_2] = & -139.34411 + (1.575701 \times 10^5/T) \\ & - (6.642308 \times 10^7/T^2) + (1.2438 \times 10^{10}/T^3) \\ & - (8.621949 \times 10^{11}/T^4) \end{aligned} \qquad (5.4.5)$$

where

T = temperature (°K)

5.4.3 Physiological Data of Fish and Other Organisms

5.4.3.1 Species-Specific Respiration Rates

In the bioenergetics-based food web model (LM Food Chain), fish respiration (or metabolism) rate is a key model parameter which determines the dynamics of chemical uptake from water and food. Fish respiration rate is dependent on fish weight, temperature, and degree of fish activity. For most of the fish species in the Lake Michigan food webs, an extensive study of respiration as a function of weight,

Table 5.4.12. PCB Concentrations in Lake Michigan Surface Sediment (1994-1995)

PCB Congeners	Sturgeon Bay		Sheboygan Reef		Saugatuck	
	Pore Water (ng/L)	Particle (ng/g-OC)	Pore Water (ng/L)	Particle (ng/g-OC)	Pore Water (ng/L)	Particle (ng/g-OC)
3	0	0	0	0	0	0
8+5	0.0279054	10.00643	0.0382893	13.72811	0.0908558	32.58473
12	0.0014341	0.71635	0	0	0	0
13	0.0013447	0.75432	0.0029074	1.63073	0.0061499	3.44944
15+17	0.0096751	5.29398	0.0252991	13.84212	0.0681406	37.28868
16	0.0038924	1.76031	0.0074487	3.36831	0.0171774	7.76701
32	0.0024807	1.41452	0.0026843	1.53063	0.0277008	15.80006
18	0.0071207	3.67665	0.018433	9.51698	0.0504009	26.02673
26	0.0026656	2.76099	0.0035926	3.72098	0.0167924	17.39422
28+31	0.049642	52.27209	0.067541	71.12439	0.2105729	221.7646
33	0.0125176	11.73799	0.0149408	14.00947	0.0549273	51.50962
37+42	0.009989	13.00778	0.019252	25.29948	0.061323	80.17273
44	0.0149115	17.92995	0.023162	27.84947	0.0644197	77.46354
49	0.0078881	11.19489	0.0098061	13,91655	0.0308258	43.75034
52	0.0174969	24.42368	0.0227162	31.70843	0.0629656	87.89781
56+60	0.0183856	40.15014	0.0281371	61.44742	0.0645118	140.8908
66	0.0446862	113.2876	0.05182	131.3768	0.1180745	299.3598
70+76	0.0180978	43.29467	0.0239207	57.22649	0.0613122	146.6866
74	0.0075816	19.2216	0.007947	20.14776	0.0219209	55.5777
77+110	0.0175742	69.76274	0.026113	102.5709	0.0514251	200.6624
81	0.0004445	1.46919	0.0006704	2.21588	0.0018093	5.98041
87	0.0049453	14.55518	0.0062292	18.33357	0.0162384	47.79412
92+84	0.0089757	22.56819	0.0178462	44.87101	0.0322442	81.07549
89	0.000158	0.3229	0.0011103	2.26910	0.0019127	3.90920
85	0.00761	22.77225	0.00995	29.77426	0.0154561	46.2521
99	0.0065556	22.77379	0.007798	27.0894	0.0150233	52.19077
101	0.0116518	39.81201	0.0138112	47.18955	0.029209	99.80335
118	0.0104703	64.97851	0.0130125	80.75468	0.0212667	131.9822
123+149	0.0034083	19.95935	0.0040488	23.71038	0.0083891	49.12844
132+153+105	0.0133833	79.90554	0.0151232	95.42261	0.0230193	145.2468
151	0.0011542	6.06862	0.0012538	6.59256	0.0026042	13.69295
163+138	0.0099996	82.25939	0.0127299	104.7201	0.0209239	172.1294
146	0.0014001	11.14243	0.0015557	12.38059	0.0028539	22.71165
170+190	0.0009791	17.12468	0.0009686	16.94218	0.0016554	28.95361
172+197	0.0002736	4.51562	0.0002758	4.53335	0.0005621	9.23983
180	0.0017814	30.90044	0.0018309	31.75848	0.0030391	52.71641
187+182	0.0010107	13.11631	0.000956	12.40633	0.0016946	21.99273
208+195	0.0001999	5.46997	0.000171	4.67938	0.0002984	8.16719
196+203	0.0006348	17.80964	0.0005772	16.19255	0.0011243	31.54036
201	0.0006772	18.07668	0.0004869	12.99829	0.0012951	34.57076

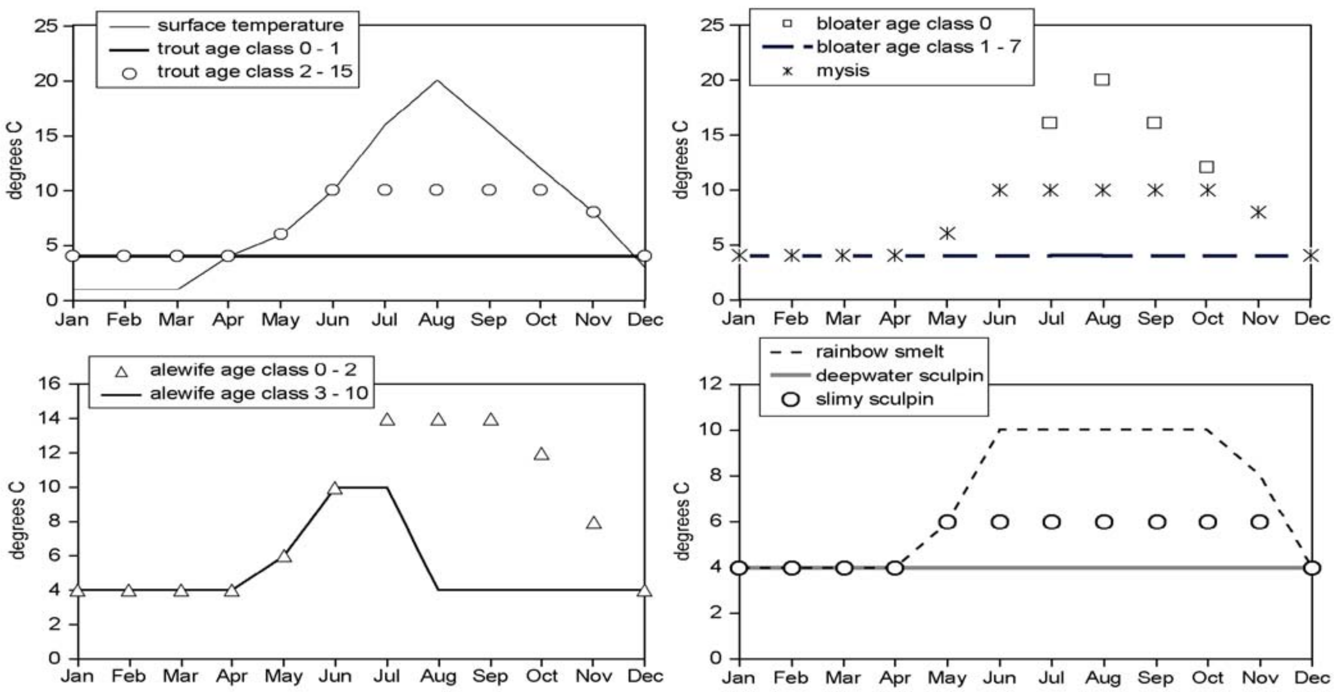

Figure 5.4.2a. Typical annual cycles of exposure temperature for Lake Michigan food webs at Saugatuck and Sturgeon Bay.

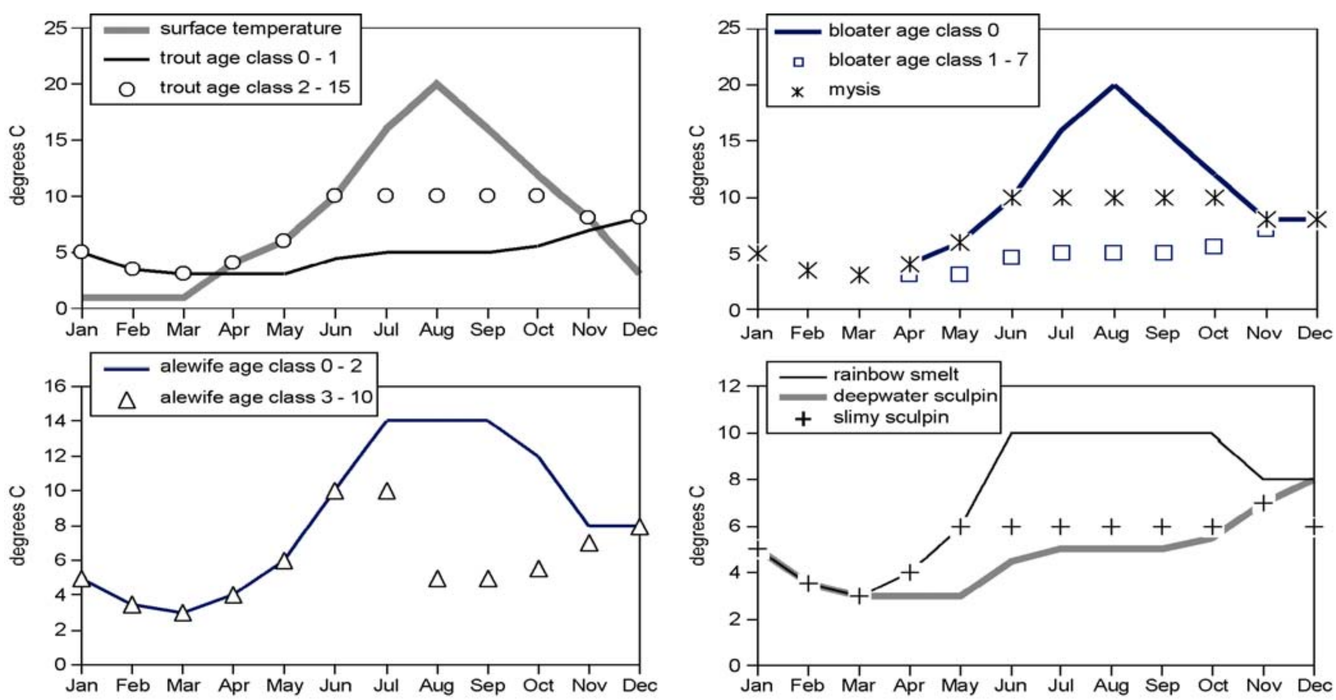

Figure 5.4.2b. Typical annual cycles of exposure temperature for Lake Michigan food web at Sheboygan Reef.

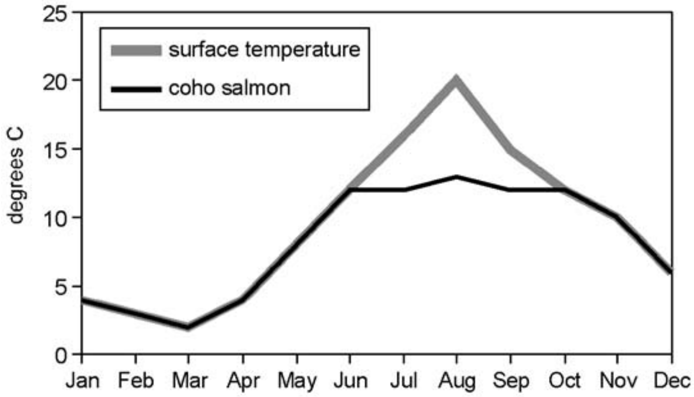

Figure 5.4.2c. Typical annual cycles of exposure temperature for coho salmon in Lake Michigan.

temperature, and swimming speed was conducted, and results were reported (Lantry and Stewart, 1993; Rudstam, 1989; Rudstam *et al.*, 1994; Stewart *et al.*, 1983; Stewart and Binkowski, 1986). In general, a fish's daily respiration rate, in g-O_2/day, can be formulated as:

$$R = \alpha W^{\beta} \cdot e^{\rho T} \cdot e^{vU} \qquad (5.4.6)$$

where α, β, ρ, v are species-specific empirical constants, W is weight, and U is the swimming speed of the fish, in cm/s.

For a given aquatic species, the swimming speed can be expressed as a function of body weight and water temperature:

$$U = \omega W^{\delta} e^{\phi T} \qquad (5.4.7)$$

where ω, δ, ϕ are species-specific empirical constants.

The values of the species-specific empirical constants used to estimate the respiration rate were collected from literature sources (Lantry and Stewart, 1993; Rudstam, 1989; Rudstam *et al.*, 1994; Stewart *et al.*, 1983; Stewart and Binkowski, 1986) and are listed in Table 5.4.13. For slimy and deepwater sculpin, there was insufficient information available to generate species-specific respiration rates. As an alternative, their respiration rates were estimated using the generalized fish respiration equation. The constants used for the calculation of their respiration rates were also given in the table.

In this study, a value of 13.56 kJ/g-O_2 (Elliott and Davison, 1975; Brafield and Llewellyn, 1982; Crisp, 1984) was used as the respiratory energy equivalent, or oxycalorific coefficient, for converting oxygen respiration to energy utilized by fish.

For zooplankton, a simple equation was used to estimate its respiration, in kJ/gwet/day, as a function of water temperature (Connolly *et al.*, 1992):

$$R = 0.60\, e^{\rho T} \qquad (5.4.8)$$

5.4.3.2 Respiration Rates Adjusted for Specific Dynamic Action (SDA)

The respiration rate estimated with Equation 5.4.6 represents the average energy requirement for the resting metabolism of a fish. It has been reported that there is an increase in respiration rate for a recently fed fish (Kayser, 1963). The additional respiration activity is often referred to as Specific Dynamic Action (SDA). The origin of the extra respiration is believed to be due to the energy necessary for the digestion of ingested foods, the absorption of nutrients, the deaminization of amino acids, and the synthesis of the products of nitrogenous excretion. In homothermic animals, it has been shown that SDA represents 30% of the caloric content of the ingested protein, 13% for a lipid, and 5% for a carbohydrate (Lucas, 1996). Due to the difficulty in experimentally discriminating SDA from additional respiration associated with excitement and activity with feeding, different SDA

Table 5.4.13. Bioenergetic Parameters of Lake Michigan Fishes

Parameter	*Mysis*	Slimy Sculpin	Deepwater Sculpin	Alewife	Rainbow Smelt	Bloater	Lake Trout	Coho Salmon
α (gO_2/gwet/day)	0.00182	0.043*	0.043*	0.00367	0.0027	0.0018	0.00463	0.00264
β	-0.161	-0.3	-0.3	-0.2152	-0.216	-0.12	-0.295	-0.217
ρ	0.0752	0.03	0.03	0.0548	0.036	0.047	0.059	0.06818
ω	0	1.19	1.19	5.78	0	7.23	11.7	9.7
δ	0	0.32	0.32	-0.045	0	0.25	0.05	0.13
ϕ	0	0.045	0.045	0.149	0	0	0.0405	0.0405
ν	0	0.0176	0.0176	0.03	0	0.025	0.0232	0.0234

*With a unit of gwet/gwet/day.

values were cited in the literature that ranged from 9% to 20% of the energy contained in the diet (Jobling, 1981).

In this study, the SDA is modeled as a portion of a fish's dietary ingestion. The respiration rate adjusted for SDA can then be written as:

$$R_{SDA} = R \cdot Q_{ox} + SDA\,(R_{SDA} + G \cdot D_f) \qquad (5.4.9)$$

where

R_{SDA} = SDA adjusted respiration rate, g-O_2/day

R = resting respiration rate calculated with empirical equations, g-O_2/day

Q_{ox} = respiratory energy equivalent or oxycalorific coefficient, kJ/g-O_2

SDA = fraction of assimilated energy spent on specific dynamic action

G = fish growth rate, 1/day

D_f = energy density of the fish

The final respiration rate, in kJ/day, was then estimated as:

$$R_{SDA} = (R \cdot Q_{ox} + SDA \cdot G \cdot D_f)/(1 - SDA) \qquad (5.4.10)$$

5.4.4 Calibrated Model Parameters

There are several constants and variables in the model's equation whose values are either not readily available or inconclusive. Their values were determined through model calibration to site-specific conditions. The calibrated parameters include food assimilation efficiency (β) for each species or age group, the chemical assimilation efficiency (α) for each species or age group for each PCB congener, the chemical relative gill transfer coefficient (E_c/E_o) for each species (or age group) for each PCB congener, and the fraction of ingested energy for SDA for each species or age group.

An acceptable value range for each of the calibrated model parameters and its general trend for PCB congeners or species in different trophic levels was established based on information from the literature and experience gained in previous modeling work. Depending upon species and its diet, food assimilation efficiency has a value ranging from 0.05 to 0.85 (Brocksen *et al.*, 1968; Brocksen and Brugge, 1974; Elliott, 1976; Averett, 1969). The value for the chemical assimilation efficiency can vary from 0.2 to 0.8 and is reported to be correlated with the K_{ow} value for the chemical (Gobas, 1988). The chemical relative gill transfer coefficient (E_c/E_o) ranges from 0.1 to 1.0 and is also believed to be related to K_{ow} for the chemical (McKim *et al.*, 1985). Energy fraction for SDA has a value ranging from 0.00 to 0.20. These data were used to guide our model calibrations for appropriate parameterization.

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