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Temperature requirements of fishes from eastern Lake Erie and the upper Niagara River: a review of the literature

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Synopsis

Literature on the temperature requirements of fishes expected to occur in eastern Lake Erie and the upper Niagara River is reviewed. Seventy-four species of fishes are reported from Lake Erie and sixty-one from the upper Niagara River. Incipient upper lethal temperatures range from 23° C for *Salmo trutta* to 41° C for *Carassius auratus* and *Ictalurus nebulosus*. Preferred temperatures ranged from 10° C for *Coregonus clupeaformis* to 31.1° C for *Lepomis macrochirus*. Spawning temperatures range from < 3.8° C for *C. artedii* to 15.6–27.7° C for *Alosa pseudoharengus*. Data is discussed in terms of the effects of thermal effluents on individuals of a species, structure of aquatic communities and impact on ecosystems. Synergistic effects of temperature and toxicants and disruption of sprawning are potentially the most damaging direct effects of thermal effluents.

Heated water may be contributing to the present rate of eutrophication in the lake and river. Increased input of thermal effluents into the eastern basin of Lake Erie will maintain a stress on the fishery and may irreversibly damage it.

Introduction

The purpose of this review is to bring together information on the effects of temperature on the fish inhabiting the New York waters of eastern Lake Erie and the upper Niagara River. Present and future population growth and energy demand will require the construction of several major power generating stations in eastern North America by the year 2000. Whether socio-economic pressures result in coal, nuclear or some other fuel systems for such facilities, an inevitable by-product will be waste heat. Eastern Lake Erie remains as one of the least exploited large bodies of water that will be available in this region for power plant siting over the next 30 years. However, the addition of thermal effluents may profoundly affect the ecology of the fishes living in these waters. We should renew our efforts to gain an understanding of the biology of these animals so that we will be able to predict the impact of thermal effluents before they are discharged into the lake and river.

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Temperature limits the distribution of organisms and determines their activity rates. It controls the nature and speed of chemical and biochemical reactions, which in turn, regulate growth and reproduction (Prosser 1973). Nearly all freshwater organisms, being poikilotherms, have no internal physiological regulation of body temperature, have little heat production, and lack effective insulation. This coupled with the high specific heat of water and the effectiveness of heat exchange by conduction and convection in the aquatic medium results in body temperatures which follow closely the temperature of the environment. Gunn (1942) demonstrated that this was true for fish under natural conditions. The same is true for freshwater invertebrates. Thus, the rates of life processes in aquatic organisms are largely determined by the temperature of the water in which they reside.

Thousands of studies concerning the lethal effects of temperature on aquatic organisms have been conducted. The classic studies of Fry, Hart and Brett (Brett 1944, 1952, 1956, 1960, Fry 1947, 1958, Fry et al. 1952, Fry & Hart 1948 a, b, Fry et al. 1946, Hart 1952) have provided much data on the thermal tolerance of individual fish species. These authors also have contributed many new developments (including the determination of median resistance time, temperature polygons, relationship of temperature, activity and metabolism and optimum temperature for growth) to the study of thermal ecology.

Most temperature research on fish has involved species such as salmon (*Salmo* and *Oncorhynchus*), trout (*Salmo*), charr (*Salvelinus*), goldfish (*Carassius auratus*), catfish (*Ictalurus*), and bass (*Micropterus*). Some research has been done on small stream fish by Hart (1952), Black (1953), Tyler (1966), Brungs (1971) and Kowalski et al. (1978). However, very few studies have considered the effects of factors, other than past thermal history, on the ability of fish to withstand high and low temperatures. Gibson (1954), Hagen (1964), and Baker et al. (1970) reported sexual differences in the heat resistance of guppies (*Lebistes reticulatus*), mosquito fish (*Gambusia*) and Ozark minnows (*Dionda nubila*). Tyler (1966) found seasonal differences in the upper lethal temperatures of two minnows of the genus *Chrosomus*. Hoar (1955, 1956) and Hoar & Robertson (1959) demonstrated that photoperiod altered the temperature resistance of goldfish (*Carassius auratus*) maintained at a constant temperature and Terpin et al. (1975) reported the same phenomenon for *Rhinichthys atratulus*, the blacknose dace. Cairns & Scheier (1957, 1959, 1962, 1963, 1964) reported that the interaction of high temperature and toxic substances sometimes increased mortality in fish over that due to one factor alone. Very little research has been conducted on the thermal tolerance of invertebrates and plants. Cairns (1969) reported on the response of freshwater protozoan communities to heated water. Patrick (1971) and Patrick et al. (1969) studied the effect of temperature on diatom communities, and Patrick (1969) and Stockner (1968) reported on the effect of temperature on algae. Sprague (1963) reported 24 h lethal temperatures for four freshwater crustaceans. Smith (1973) studied the thermal tolerance of *Gammarus* and Aiken (1969) and Spoor (1955) reported on the effects of temperature on crayfish (*Orconectes virilis* and *Orconectes rusticus*). Ide (1935) demonstrated that temperature affected the distribution of mayflies in an Ontario stream. Nebeker (1971) reported the optimum and limiting temperatures for nymphal feeding rate, emergence and adult longevity in the stonefly (*Pteronarcys dorsata*).

Studies on the effect of temperature on aquatic organisms have been the subject of numerous literature reviews and bibliographies (Brett 1956, Coutant 1970a, 1970b, 1976, Fry 1957, 1964, 1967, Fry & Hochachka 1970, Jensen et al. 1969, Kennedy & Mihursky 1967, Krenkel & Parker 1969, Mihursky & Kennedy 1967, Parker & Krenkel 1969, Prosser 1973, Raney & Menzel 1969, Speakman & Krenkel 1971).

This report is not intended as another attempt to review comprehensively all published material on temperature effects upon aquatic organisms. Rather, it is limited to a consideration of the effects of temperature on the fishes expected to occur in the New York waters of eastern Lake Erie and the upper Niagara River.

Some environmental surveys have been conducted in these waters by federal, state and industrial organizations. The Great Lakes Laboratory of the State University College at Buffalo has studied the phytoplankton, zooplankton and benthos of both the eastern basin of Lake Erie and the upper Niagara River. Surveys of the biota of the lake near Dunkirk have recently been completed for the Niagara Mohawk Corporation (Niagara Mohawk Power Corporation 1976, 1977). The New York Department of Environmental Conservation and the Biology Department of the State University College at Buffalo have made periodic fish collections during the last few years. Nevertheless, information on the fish communities in these areas is very limited. Our approach has been to assess the present status of the fishes in these areas and then to determine from the literature the effect of temperature on these fishes. We hope that this compilation will be of use to fisheries biologists and consultants who are or will be charged with making recommendations about the siting of future power facilities, industrial complexes, urban centers and commercial developments in this area. In addition, information tabulated for some fishes may be applicable to studies involving other bodies of water.

Field observations and literature review

With the possible exception of fish, little is published about the flora and fauna of the areas in question. Fish known to occur in New York waters of eastern Lake Erie and the upper Niagara River are listed in Table 1. Seventy-four species are reported for the lake but only 46 have been confirmed by recent observations by the New York Department of Environmental Conservation (N.Y.D.E.C.), Niagara Mohawk Power Corporation and local fishermen. Sixty-one species of fish are reported for the upper Niagara River. Of these, 43 have been found in recent collections by personnel of the N.Y.D.E.C. and/or Biology Department of State University College at Buffalo

Table 1. The status of fish in New York waters of eastern Lake Erie and in the upper Niagara River.

		Occurrence					
Family	Species	L. Erie	Niagara R.	Authority	Trophic position	Abundance	Thermal information
Petromyzontidae	*Ichthyomyzon unicupsis* (silver lamprey)	X		Trautman 1957	parasite	?	
	Petromyzon marinus (sea lamprey)	X	X	Trautman 1957 NMPC 1976[1]	parasite	Present in lake	X
Acipenseridae	*Acipenser fulvescens* (lake sturgeon)	X	X	NYDEC[2] 1929 Trautman 1957 NMPC 1976, 1977	1st order carnivore & detritivore	Rare in river Rare in lake	
Lepisosteidae	*Lepisosteus oculatus* (spotted gar)	X		Trautman 1957 NMPC 1976	3rd order carnivore	Rare in lake	
	Lepisosteus osseus (longnose gar)	X	X	NYDEC 1929, 1972[3] Trautman 1957	3rd order carnivore	Rare in river Present in lake	X
	Lepisosteus platostomus (shortnose gar)	X		NYDEC 1929	3rd order carnivore	?	
Amiidae	*Amia calva* (bowfin)	X	X	Trautman 1957 NYDEC 1972 NMPC 1976	2nd order carnivore	Rare in river Present in lake	
Anguillidae	*Anguilla rostrata* (american eel)	X	X	NYDEC 1964 NMPC 1977	2nd order carnivore	Rare	
Clupeidae	*Alosa pseudoharengus* (alewife)	X	X	NYDEC 1929, 1967 NMPC 1977	herbivore	Locally common	X
	Dorosoma cepedianum (gizzard shad)	X	X	NYDEC 1929 NMPC 1977	herbivore	Common	X
Hiodontidae	*Hiodon tergisus* (mooneye)	X		Trautman 1957	1st order carnivore	Probably extirpated	
Salmonidae	*Coregonus artedii* (cisco or lake herring)	X		White 1974	herbivore & 1st order carnivore	Probably extirpated	X
	Coregonus clupeaformis (lake whitefish)	X		White 1974	herbivore & 1st order carnivore	Probably extirpated	X
	Oncorhynchus kisutch (coho salmon)	X	X	NYDEC 1974 NMPC 1977 SUCB collection (local fishermen)	2nd order carnivore	Seasonally common	X
	Oncorhynchus tshawytscha (chinook salmon)	X	X	NYDEC 1974 White 1974 NMPC 1977	2nd order carnivore	Seasonally common	X
	Salmo gairdneri (rainbow trout or steelhead)	X	X	NYDEC 1929, 1974 NMPC 1977	2nd order carnivore	Seasonally common	X
	Salmo trutta (brown trout)	X	X	NYDEC 1974 NMPC 1977	2nd order carnivore	Rare	X
	Salvelinus namaycush (lake trout)	X		NYDEC 1929	2nd order carnivore	Probably extirpated	X
Osmeridae	*Osmerus mordax* (rainbow smelt)	X	X	SUCB collection White 1974 NMPC 1977	2nd order carnivore	Seasonally abundant	
Umbridae	*Umbra limi* (central mudminnow)	X	X	SUCB collection White 1974	1st order carnivore	Common in river	
Esocidae	*Esox americanus* (redfin pickerel)	X	X	NYDEC 1929	3rd order carnivore	?	X
	Esox lucius (northern pike)	X	X	SUCB collection Trautman 1957 NYDEC 1972 NMPC 1976, 1977	3rd order carnivore	Rare in river Rare in lake	X
	Esox masquinongy (muskellunge)	X	X	SUCB collection NYDEC 1929, 1972 NMPC 1976, 1977	3rd order carnivore	Common in river Rare in lake	X
	Esox niger (chain pickerel)	X	X	NYDEC 1929	3rd order carnivore	?	X
Cyprinidae	*Campostoma anomalum* (stoneroller)		X	NYDEC 1929 NMPC 1977	herbivore	?	X
	Carassius auratus (goldfish)	X	X	White 1974 NYDEC 1972 NMPC 1977	herbivore & detritivore	Abundant	X
	Clinostomous elongatus (redside dace)	X		NMPC 1977	1st order carnivore	Rare	
	Cyprinus carpio (carp)	X	X	White 1974 NYDEC 1972 NMPC 1977	herbivore & detritivore	Abundant	X
	Hybopsis storeriana (silver chub)	X		Trautman 1957	1st order carnivore	?	
	Nocomis micropogon (river chub)		X	SUCB collection NYDEC 1929	1st order carnivore	?	X
	Notemigonus crysoleucas (golden shiner)	X	X	SUCB collection White 1974 NYDEC 1972 NMPC 1976	herbivore & 1st order carnivore	Locally Common in river Present in lake	X
	Notropis atherinoides (emerald shiner)	X	X	NYDEC 1929, 1972 White 1974 SUCB collection NMPC 1977	1st order carnivore	Abundant in lake & river	X
	Notropis cornutus (common shiner)	X	X	NYDEC 1972 NMPC 1976, 1977	1st order carnivore	Rare in river Present in lake	X
	Notropis heterolepis (blacknose shiner)		X	NYDEC 1967	1st order carnivore	Common	
	Notropis hudsonius (spottail shiner)	X	X	White 1974 SUCB collection NYDEC 1972 NMPC 1977	herbivore & 1st order carnivore	Common in lake & river	X
	Notropis stramineus (sand shiner)	X	X	NYDEC 1929, 1942	herbivore & 1st order carnivore	Common in river	X
	Notropis volucellus (mimic shiner)	X	X	NYDEC 1929	herbivore & 1st order carnivore	?	
	Pimephales notatus (bluntnose minnow)	X	X	NYDEC 1929, 1972 SUCB collection	herbivore	Rare in river Abundant in lake	X
	Rhinichthys cataractae (longnose dace)	X		NYDEC 1929, 1972	1st order carnivore	?	X
Catostomidae	*Carpiodes cyprinus* (quillback)	X	X	NYDEC 1929, 1965 Trautman 1957 NMPC 1976, 1977	detritivore	Present in lake	X
	Catostomus commersoni (white sucker)	X	X	NYDEC 1929, 1972 NMPC 1977	detritivore	Abundant in lake Common in river	X
	Erimyzon sucetta (lake chubsucker)	X		NYDEC 1929	detritivore	?	
	Hypentelium nigricans (northern hognose sucker)	X	X	SUCB collection NYDEC 1929, 1972 NMPC 1976, 1977	detritivore	Locally common in river Present in lake	X
	Minytrema melanops (spotted sucker)	X		NYDEC 1929	detritivore	?	X
	Moxostoma anisurum (silver red horse)		X	NYDEC 1967	detritivore	Common	
	Moxostoma duquesnei (black red horse)	X		NYDEC 1929	detritivore	?	
	Moxostoma erythrurum (golden red horse)	X	X	NYDEC 1929	detritivore	?	
	Moxostoma macrolepidotum (short head red horse)	X		White 1974 NMPC 1976, 1977	detritivore	Present in lake	
Ictaluridae	*Ictalurus melas* (black bullhead)	X	X	NYDEC 1929	1st order carnivore	?	X
	Ictalurus natalis (yellow bullhead)	X	X	NYDEC 1929 NMPC 1976, 1977	1st & 2nd order carnivore	Present in lake	X
	Ictalurus nebulosus (brown bullhead)	X	X	SUCB collection NYDEC 1929 NMPC 1976, 1977	herbivore & 2nd order carnivore	Common in river Present in lake	X
	Ictalurus punctatus (channel catfish)	X	X	NYDEC 1929, 1963 NMPC 1976, 1977	2nd order carnivore	Present in lake	X
	Noturus flavus (stone cat)	X	X	NYDEC 1929, 1964 NMPC 1976, 1977	1st order carnivore	Present in lake	X
	Noturus gyrinus (tadpole madtom)	X	X	SUCB collection NYDEC 1929	1st order carnivore	Common in river	
Percopsidae	*Percopsis omiscomaycus* (trout-perch)	X	X	NYDEC 1929 White 1974 NMPC 1976, 1977	1st & 2nd order carnivore	Present in lake	X
Gadidae	*Lota lota* (burbot)	X		NYDEC 1963 White 1974 NMPC 1976	3rd order carnivore	Present in lake	X
Cyprinodontidae	*Fundulus diaphanus* (banded killfish)	X	X	SUCB collection NYDEC 1929, 1972	1st order carnivore	Locally common in river	
Atherinidae	*Labidesthes sicculus* (brook silverside)	X	X	White 1974 NYDEC 1972 NMPC 1976, 1977	1st order carnivore	Rare in river Present in lake	
Percichthyidae	*Morone chrysops* (white bass)	X	X	Local fishermen NYDEC 1929, 1972 NMPC 1977	1st & 2nd order carnivore	Common	X
Centrarchidae	*Ambloplites rupestris* (rock bass)	X	X	SUCB collection NYDEC 1972 Trautman 1957 NMPC 1977	1st & 2nd order carnivore	Common in lake and river	X
	Lepomis gibbosus (pumpkinseed)	X	X	SUCB collection NYDEC 1972 NMPC 1976 Trautman 1957	1st & 2nd order carnivore	Common in river Present in lake	X
	Lepomis gulosus (warmouth)	X		Trautman 1957	1st & 2nd order carnivore	?	
	Lepomis macrochirus (bluegill)	X	X	SUCB collection NYDEC 1972 NMPC 1976, 1977 Trautman 1957	1st & 2nd order carnivore	Common in river Present in lake	X
	Lepomis megalotis (longear sunfish)	X		NYDEC 1929	1st & 2nd order carnivore	?	
	Micropterus dolomieui (smallmouth bass)	X	X	SUCB collection NYDEC 1972 Trautman 1957 NMPC 1977	2nd order carnivore	Locally common in lake Common in river	X
	Micropterus salmoides (largemouth bass)	X	X	NYDEC 1929, 1972	2nd order carnivore	Locally common in lake	X
	Pomoxis annularis (white crappie)	X	X	SUCB collection Trautman 1957 NMPC 1976	1st & 2nd order carnivore	Common in river Present in lake	X
	Pomoxis nigromaculatus (black crappie)	X	X	SUCB collection NYDEC 1972 Trautman 1957 NMPC 1976, 1977	1st & 2nd order carnivore	Common in river Present in lake	X
Percidae	*Etheostoma blennioides* (greenside darter)	X	X	White 1974 NYDEC 1961	1st order carnivore	?	X
	Etheostoma caeruleum (rainbow darter)		X	NYDEC 1967	1st order carnivore	Common in river	X
	Etheostoma exile (Iowa darter)	X		NYDEC 1929, 1964	1st order carnivore	?	
	Etheostoma flabellare (fantail darter)		X	NYDEC 1965 NMPC 1977	1st order carnivore	Rare	X
	Etheostoma nigrum (johnny darter)	X	X	SUCB collection NYDEC 1929, 1967 NMPC 1977	1st order carnivore	Common in river	X
	Perca flavescens (yellow perch)	X	X	SUCB collection NYDEC 1929, 1972 NMPC 1977	1st & 2nd order carnivore	Abundant	X
	Percina caprodes (log perch)	X	X	NYDEC 1929, 1967 NMPC 1976, 1977	1st order carnivore	Present in lake	
	Percina copelandi (channel darter)	X		White 1974	1st order carnivore	?	
	Stizostedion vitreum viteum (walleye)	X	X	NYDEC 1929 NMPC 1977	2nd order carnivore	Rare	X
	Stizostedion vitreum glaucum (blue pike)	X	X	White 1974	2nd order carnivore	Probably extirpated	
Scicenidae	*Aplodinotus grunniens* (freshwater drum)	X	X	Local fishermen NYDEC 1963 NMPC 1977	detritivore & 1st order carnivore	Common	X
Cottidae	*Cottus bairdi* (mottled sculpin)	X	X	SUCB collection NYDEC 1929, 1967	1st order carnivore	?	X
	Cottus cognatus (slimy sculpin)	X		NMPC 1976, 1977	1st order carnivore	Present in lake	

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[1] Niagara Mohawk Power Corporation (1976, 1977).

[2] New York State Department of Environmental Conservation (1929).

[3] New York State Department of Environmental Conservation (1942-1977).

(S.U.C.B.). All N.Y.D.E.C. surveys listed since 1963 were taken in the upper river near the south end of Grand Island and near Strawberry Island. The S.U.C.B. collections were made along the Grand Island shore of the east branch of the River. The place of each species in the food web is described by Carlander (1969) and Trautman (1957). This information indicates that the total fish community is well balanced, being composed of ample representatives of each trophic level (herbivores, 1st, 2nd, 3rd level carnivores, etc.). Of the 74 species recorded for eastern Lake Erie only 6 are considered abundant, 1 is seasonally abundant, 5 are common, 3 are seasonally common, 3 are locally common, 7 are rare, while 21 are known only as being present, and 4 are extirpated. The present status of the remaining 24 is not known. Of the 61 species listed for the Niagara River, 4 are listed as abundant, 1 is seasonally abundant, 20 are common, 3 are seasonally common, 4 are locally common, and 11 are rare. The present status of the remaining 17 species is in doubt. One subspecies, the blue pike (*Stizostedion vitreum glaucum*) is probably extirpated from both the lake and river.

Temperature data were available for 53 of the 80 species of fish found in the lake and river. These data have been summarized in Tables 2-5. Incipient upper lethal temperatures (IULT) range from 23° C for *Salmo trutta* to 41° C for *Carassius auratus* and *Ictalurus nebulosus*. The IULT was defined as the test temperature that killed exactly 50% of the test population during unlimited exposure (Fry et al. 1946). In a typical test, groups of fish were placed in a series of baths with temperatures selected to cause rapid, complete mortality in some groups and slow and possibly incomplete mortality in others. Tests normally lasted 10000 minutes (Edsall & Colby 1970). In addition, *I. punctatus* had a death point (D.P.) of 42.5° C and *Lepomis macrochirus* a D.P. of 41.9° C when exposed to a rapid rate of heating.

Preferred temperatures ranged from 10° C for *Coregonus clupeaformis* to 31.1° C for *Lepomis macrochirus*. Salmonids preferred temperatures from 11.4° C to 22.0° C, bass and sunfish from 18-33.1° C, pike from 9.9-26.0° C and perch (*Perca flavescens*) from 11-29° C. Data were available for four minnows: *Notropis atherinoides* (6-23° C), *N. hudsonius* (10.2-14.3° C), *Pimephales notatus* (15.7-28.9° C) and *Campostoma anomalum* (13.4-28.6° C). Spawning temperatures ranged from < 3.8° C for *C. artedii* to 15.6-27.7° C for *Alosa pseudoharengus*.

Because of lack of published data, it was impossible to assess accurately the temperature require-

Table 2. Temperature tolerances of fish found in eastern Lake Erie and the upper Niagara River. All temperatures are in °C.

Species	Temperature tolerance		
Alosa pseudoharengus	Acclimation temperature 17,2 hour incipient lower lethal temperature 7,		
	(Great Lakes Fishery Laboratory 1970)		
	IULT[1]		
	Acclimation Temperature	Adults	Young of Year
	10	23.5	26.5
	15	23.5	- -
	20	24.5	30.3
	25	- -	32.1
	Equations for CTM[2]		
	Adults CTM = 24.6C+0.4T_A		
	Young of year CTM	= 21.9C+0.5T_A	
	where T_A	= acclimation temperature	
	(Otto et al. 1976)		
Ambloplites rupestris	Ambient Temperature	CTM	
	23.5	36.0	
	(Reutter & Herdendorf 1976)		
Aplodinotus grunniens	Ambient Temperature	CTM	
	21.2	34.0	
	(Reutter & Herdendorf 1976)		
	Season	IULT	
	Summer	32.8	
	(Cvancara et al. 1976)		
Carassius auratus	Acclimation Temperature	IULT	
	5	29.0	
	10	30.8	
	15	32.8	
	20	34.8	
	25	36.6	
	30	38.6	
	(Brett 1956)		
	Acclimation Temperature	IULT	
	5	29.9	
	10	31.5	
	15	33.0	
	20	35.0	

Table 2. (cont.)

Species	Temperature tolerance	
Carassius auratus (cont.)	25	37.5
	30	39.0
	35	41.0
	40	41.0
	(Brett 1944)	
	Acclimated to 25, subjected to 1°C h^{-1} rise in temperature, lethal temperature, 36.6	
	(Hart 1947)	
	CTM > 35.0	
	(Reutter & Herdendorf 1976)	
Carpiodes cyprinus	Ambient temperature	CTM
	23.3	37.2
	(Reutter & Herdendorf 1976)	
Catostomus commersoni	Acclimation temperature	IULT
	5	26.3
	10	27.7
	15	29.3
	20	29.3
	25	29.3
	(Brett 1956)	
	Temperature raised 1°C h^{-1}, lethal temperature 32.7	
	(Hart 1947)	
	Ambient temperature	CTM
	19.0	31.6
	(Reutter & Herdendorf 1976)	
Coregonus artedii	Acclimation temperature	IULT
	2	19.75
	5	21.15
	10	24.25
	20	26.75
	25	25.75
	(Edsall & Colby 1970)	
Coregonus clupeaformis	Fry exposed to 10-15°C temperature shock for 1 minute were more vulnerable to predation than were controls	
	(Yocum & Edsall 1974)	

Table 2. (cont.)

Species	Temperature tolerance	
	Acclimation temperature	IULT
	5.0	20.6
	10.0	22.7
	15.0	25.8
	20.0	26.6
	22.5	26.6
	(Edsall & Rottiers 1976)	
Cottus bairdi	Acclimation temperature	CTM
	15	30.9
	(Kowalski et al. 1978)	
Cyprinus carpio	Acclimation temperature	IULT
	20	31-34
	26	35.7
	(Black 1953)	
	Ultimate upper lethal temperature small fish, 38-39°C, large fish, 35-36°C	
	(Meuwis & Heuts 1957)	
	Ambient temperature	CTM
	23.3	39.0
	(Reutter & Herdendorf 1976)	
Dorosoma cepedianum	Acclimation temperature	IULT
	25	34.0
	30	36.0
	35	36.5
	(Hart 1952)	
	Ambient temperature	CTM
	15.9	31.7
	(Reutter & Herdendorf 1976)	
	Season	IULT
	Summer	28.5
	(Cvancara et al. 1976)	
Esox lucius	Stage	IULT
	2-4 cells	19.8
	eyed	28.0
	(Lillelund 1969)	

Table 2. (cont.)

Species	Temperature tolerance	
Esox lucius (cont.)	Juveniles acclimated to 30 had IULT of 33	
	(Hokanson et al. 1973)	
	Acclimation temperature	IULT
	Yolk sac 17.7	24.8
	" " 11.8	24.1
	" " 6.1	20.6
	(Hokanson et al. 1973)	
	Season	IULT
	Summer	30.8
	(Cvancara et al. 1976)	
Esox masquinongy	Newly hatched	
	Acclimation temperature	CTM
	7	28.8
	15	31.9
	25	34.5
	(Hassan & Spotila 1976)	
	Larvae	
	Ambient temperature	CTM
	16.0-22.5	29.9-35.6
		$\bar{x} = 32.8$
	(Bonin & Spotila 1978)	
	Larvae	
	Acclimation conditions	CTM
	15°C, 0 mg l^{-1} As	32.4
	15°C, 0.05 mg l^{-1} As	31.5
	15°C, 1.0 mg l^{-1} As	30.7
	15°C, 5.0 mg l^{-1} As	30.5
	(Paladino & Spotila 1978)	
Etheostoma blennioides	Acclimation temperature	CTM
	15	32.2
	(Kowalski et al. 1978)	
Etheostoma caeruleum	Acclimation temperature	CTM
	15	32.1
	(Kowalski et al. 1978)	
Etheostoma flabellare	Acclimation temperature	CTM
	15	32.1
	(Kowalski et al. 1978)	
Etheostoma nigrum	Acclimation temperature	CTM
	January 15	30.7
	March 15	31.4
	(Kowalski et al. 1978)	
Hypentelium nigricans	Acclimation temperature	CTM
	15	30.8
	(Kowalski et al. 1978)	
Ictalurus melas	Acclimation temperature	IULT
	23	35
	(Black 1953)	
	Season	IULT
	Summer	35.7
	(Cvancara et al. 1976)	
Ictalurus natalis	Ambient temperature	CTM
	22.2	36.4
	(Reutter & Herdendorf 1974)	
Ictalurus nebulosus	Acclimation temperature	IULT
	10	29.0
	20	32.3
	25	33.7
	30	34.7
	(Hart 1952)	
	Acclimation temperature	IULT
	5	29.9
	10	31.5
	15	33.0
	20	35.0
	25	37.5
	30	39.0
	35	41.0
	40	41.0
	(Brett 1944)	
	IULT	Summer 35.5
	IULT	Winter 29.0
	(Fry 1947)	

Table 2. (cont.)

Species	Temperature tolerance		
Ictalurus nebulosus (cont.)	Seasonal variation in lethal temperatures		
	(Fish taken directly from stream and tested)		
	May 12		29.1
	May 28		32.6
	June 14		33.2
	June 25		34.9
	July 8		35.3
	July 25		35.5
	August 15		34.1
	August 26		33.4
	September 6		32.9
	September 11		32.6
	(Brett 1944)		
	Ambient temperature		CTM
	23.0		37.8
	(Reutter & Herdendorf 1976)		
Ictalurus punctatus	Acclimation temperature		IULT
	15		30.3
	20		32.8
	25		33.5
	(Strawn 1958)		
	Acclimation temperature		IULT
	26		36.6
	30		37.3
	34		37.8
	(Allen & Strawn 1967)		
	Acclimation temperature	CTM	DP[3]
	12	34.5	36.0
	16	34.2	36.2
	20	35.5	36.6
	24	37.5	38.5
	28	39.2	40.3
	32	41.0	42.5
	(Cheetham et al. 1976)		
	Ambient temperature		CTM
	22.7		38.0
	(Reutter & Herdendorf 1976)		

Table 2. (cont.)

Species	Temperature tolerance		
Lepomis gibbosus	Acclimation temperature		IULT
	18		28.0
	24		30.2
	(Black 1953)		
	Acclimation temperature		IULT
	25		34.5
	(Brett 1944)		
	Ambient temperature		CTM
	23.1		37.5
	(Reutter & Herdendorf 1976)		
Lepomis macrochirus	Acclimation temperature		IULT
	15		30.7
	20		31.7
	30		33.8
	(Brett 1956)		
	Acclimation temperature	CTM	DP
	25	37.8	37.3
	30	40.0	39.4
	35	43.4	41.9
	(Holland et al. 1974)		
	Ambient temperature		CTM
	22.8		38.3
	(Reutter & Herdendorf 1976)		
	Season		IULT
	Summer		28.5
	(Cvancara et al. 1976)		
Micropterus dolomieui	Ambient temperature		CTM
	23.3		36.3
	(Reutter & Herdendorf 1976)		
Micropterus salmoides	Acclimation temperature		IULT
	20		32.5
	25		34.5
	30		36.4
	(Brett 1956)		

Table 2. (cont.)

Species	Temperature tolerance	
Micropterus salmoides (cont.)	Acclimation temperature	Lethal temperature
	20-21	28.9
	(Black 1953)	
	Eggs died at 32.5	
	(Strawn 1961)	
	Acclimation temperature	CTM
	20	36.7
	28	40.1
	(Smith & Scott 1975)	
	Season	IULT
	Summer	35.6
	(Cvancara et al. 1976)	
Minytrema melanops	Ambient temperature	CTM
	20.0	> 31.0
	(Reutter & Herdendorf 1976)	
Morone chrysops	Ambient temperature	CTM
	21.7	35.3
	(Reutter & Herdendorf 1976)	
	Season	IULT
	Summer	33.5
	(Cvancara et al. 1976)	
Nocomis micropogon	Acclimation temperature	CTM
	15	30.9
	(Kowalski et al. 1978)	
Notemigonus crysoleucas	Acclimation temperature	IULT
	10	29.3
	15	30.5
	20	31.8
	25	33.2
	30	34.7
	(Brett 1956)	
	Seasonal variation in lethal temperatures	
	May 28	30.3
	June 17	31.8
	June 28	33.5
	July 8	33.4
	July 28	33.2
	August 9	32.8
	August 26	31.6
	September 8	30.4
	(Brett 1944)	
Notropis atherinoides	Acclimation temperature	IULT
	5	23.2
	10	26.7
	15	28.9
	20	30.7
	25	30.7
	(Brett 1956)	
	1°C h^{-1} rise in temperature results in a lethal temperature of 34.3	
	(Hart 1947)	
	IULT	35.2
	(McCormick & Kleiner 1976)	
Notropis cornutus	IULT	32.0
	(Brett 1944)	
	Acclimation temperature	CTM
	December 15	30.6
	March 15	31.9
	(Kowalski et al. 1978)	
Notropis hudsonius	Ambient temperature	CTM
	21.7	32.8
	(Reutter & Herdendorf 1976)	
Notropis stramineus	Acclimation temperature	CTM
	December 15	32.3
	January 15	32.3
	March 15	33.0
	(Kowalski et al. 1978)	
Noturus flavus	Ambient temperature	CTM
	1.6	29.0
	(Reutter & Herdendorf 1976)	
Oncorhynchus kisutch	Ultimate upper lethal	
	26	
	(Brett et al. 1958)	

Table 2. (cont.)

Species	Temperature tolerance	
Oncorhynchus kisutch (cont.)	Acclimation temperature	IULT
	5	22.9
	10	23.1
	15	24.3
	20	25.0
	23	25.0
	(Brett 1952)	
	Rapid (3 min) increase in temperature from 10 to 20°C caused hyperglycemia, hypocholesterolemia, decreased blood sugar regulatory precision. Recovery occurs in 24-72 hours.	
	(Wedemeyer 1973)	
Oncorhynchus tshawytscha	Acclimation temperature	IULT
	5	21.5
	10	24.3
	15	25.0
	20	25.1
	25	25.1
	Ultimate upper lethal temperature	
	25.1	
	(Brett 1952)	
	Exposure to 28°C for 67 sec did not cause obvious loss of equilibrium but did increase susceptibility to predation by larger fish	
	(Coutant 1973)	
Osmerus mordax	Ambient temperature	CTM
	6.0	24.9
	(Reutter & Herdendorf 1976)	
Perca flavescens	Acclimation temperature	IULT
	5	21.3
	10	25.0
	15	27.7
	25	29.7
	(Brett 1956)	
	Acclimation temperature	IULT
	18	26.5
	22-24	29.2
	(Black 1953)	

Table 2. (cont.)

Species	Temperature tolerance	
	Ambient temperature	CTM
	22.0	35.0
	(Reutter & Herdendorf 1976)	
Percopsis omiscomaycus	Ambient temperature	CTM
	1.7	22.9
	(Reutter & Herdendorf 1976)	
Petromyzon marinus	Ammocoetes	
	Acclimation temperature	CTM
	5	29.5
	15	30.0
	25	31.0
	IULT 31.4	
	(Potter & Beamish 1975)	
Pimephales notatus	Acclimation temperature	IULT
	5	26.0
	10	28-28.3
	15	30.6
	20	31.7-32.0
	25	33.3
	(Brett 1956)	
	1°C h^{-1} rise in temperature, lethal temperature 34.8	
	(Hart 1947)	
	Ambient temperature	CTM
	6.0	27.8
	(Reutter & Herdendorf 1976)	
	Acclimation temperature	CTM
	15	31.9
	(Kowalski et al. 1978)	
Pomoxis annularis	Ambient temperature	CTM
	24.4	> 32.8
	(Reutter & Herdendorf 1976)	
Pomoxis nigromaculatus	Ambient temperature	CTM
	23.8	34.9
	(Reutter & Herdendorf 1976)	

Table 2. (cont.)

Species	Temperature tolerance	
Rhinichthys cataractae	Acclimation temperature	CTM
	15	31.4
	(Kowalski et al. 1978)	
Salmo gairdneri	Acclimation temperature	Lethal temperature
	11	24
	(Black 1953)	
	At 30°C, a 0.55 min duration of exposure produced loss of equilibrium, while 2 min was required at 28°C. The predation response after exposure paralleled dose responses of equilibrium loss and death	
	(Coutant 1972)	
	Rapid (3 min) increase in temperature from 10 to 20°C caused hyperglycemia, hypocholesterolemia, increased blood hemoglobin and decreased blood sugar regulatory precision. Recovery occurs in 24-28 hours	
	(Wedemeyer 1973)	
	Exposure to 30°C for 90 sec did not result in increased vulnerability to predation by larger fish	
	(Coutant 1973)	
Salmo trutta	Acclimation temperature	DP
	Adult 14-18	25
	26	26
	Fry 5-6	22.5
	20	23
	(Klein 1962)	
Salvelinus namaycush	IULT 25.1	
	(Parker & Krenkel 1969)	
Stizostedion vitreum	Acclimation temperature	IULT
	8-26	27.0-31.6
	(Koenst & Smith 1976)	
	Acclimation temperature	Lower lethal
	25	8
	(Koenst & Smith 1976)	
	Ambient temperature	CTM
	23.3	34.3
	(Reutter & Herdendorf 1976)	

ments of many of the most important fish species. These organisms include *Acipenser fulvescens*, *Lepisosteus* sp., *Osmerus mordax*, *Esox sp.*, *Nocomis micropogon*, *Notropis sp.*, *Moxostoma* sp., *Ambloplites rupestris*, and *Etheostoma* sp. We found a small amount of temperature data for phytoplankton, zooplankton, and benthic macroinvertebrates. Only one lethal temperature was available for zooplankton (30° C for *Eurytemora affinis*, Heinle 1969). Optimum temperatures for zooplankton generally appeared to be below 27° C (Burns 1969, Moshiri et al. 1969). Temperature information was available for some species of benthic macroinvertebrates. *Gammarus fasciatus* had an upper lethal temperature of 31° C, *Asellus intermedius* an upper limit of 33° C (Sprague 1963), *Procladius* an upper limit of 30° C, and *Cryptochironomus* an upper limit of 32.8° C (Curry 1965). Three species of the genus *Chironomus* had lethal temperatures of from 34.5 to 35.5° C (Walshe 1948). No lethal temperatures were available for crayfish (*Orconectes*) found in the Niagara River. Optimum temperatures reported for the benthic macroinvertebrates ranged from 14 to 25° C (Appleby & Brinkhurst 1971, Langford 1971, Langford & Aston 1972).

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[1] IULT = Incipient Upper Lethal Temperature. See text for definition.

[2] CTM = Critical Thermal Maximum (Hutchison 1961). Defined as temperature at which there is a loss of coordinated locomotion when heated at 1°C min^{-1}. Endpoint is onset of spasms.

[3] DP-Death Point. Cessation of opercular movement.

Table 3. Preferred temperatures of fish found in eastern Lake Erie and the upper Niagara River. All temperatures are in °C.

Species	Preferred temperatures			
Alosa pseudoharengus	Final preferendum adults in spring			
	21.3			
	(Reutter & Herdendorf 1974)			
	Young of year		Adults	
	Summer	31.3	Summer	26.5
			Fall	19.6
	(Reutter & Herdendorf 1974)			
			Preferred	temperature
	Month	Acclimation temperature	Adults	Young of year
	Jan.	1- 3	12.0	-
	May	7-11	21.0	–
	June	10-11	19.0	–
	Aug.	15-18	16.0	25.0
		24-25	–	25.0
	Sept.	10-12	16.0	24.0
	Nov.	5- 9	16.0	21.0
	Dec.	1- 4	11.0	19.0
	(Otto et al. 1976)			
Ambloplites rupestris		Adults		
	Winter	21.6		
	Spring	20.5		
	Summer	18.7		
	Fall	22.8		
	(Reutter & Herdendorf 1974)			
Aplodinotus grunniens	Young of year		Adults	
	Summer	31.3	Summer	26.5
			Fall	19.6
	(Reutter & Herdendorf 1976)			
Campostoma anomalum	Acclimation temperature		Preferred temperature	
	6		13.4	
	9		15.2	
	12		20.7	
	15		21.5	
	18		22.3	
	21		23.6	
	24		25.3	
	27		28.6	
	(Cherry et al. 1975)			
	Preferred temperature			
	19-27			
	(Stauffer et al. 1974)			
Carassius auratus	Final preferendum			
	28.1			
	(Ferguson 1958)			
	Maximum O_2 consumption			
	30.0			
	(Fry & Hart 1948b)			
	Peak cruising speed			
	28.0			
	(Fry & Hart 1948a)			
	Preferred temperatures			
	Adults			
	Winter	24.2		
	Spring	25.3		
	Summer	27.0		
	Fall	24.0		
	(Reutter & Herdendorf 1974)			
Carpiodes cyprinus	Preferred temperature			
	22.1			
	(Reutter & Herdendorf 1976)			
Catostomus commersoni	Adults			
	Fall	22.4		
	(Reutter & Herdendorf 1974)			
Coregonus artedii	Optimum temperatures			
	13-18			
	(McGormick et al. 1971)			
Coregonus clupeaformis	Final preferendum			
	12.7			
	(Ferguson 1958)			
	Fingerlings (4.2-7.2 g)			
	10			
	Young fish (1.1-1.7 g)			
	17			
	Position of vertical gradient affected selected temperature			
	(Opuszynski 1974)			
Cyprinus carpio	Acclimation temperature		Preferred temperature	
	10		17	
	15		25	
	20		27	
	25		31	
	30		31	
	35		32	
	(Pitt et al. 1956)			
	Final preferendum			
	32			
	(Pitt et al. 1956)			
	Optimum temperature			
	27			
	(Meuwis & Heuts 1957)			
	Adults			
	Spring	27.4		
	Summer	29.4		
	(Reutter & Herdendorf 1974)			
Dorosoma cepedianum	Adults			
	Summer	19.0		
	Fall	20.5		
	(Reutter & Herdendorf 1974)			

Table 3. (cont.)

Species	Preferred temperatures	
Esox americanus	Final preferendum	
	26.0	
	(Ferguson 1958)	
Esox lucius	Best condition for fry	
	9.9-11.1	
	(Walker 1968)	
Esox masquinongy	Final preferendum	
	24.0	
	(Ferguson 1958)	
Hypentelium nigricans	Preferred temperatures in the field	
	23-32.5	
	(Stauffer et al. 1974)	
Ictalurus natalis	Adults	
	Summer 28.3	
	(Reutter & Herdendorf 1974)	
Ictalurus nebulosus	Preferred temperatures	
	26	
	(Crawshaw & Hammel 1974)	
	Adults	
	Winter 11.9	
	Spring 23.5	
	Summer 24.9	
	Fall 23.6	
	(Reutter & Herdendorf 1974)	
Ictalurus punctatus	Preferred temperatures in the field	
	23-32.5	
	Congregates in water at temperatures above 32	
	(Stauffer et al. 1974)	
	Acclimation temperature	Preferred temperature
	6	18.9
	9	20.4
	12	19.9
	15	21.7
	18	22.9
	21	26.1
	24	29.4
	27	29.5
	30	30.5
	(Cherry et al. 1975)	
	Adults	
	Summer 25.2	
	Fall 25.3	
	(Reutter & Herdendorf 1974)	
	Acclimation temperature	Preferred temperature
	12	17
	16	21
	20	22
	24	28
	28	26
	32	30
	(Cheetham et al. 1976)	
Lepisosteus osseus	Young of year	Adults
	Summer 25.3	Summer 33.1
	(Reutter & Herdendorf 1976)	
Lepomis gibbosus	Final preferendum	
	31.5	
	(Ferguson 1958)	
	Adults	
	Spring 24.2	
	Summer 27.7	
	(Reutter & Herdendorf 1974)	
Lepomis macrochirus	Final preferendum	
	32.3	
	(Ferguson 1958)	
	Acclimation temperature	Preferred temperature
	6	18.7
	9	19.6
	12	23.9
	15	25.9
	18	29.2
	21	30.1
	24	31.2
	27	31.4
	30	31.7
	(Cherry et al. 1975)	
	Mean preferred temperature	
	29.2	
	(Beitinger & Magnuson 1976)	
	Adults	
	Winter 27.4	
	(Reutter & Herdendorf 1974)	
	Preferred temperatures	
	29.3-33.1	
	(Beitinger 1974)	
Lota lota	Final preferendum	
	21.2	
	(Crossman et al. 1953)	
Micropterus dolomieui	Preferred temperatures	
	18-31	
	(Barans & Tubb 1973)	
	Maximum field temperature	
	36.7	
	(Churchill & Wojtalik 1969)	
	Final preferendum	
	28	
	(Ferguson 1958)	
	Field study- -preferred temperatures	
	20.3-21.3	
	(Bennett 1965)	

Table 3. (cont.)

Species	Preferred temperatures	
Micropterus dolomieui (cont.)	Modal selected temperatures during winter increased at rates of 20°C in 24 hours	
	(Barans & Tubb 1973)	
	Preferred temperatures	
	20.2-31.3	
	(Cherry et al. 1975)	
	Young of year	
	Fall	26.6
	(Reutter & Herdendorf 1974)	
Micropterus salmoides	Final preferendum	
	30-32	
	(Ferguson 1958)	
	Preferred temperatures	
	26.6-27.7	
	(Bennett 1965)	
	Final preferendum	
	27	
	(Coutant 1975)	
	Preferred temperature	
	30.2	
	(Reynolds et al. 1976)	
Morone chrysops	Preferred temperatures	
	18-30	
	(Barans & Tubb 1973)	
	Modal selected temperatures during the winter increased at rates of 20°C in 24 hours.	
	(Barans & Tubb 1973)	
	White bass have been collected at maximum temperatures ranging from 29 (Hatch 1973) to 34.4	
	(Churchill & Wojtalik 1969)	
Notemigonus crysoleucas	Adults	
	Winter	16.8
	Spring	23.7
	Summer	22.3
	Fall	21.0
	(Reutter & Herdendorf 1974)	
Notropis atherinoides	Range	
	6-23	
	(Barans & Tubb 1973)	
	Modal selected temperature during the winter increased at rates of 4°C in 24 hours for adult emerald shiners	
	(Barans & Tubb 1973)	
	First have been observed in an area of elevated temperatures ranging from 28 to 30	
	(Agersborg 1930)	
	Adults	
	Winter	8.3
	(Reutter & Herdendorf 1974)	

Table 3. (cont.)

Species	Preferred temperatures		
Notropis hudsonius	Preferred temperature		
	14		
	(Meldrim & Gift 1971)		
	Adults		
	Winter	10.2	
	Spring	14.3	
	(Reutter & Herdendorf 1974)		
Noturus flavus	Adults		
	Winter	5.5	
	Fall	25.1	
	(Reutter & Herdendorf 1974)		
Oncorhynchus kisutch	Optimum growth		
	14.8		
	(Great Lakes Fishery Laboratory 1970)		
	Optimal cruising speed		
	Underyearlings	22	
	Yearlings	20	
	(Brett et al. 1958)		
	Peak swimming speed		
	20		
	(Fry 1967)		
	Adults		
	Spring	11.4	
	(Reutter & Herdendorf 1974)		
Oncorhynchus tshawytscha	Final preferendum		
	11.7		
	(Ferguson 1958)		
Perca flavescens	Preferred temperatures		
	0-29		
	(Barans & Tubb 1973)		
	Spring	22-23	
	(Meldrim & Gift 1971)		
	Spring	23.4	
	(Neill 1971)		
	Acclimation temperature	Preferred temperature Fingerlings	Preferred temperature > 2 yr old
	5	--	11.0
	8	18.6	--
	10	19.3	17.0
	15	23.0	20.0
	20	23.1	20.5
	25	24.5	21.5
	30	26.7	27.5
	Final preferendum		
	24.2		
	(Ferguson 1958)		
	Adults		
	Winter	14.1	
	Summer	20.9	
	Fall	19.9	
	(Reutter & Herdendorf 1974)		

Table 3. (cont.)

Species	Preferred temperatures		
Perca flavescens (cont.)	Acclimation temperature	Age	Preferred temperature
	24	Juveniles	20.0-23.3
	LD 12: 12	Adults	17.6-20.1
	(McCauley & Read 1973)		
Pimephales notatus	Acclimation temperature	Preferred temperature	
	6	15.7	
	9	17.2	
	12	20.5	
	15	20.4	
	18	21.5	
	21	22.8	
	24	25.7	
	27	28.9	
	(Cherry et al. 1975)		
	Preference in the field		
	23-29.5		
	(Stauffer et al. 1974)		
Pomoxis annularis	Adults		
	Winter	19.8	
	Spring	18.3	
	Summer	19.4	
	Fall	10.4	
	(Reutter & Herdendorf 1974)		
Pomoxis nigromaculatus	Adults		
	Winter	20.5	
	Spring	21.0	
	Summer	21.7	
	Fall	22.2	
	(Reutter & Herdendorf 1974)		
Salmo gairdneri	Optimum temperature for growth		
	12		
	(Parker & Krenkel 1969)		
	Acclimation temperature	Preferred temperature	
	10	15.8	
	15	17.5	
	20	22.0	
	(Javaid & Anderson 1967)		
	Final preferendum		
	13.6		
	(Ferguson 1958)		
	Acclimation temperature	Preferred temperature	
	6	11.6	
	9	12.6	
	12	14.4	
	15	16.9	
	18	18.1	
	21	20.1	
	24	22.0	
	(Cherry et al. 1975)		
	Acclimation temperature	Preferred temperature	
	15-20	17-20	
	(McCauley & Pond 1971)		

Table 3. (cont.)

Species	Preferred temperatures
Salvelinus namaycush	Final preferendum
	12.0
	(Ferguson 1958)
	Final preferendum
	11.7
	(McCauley & Tait 1970)
Salmo trutta	Optimum temperature for growth
	12
	(Swift 1961)
	Final preferendum
	12.4-17.6
	(Ferguson 1958)
Stizostedion vitreum	Preferred temperature
	22
	(Koenst & Smith 1976)
	Preferred temperature
	20
	(Kelso 1972)
	Optimum growth
	22
	(Huh et al. 1976)

Table 4. Temperature requirements for reproduction and early development of fish found in eastern Lake Erie and the upper Niagara River. All temperatures are in °C.

Species	Spawning temperatures	Early development	
Alosa pseudoharengus	Range	Optimum hatching temperature	
	15.6-27.7	17.7	
	(Great Lakes Fishery Laboratory 1970)	(Edsall 1970)	
Aplodinotus grunniens	Range	Incubation period for eggs	
	18.0-24.5	Temperature	Time
		21	36 h
		23	23 h
	(Swedberg & Walburg 1970)	25	22 h
		(Swedberg & Walburg 1970)	

Table 4. (cont.)

Species	Spawning temperatures	Early development
Coregonus artedii	Less than 3.8 (Great Lakes Fishery Laboratory 1970)	Optimum range for normal development 2 - 8 Most successful 5.6 Above 7 Less than 50%hatch (Colby & Brooke 1970) Equations given to compute developmental stages as a function of time (days) and temperature. (Colby & Brooke 1973)
Coregonus clupeaformis	Not less than 5.5 (Great Lakes Fishery Laboratory 1970)	Optimum hatching temperature 0.5 Above 6.1 Less than 50% hatch (Price 1940) Optimum range for incubation 3.2-8.1 Highest hatch 4.0, 5.9, 7.8 Lowest hatch 0.5, 2.0, 10.0 Time to hatching ranged from 41.7 days at 10°C to 182 days at 0.5°C. (Brooke 1975)
Cyprinus carpio		During the earliest period of larval development, there is a high sensitivity to 38. Sensitivity decreased with age. (Tatarko 1970) Best temperature for development is between 20-25 (Meuwis & Heuts 1957)
Esox lucius		Optimum hatch 6.4-17.7 only 10% hatch at 24.2 Best growth occurs at 21.0 (Hokanson et al. 1973)

Table 4. (cont.)

Species	Spawning temperatures	Early development
		Hatching Temperature — Success 9-15 — Constant 21 — 19-34% 5.8 — 60% (Lillelund 1969) Oscillations of temperatures in daily rhythms between 15-20 decreased hatching rate by 12% (Lillelund 1969) Larvae from eggs exposed to temperatures above 18 at early embryonic stages demonstrated a decrease of vitality (Lillelund 1969)
Esox masquinongy	9-15 (Scott & Crossman 1973)	Water temperature — Days to hatch 10.4 — 16 12.1 — 12 12.6 — 11 13.2 — 10 15.6 — 8 (Walker 1968) Optimum temperature 13 (Galat & Eipper 1969)
Lepomis macrochirus		Maximum hatch 22.2-23.9 Upper lethal temperature for normal hatch 33.8 (Banner & Van Arman 1973)
Micropterus dolomieui	16.7 (Bennett 1965)	
Micropterus salmoides	Begin nest building at 13.3 and spawned at 18.9 (Bennett 1965) Active spawning at 15 (Olmsted 1974)	Maximum growth of fry at 27.5 and 30 (Strawn 1961)

Table 4. (cont.)

Species	Spawning temperatures	Early development	
Petromyzon marinus	Acclimation temperature	Test temperature	% mortality
64 cell stage	18	12	100
		14	100
		23	100
	(McCauley 1963)	20	100
Salmo gairdneri	Temperature	Time to hatching (days)	
	3.2	101	
	4.8	75	
	7.5	44	
	10.3	29	
	11.5	27	
	12.0	25	
	14.5	21	
	15.5	18	
		(Carlander 1969)	
		Lowest mortality rates of embryos at 7 and 10 with light intensities of 0.2 and 20 lx.	
		3 and 15 with a light intensity of 400 lx were near the thresholds for development	
		(Kwain 1975)	
Stizostedion vitreum	Maximum spawning at temperatures between 7.1 and 9.9 (Rawson 1956)	Temperature fluctuations, consisting of an increase of 4.5°C over the normal 6.6°C had little effect on percent hatch when compared to the control.	
	Optimum fertilization at temperatures between 6 and 12	(Allbaugh & Manz 1964)	
	(Koenst & Smith 1976)	Optimum incubation 9-15 (Koenst & Smith 1976) Optimum fry survival 15-21 (Koenst & Smith 1976)	

Table 5. Miscellaneous information on temperature requirements of fish from eastern Lake Erie and the upper Niagara River. Temperatures are in °C.

Species	Information	
Cyprinus carpio	Maximum spontaneous activity occurs between 25-30	
	(Beamish 1964)	
	attracted to a thermal effluent in spring and summer	
	(McNeely & Pearson 1974)	
Ictalurus natalis	Relationship between log weight and log metabolic rate	
	Acclimation temperature	Regression equations
	12	$Y = -2.8414 + 0.1157X$
	17	$Y = -1.3393 - 0.4742X$
	22	$Y = -1.5293 - 0.4588X$
	27	$Y = -1.5814 - 0.5955X$
	Y = Log O_2 consumption (mg g^{-1} h^{-1})	
	Y = Log body weight (g)	
	Relationship between temperature and metabolic rate	
	Acclimation temperature	Regression equations
	12	$Y = -3.0901 + 0.1943X -0.0038X^2$
	17	$Y = -3.8294 + 0.0651X$
	22	$Y = -3.6951 + 0.0689X$
	27	$Y = -3.1161 + 0.1438X -0.0025X^2$
	Y = Log O_2 consumption (mg g^{-1} h^{-1})	
	X = Temperature (°C)	
	(Morris 1965)	
Ictalurus nebulosus	Temperature	Standard O_2 consumption (mg kg^{-1} h^{-1})
	10	20.0
	20	66.1
	30	196.1
	(Beamish 1964)	
	Normal movement patterns interrupted by presence of a thermal discharge	
	(Kelso 1974)	

Table 5 (cont.)

Species	Information
Ictalurus punctatus	Acute cold stress causes increased predation on juveniles
	(Coutant et al. 1974)
	Critical swimming speed[1] Temperature ambient test — Relative speed (lengths/per sec) 30 15 2.08 30 20 3.26 30 25 3.85 30 30 4.20 30 35 3.63
	(Hocutt 1973)
	Optimum temperature for growth 32 with 14 h photoperiod
	(Kilambi et al. 1970)
Lepomis gibbosus	Maximum growth rate at 25 and 30, growth retarded at 10 and stopped at 5
	(Pessah & Powles 1974)
	Fish consumed 3 times as much food per day at 20 as at 10
	(Hathaway 1927)
	Peak swimming speed 31.0
	(Fry 1967)
Lepomis macrochirus	Peak speed 27
	(Fry 1967)
	Fish consumed 3 times as much food per day at 20 as at 10
	(Hathaway 1927)
	Fish in heated effluent from a power plant had a higher incidence of infection with the viral disease lymphocystis than fish in unheated areas
	(Petty & Magnuson 1974)
Micropterus dolomieui	Fry acclimated to 30 and 35 could not swim at higher test temperatures
	(Larimore & Duever 1968)
Micropterus salmoides	Number of parasites per host was significantly higher in fish taken from areas with elevated water temperatures
	(Eure & Esch 1974)
	Reproductive cycles of bass in the heated arm of a reservoir were accelerated. Extent of alteration was correlated with residence time
	(Bennett & Gibbons 1975)
	Acute cold stress caused increased predation on fry
	(Coutant et al. 1974)
	Critical swimming speed Temperature Ambient Test — Relative speed (lengths/per sec) 30 15 5.18 30 20 5.59 30 25 7.06 30 30 8.08 30 35 7.62
	(Hocutt 1973)
	Temperature for peak speeds 26
	(Fry 1967)
	From 10-30 maximum sustained swimming speed increased. From 30-34 speed decreased
	(Beamish 1970)
	Fish consumed 3 times as much food per day at 20 as at 10
	(Hathaway 1927)
	For a fixed rate of feeding growth rate was greatest at 18
	(Niimi & Beamish 1974)
Notropis atherinoides	Maximum growth at 24.0-28.9
	(McCormick & Kleiner 1976)
Perca flavescens	Temperature — Standard metabolism (ml 0_2 kg^{-1} h^{-1}) 5 20 10 25 15 60 20 100 25 160
	(Fry 1957)
	Swimming speed 10° C-21 cm sec^{-1} 20°C - 33 cm sec^{-1}
	Moved from 10 to 20 speed increased to 33.5 cm s^{-1}

Table 5 (cont.)

Species	Information			
	Moved from 20 to 10 speed decreased to 15.5 cm s^{-1}, after 24 h it rose to 24.5 cm s^{-1}			
	(Otto & Rice 1974)			
	Best growth at 22			
	(Huh et al. 1976)			
	Criterion	Lower lethal	Upper lethal	Optimum range
	Total hatch	4.8	20.5	--
	Normal hatch	6.8	19.9	10.1-18.
	Swim-up larvae	9.8	18.8	13.1-18.
	(Hokanson & Kleiner 1974)			
Pomoxis annularis	Attracted to thermal effluent in spring and summer			
	(McNeely & Pearson 1974)			
Salmo gairdneri	Embryonic development was accelerated by increasing temperature and retarded by lower levels of O_2.			
	(Garside 1966)			
	Temperature	Standard metabolism (ml O_2 kg^{-1} h^{-1})		
	5	63		
	10	100		
	15	175		
	20	200		
	(Fry 1957)			

[1] Critical Swimming Speed = water speed at which a test specimen can no longer maintain an actively oriented position in a current.

Discussion

There are three basic ways in which thermal discharges can affect aquatic organisms. First, through effects on individuals of a given species; secondly, through effects on the structure of aquatic communities; and thirdly, through an impact on ecosystems. Data available on the temperature responses of fish from Lake Erie and the Niagara River can best be discussed in light of these three effects.

Effects on individuals of a species

Effects of heated effluents on individual organisms include: 1. death through immediate effects of heat; 2. internal functional alterations (e.g. changes in respiration, growth); 3. death through synergistic effects of heat and other factors (reduced oxygen, disruption of food supply, decreased resistance to toxic substances); 4. interference with spawning or other critical activities in life cycles; and 5. competitive replacement by more tolerant species as a result of the above physiological effects (Cairns 1971).

The data presented above (Table 2) indicated that some fishes and invertebrates may be in danger of death if they were trapped in the thermal plumes of power plants. Some evidence of impairment of internal functions also was found (Tables 2 and 5). Wedemeyer (1973) reported that coho salmon (*O. kisutch*) and rainbow trout (*S. gairdneri*) experienced hyperglycemia, hypocholesterolemia, increased blood hemoglobin and decreased blood sugar regulatory precision when exposed to heat shock. Coutant (1973) and Yocum & Edsall (1974) reported that fish exposed to thermal shock were more vulnerable to predation than were controls, even when these fish suffered no observable loss of equilibrium. Coutant (1973) reported that juvenile chinook salmon (*O. tshawytscha*) and rainbow trout (*S. gairdneri*) shocked sublethally, were selectively preyed upon by large fishes when shocked and when control fish were offered simultaneously. Significant increases in predation rates were found at doses 10 to 20% of those required for obvious loss of equilibrium. For rainbow trout (*S. gairdneri*) 30 minutes exposure time was required for this effect at 26° C, 2 minutes at 28° C and 1/2 minute at 30° C (Coutant 1972). However, adult fish of susceptible species appeared to be able to avoid potentially lethal temperatures. This ability has been demonstrated for several species by Alabaster (1963) and more recently for fish affected by heated effluent of a steam electric station on the White River in Indiana by Benda & Proffitt (1974).

Very little information was available on the effect of elevated temperatures on eggs, embryos, larvae and juveniles of fish found in the lake and river. These life intervals as well as phyto- and zooplankton may not be able to avoid an area of elevated temperature and may die or suffer impairment of internal functions because of entrainment in the thermal plume or passage through the condensers of a power plant. These effects have been reported for young fish in the discharge canal of a nuclear power plant (Marcy 1971), and for zooplankton (Heinle 1969) and phytoplankton (Morgan & Stross 1969, and Gurtz & Weiss 1974) that passed through the condensers of power plants. For example, Marcy (1971) reported survival percentages of 34.5% and 16.6% for fish larvae exposed to a 93 second passage time in a cooling water system with a ΔT of 12.5° C above ambient and 7.5% and 9% survival after a 50–100 minute passage through the 1.8 km long discharge canal of the Connecticut Yankee nuclear power plant (no ΔT given for canal). Later Marcy (1973) noted that 80% of the mortality at the Connecticut Yankee facility was caused by mechanical damage and 20% was due to heat shock and prolonged exposure to temperatures elevated above 28° C.

The third effect of heat on individuals of a species included synergistic effects such as loss of condition, increased susceptibility to parasites and disease, enhancement of the toxic effects of numerous pollutants, and stress due to the lowering of the oxygen content of heated waters (Tables 2, 3, 5). Massengill (1973) reported that brown bullheads (*Ictalurus nebulosus*) overwintering in the heated effluent of a power plant were in poorer physical condition than fish overwintering under normal conditions. The condition factors for bullheads from the heated area, 12.8–16.7° C, were significantly lower ($P < 0.05$) than those from an unheated area, 2.2–4.0° C, in December 1971 and March 1972; average weights – heated = 164.5–189.8 g, unheated = 241.2–257.4 g. Bass (*Micropterus salmoides*) caught in the thermal effluent region of a South Carolina cooling reservoir were thinner and appeared to be in poorer condition than bass caught in a cooler arm of the reservoir (Spotila, personal observation; Gibbons, personal communication). Bass from the thermal effluent region had a higher burden of helminth parasites than bass from cool areas (Eure & Esch 1974). Petty & Magnuson (1974) reported that *L. macrochirus* in the heated effluent of a power plant had a higher incidence of infection with the viral disease lymphocystis than fish from unheated areas. Fish and alligators (*Alligator mississippiensis*) in PAR pond – a cooling reservoir receiving thermal effluents from a nuclear production facility on the Savannah River Plant in South Carolina – have experienced an epidemic of *Aeromonas hydrophila*. Infection rates of largemouth bass (*M. salmoides*) in the summer of 1976 ran as high as 76% (Esch et al. 1976). The ability of infected alligators to withstand capture stress was greatly reduced and several died (Brisbin 1976). Cairns & Scheier (1957, 1959, 1962, 1964) reported that high temperatures sometimes increased mortality in *Lepomis gibbosus* and *L. macrochirus* exposed to toxic substances. Mercury toxicity in rainbow trout fingerlings (*S. gairdneri*) increased as temperature increased (MacLeod & Pessah 1973). A similar effect was noted for arsenic toxicity to green sunfish (*L. cyanellus*) by Sorensen (1976). The effects of temperature upon the toxicity of chemicals to aquatic organisms have been reviewed by Cairns et al. (1975a,b). No direct information was available on these possible effects in relation to thermal effluents presently entering the lake and river.

The fourth direct effect of heat was interference with spawning (Table 4). Alterations occurred in the reproductive cycles of largemouth bass (*Micropterus salmoides*) in the heated area of a reservoir (Bennett & Gibbons 1975). Lehmkuhl (1974) reported that an altered thermal regime below a reservoir, resulting in lack of or abnormal timing of reproductive signals, exterminated most of the intermediate members of an aquatic food chain.

Another possible effect on spawning is alteration of the migration patterns of prespawning adults. No quantitative information is available on the spawning habits of fish in New York waters of Lake Erie or in the upper Niagara River. Casual observations (Spotila), discussions with local fishermen, and examination of collection data from the Department of Environmental Conservation give some indication of spawning sites. In the upper Niagara River, many game fish, such as bass (*Micropterus dolomieui* and *M. salmoides*), muskellunge (*Esox masquinongy*), and northern pike (*Esox lucius*), spawn in shallow water in the area around Strawberry Island, Motor Island, the south end of Grand Island, along the shore and over rocky areas near the Grand Island shore, in small creeks on the island and in swampy portions of Buckhorn State Park at the north end of the island. Examination of thermal plume data for the Huntley power station, Tonawanda, New York (Niagara Mohawk Power Corporation 1971) indicates that spawning sites probably are not directly affected by the plume. No information is available on migratory behavior of fish in this part of the river. It is not known to what extent entrainment in the thermal plume inhibits normal migratory behavior of spawning adults. Kelso (1974) reported that the normal movement of bullheads (*I. nebulosus*) was interrupted by the presence of a thermal discharge. No information is available on the movement or location of juveniles in the upper river. If young drift or migrate downstream from the Strawberry Island area past the power plant, they might be impinged into the cooling systems or entrained in the thermal effluent and suffer damage as discussed above. Juveniles from the other spawning areas around Grand Island probably would not be affected.

In Lake Erie walleye (*Stizostedion vitreum*) probably spawn along the shoreline in rocky areas, over shallow reefs, and possibly along breakwalls. Bass (*M. dolomieui*) spawn in similar areas. White (1974) states that in the central and eastern basins of the lake most fish probably spawn along the shore and in the mouth and upstream regions of creeks and rivers. Dunkirk Harbor, other harbors, creek mouths and lagoons should be good spawning sites for many warm water fish – bass (*M. dolomieui, M. salmoides*), walleye (*S. vitreum*), perch (*Perca flavescens*), and bluegill sunfish (*Lepomis macrochirus*). Fish spawning in Dunkirk Harbor would be directly affected by the thermal effluent of a steam station located there. It is not known to what extent spawning adults, eggs, embryos, larvae and juveniles experience direct or indirect effects due to high water temperatures. Migrating adults may be entrained in the inner harbor, and spawn there. Adults are attracted to the inner harbor in early spring (March–April) and remain there until late June (local fishermen, Sheppard 1974). Extensive field research is needed to ascertain the impact of both power stations on the spawning activities of local fish.

The fifth direct effect noted was the competitive replacement of sensitive species by more tolerant species. Cairns (1969) has demonstrated that this occurs in freshwater protozoan communities exposed to heated waste waters. Cory & Nauman (1969) and Nauman & Cory (1969) reported that thermal additions from a steam electric station resulted in changes in species abundance and distribution in the upper Patuxent River estuary. Cairns (1956) and Patrick (1969) reported that as water temperature rose the dominant diatoms (20–30° C) in an algal community were replaced by green algae (30–35° C) and finally by blue green algae (35–40° C). Patrick (1971) reported that increases in temperature near the upper end of the range of tolerance produced severe degradation in the structure of diatom communities.

The available thermal data in the literature is insufficient to determine the most sensitive species of plankton in these waters. The most sensitive species of fish probably include some of the darters (*Etheostoma*), suckers (*Moxostoma*), minnows (*Notropis*), and other fish which have not yet been tested. Newly hatched fish are generally regarded as being very sensitive to temperature, much more so than adults of the same species (Fry & Hochachka 1970). Little data is available for these forms because their great sensitivity makes laboratory tests very difficult. These individuals rapidly undergo thermal and osmotic shock during transfer to holding tanks and transit to the laboratory. This is another area that needs more research.

Community effects

Aquatic communities are complex, dynamic, interrelated systems of species, each of which responds differently to biological, chemical and/or physical alterations in the environment. The complexity of an ecosystem derives from the multitude of interactions such as predation, parasitism, and competition, which occur between the many species of organisms that make up the biological part of the system (Cairns 1968). It is generally recognized that the stability of an ecosystem is directly related to its complexity and diversity. This concept was discussed extensively by Odum (1971).

Most forms of stress cause a decrease in the complexity of aquatic communities (Cairns 1967). As stress is applied to an ecosystem, the first response generally is a reduction in the number of individuals of the more sensitive species. Numbers of individuals of more tolerant species may increase. If the stress increases, species begin to disappear as conditions exceed their tolerance limits (Cairns 1968). Thus a 'healthy' community will have many species present, with each species having few individuals. A stressed community will have few species with large numbers of individuals per species.

The above applies to any type of stress including heated effluents. Patrick (1949) demonstrated similar responses with regard to the impact of organic pollution on the diversity of an entire aquatic ecosystem. Patrick et al. (1954) examined the effects of pollution on the diversity of diatom populations. Wurtz & Dolan (1960) concluded that hot water discharged into the Schuylkill River reduced the diversity of the biological community in the river. Cairns (1956) showed that when mixed algae populations were subjected to a gradual rise in temperature, there was a shift in predominance from diatoms at 20–25° C to green algae at 30–35° C and blue green algae at 35–40° C. Trembley (1960, 1961, 1965) and Coutant (1962) reported many important ecological changes in the Delaware River in an area affected by heated effluents. Some of these included: 1) reduction in dissolved oxygen; 2) reduction of species diversity in the protozoan – algae community; 3) decrease in green algae; 4) reduction in protozoans; 5) increase in blue green algae; 6) decrease in species diversity and standing crops of macroinvertebrates; 7) decrease in species diversity and standing crops of fish during the warmer season; and 8) decrease in species diversity and standing crops of rooted aquatic plants. Because of a lack of field and temperature data we cannot begin to assess the effects of elevated temperatures on the structure of the aquatic communities in the lake and river. Almost nothing is known about the temperature relations of phytoplankton, zooplankton and benthic macroinvertebrates. The present ecological status of 24 out of 74 species of fish reported for Lake Erie and 17 out of 61 species of fish reported for the Niagara River is in doubt. Temperature data is available for only 53 of the 80 species in question. Little quantitative field data is available on seasonal occurrence or abundance of organisms in the upper Niagara River or eastern Lake Erie.

Ecosystem effects

The third way in which a heated discharge can affect aquatic organisms is through an impact on the total ecosystem in an area. One factor that influences aquatic ecosystems, and which in turn is affected by heat, is eutrophication. A recent report by the Great Lakes Fishery Laboratory (1970) entitled 'Physical and ecological effects of waste heat on Lake Michigan' expressed concern over the role of heated discharges in the eutrophication of Lake Michigan. This report indicated that acceleration of eutrophication may occur as a consequence of heated effluent from industrial processes, including those at power plants. The western and central basins of Lake Erie are undergoing rapid eutrophication. The eastern basin is undergoing similar physical and chemical alterations but at a much slower rate (Regier & Hartman 1973). Increasing the temperature of the nearshore waters may accelerate eutrophication in these regions.

Trembley (1960) and Coutant (1962) reported that algal photosynthesis proceeded very rapidly at elevated temperatures in the discharge canal of a steam electric station on the Delaware River. Dense algal mats developed which were periodically dislodged and washed downstream. Coutant (1970a) cited several other instances of increased production of algae in areas affected by thermal effluents from steam electric stations on the White River in Indiana, Lake Lichen in Poland, and on Biscayne Bay in Florida.

The fishery in Lake Erie has been subjected to over 150 years of cultural stress (Regier & Hartman 1973, Hartman 1973). Major stresses that have acted on the fish community have included the commercial fishery, cultural eutrophication, the introduction of new species, tributary and shoreline restructuring, shoreline erosion and consequent siltation, and the introduction of toxic materials. Christie (1974) and Leach & Nepszy (1976) have called for the control of overfishing and eutrophication as essential in order to preserve fish communities in the lake. Busch et al. (1975) reported on the precarious state of the walleye (*S. vitreum*) and noted that siltation and eutrophication have become so critical in the western basin that unfavorable weather now has a much more damaging effect on reproductive success than in the past. Continued eutrophication of the eastern basin can be expected to cause similar consequences.

Conclusions

Despite the information contained in Tables 1–5 we have at best a minimal understanding of the temperature requirements of the fish communities living in the New York waters of Lake Erie and the upper Niagara River. Because of a lack of comprehensive, year round field data we cannot even assess the effects of present thermal effluents on these organisms. This situation is not much different from that which exists for many other large bodies of water. Lack of field data cannot be taken as evidence that no ill effects are occurring. Much additional research is needed before we will have the capability to predict accurately the effects of particular thermal discharges on a given lake or river. We hope that this compilation will serve as a basis for future field, laboratory and modeling studies on the effects of heat on the organisms present in eastern Lake Erie and the Niagara River.

We cite the following as major temperature related problems that should be investigated as soon as possible:

1. Direct effects of thermal effluents on aquatic organisms in the lake and river such as functional alterations, synergistic effects of toxicants and high temperatures, damage to eggs, embryos, larvae and juveniles and disruption of spawning activity require immediate attention and intensified research. Synergis-

tic effects and disruption of spawning are potentially the most damaging.

2. Well planned field research is urgently needed to quantify the effects of present effluents on the structure and function of aquatic communities in Lake Erie and upper Niagara River.

3. We suspect that eutrophication may be occurring in response to present thermal effluents in the lake and river. Continued or increased input of heated water into these areas may greatly accelerate the rate of eutrophication and push these areas towards conditions similar to those prevailing in the central and western basins of Lake Erie.

4. Increased input of thermal effluents into the eastern basin of Lake Erie will maintain a stress on the fishery and may irreversibly damage it.

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