Physical and Ecological Effects of Waste Heat on Lake Michigan

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PHYSICAL AND ECOLOGICAL EFFECTS
OF WASTE HEAT ON LAKE MICHIGAN

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I. INTRODUCTION

There is reason for concern about potential serious ecological damage to Lake Michigan as a result of the discharge of industrial and municipal waste heat. At the predicted rate of increase, the waste heat load rejected to Lake Michigan by year 2000 would be more than 10 times the present load. The source of most of the waste heat will be the power industry. Required power capacity has been doubling each decade and there is no sign that this rate will diminish.

Everyone concerned with the problem agrees that not enough is known about the ecological effects of massive heated effluents and that a great deal of research is needed on this problem. Unfortunately, the information is needed now; since it is not available, however, interim standards must be set for Lake Michigan on the basis of existing knowledge.

The purpose of the present report is to present the available evidence that substantiates this concern. The evidence reasonably demonstrates that heat addition, as presently proposed, is an essentially cumulative problem that would contribute to inshore eutrophication and be intolerable from the fish and wildlife standpoint by year 2000. Therefore, it is in the public interest to stop this process now, rather than attempt the difficult task of correcting or reversing it after it has occurred. On the basis of the evidence presented herein, this Department supports stringent standards for Lake Michigan, and concludes that no significant amounts of waste heat should be discharged into Lake Michigan.

II. DESCRIPTION OF LAKE MICHIGAN

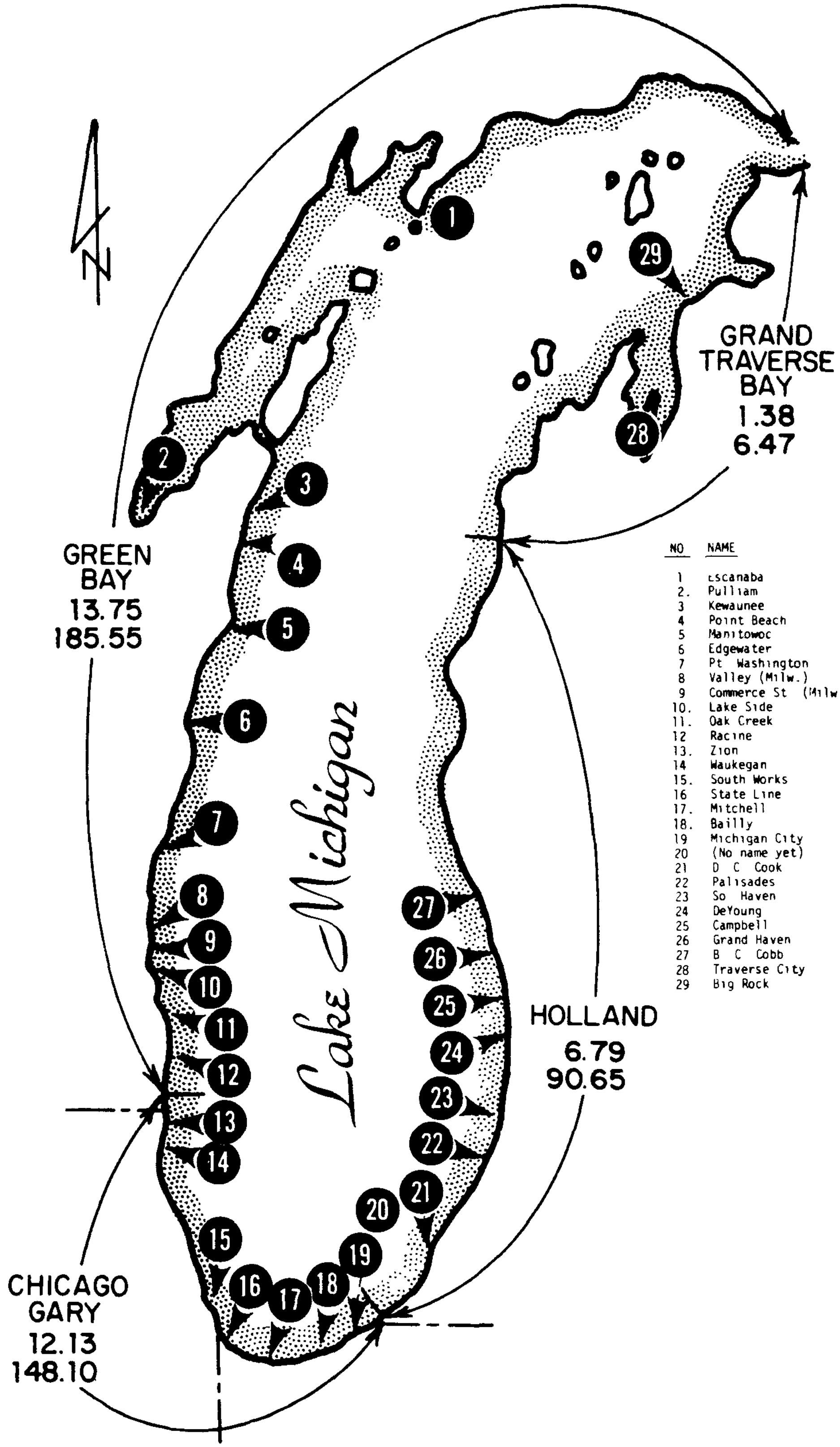
A. OVERVIEW

The following general information is largely from Beeton and Chandler (1963) and United States Department of the Interior (1966).

Lake Michigan, the sixth largest freshwater lake in the world, has an area of 22,400 square miles and a shoreline of 1,661 miles (including Green Bay) (Figure 1). It is bordered by Michigan, Indiana, Illinois, and Wisconsin; most of the 67,860 square-mile drainage area is in Michigan and Wisconsin. Maximum length of the lake is 307 miles, and maximum width is 118 miles in the northern basin (from Little Traverse Bay to Little Bay de Noc) and 75 miles in the southern basin (from Grand Haven to Milwaukee). Maximum depth is 923 feet and mean depth is 276 feet. Lake volume is estimated at 173 trillion cubic feet or 1,170 cubic miles.

The southern two-thirds of the lake is an open water area free of islands. The shoreline is regular and the bottom contours are gentle. The northern one-third of the lake is characterized by more rugged bottom relief and shoreline. Islands and bays are common.

No large tributaries (over 5,000 cfs) flow into Lake Michigan, and it has the smallest discharge of the five Great Lakes--55,000 cfs at the Straits of Mackinac. Lake level is subject to an annual fluctuation of slightly more than 1 foot. Water levels are highest in summer and lowest in late winter or early spring. The average surface elevation of the lake is 578.77 feet above the mean sea level (International Great Lakes 1955 datum).



NO	NAME	CAPACITY (M W)
1	Escanaba	23
2.	Pulliam	392
3	Kewaunee	527 NU 1972 -
4	Point Beach	2x497 NU 1971&72 -
5	Manitowoc	52
6	Edgewater	129(+330 in 1969)
7	Pt Washington	411
8	Valley (Milw.)	280 in 1969
9	Commerce St (Milw.)	35
10.	Lake Side	311
11.	Oak Creek	1619
12	Racine	23
13.	Zion	2x1100 NU 1972&73 -
14	Waukegan	1066
15.	South Works	105
16	State Line	923
17.	Mitchell	390(+115 1970) -
18.	Bailly	590
19	Michigan City	203 1973
20	(No name yet)	400 1973
21	D C Cook	2x1100 NU 1972&73 -
22	Palisades	811 NU 1970 -
23	So Haven	17.5
24	DeYoung	53 5
25	Campbell	650
26	Grand Haven	23
27	B C Cobb	510
28	Traverse City	15
29	Big Rock	75 NU

Figure 1.--Lake Michigan map showing four shoreline sectors described by Acres (1970), and estimate of total waste heat production (billions of BTU's/hr) for 1968 (upper number) and 2000 (lower number). The sites of existing power installations (numbers 1 to 29) are from Krezoski (1969).

Ice is common along the shores of Lake Michigan in winter but the open lake remains ice-free during all but the most severe winters. The open lake surface waters range in temperature from a low of 32 to 35°F in March to a peak of 75°F or greater in August. The lake is stratified in summer and deep waters remain near 39°F throughout the year (Figure 2). A graphic generalized annual temperature cycle, by lake sector, is shown in Figure 3.

Winds over Lake Michigan are primarily westerly; at least 60 percent of all observations at Grand Rapids, Michigan, and Chicago, Illinois, recorded wind from the western half of a north-south line.

The chemical environment of Lake Michigan has changed and is changing at a significant rate. The concentrations of total dissolved solids in Lake Michigan are increasing at a rate of about 2 percent per decade. Typical values were 128 mg per liter in 1880, 142 in 1920, 155 in 1960, and about 158 in 1969. Concentrations of phosphate and nitrate are also presumably increasing, although this increase cannot be demonstrated because measurements in past decades were not reliable.

Dissolved oxygen in Lake Michigan, except in southern Green Bay, is usually above 90 percent of saturation at all depths. A few isolated measurements of 65 to 90 percent of saturation have been reported for the hypolimnion of the southern basin. No values below 90 percent were detected, however, in studies by the Bureau of Commercial Fisheries Great Lakes Fishery Laboratory in 1968.

Although Lake Michigan in 1970, by generally accepted standards (and excluding pesticides), has high water quality and most of the characteristics of an oligotrophic lake, a measurable loss of water quality is taking place and the rate of change has not been altered.

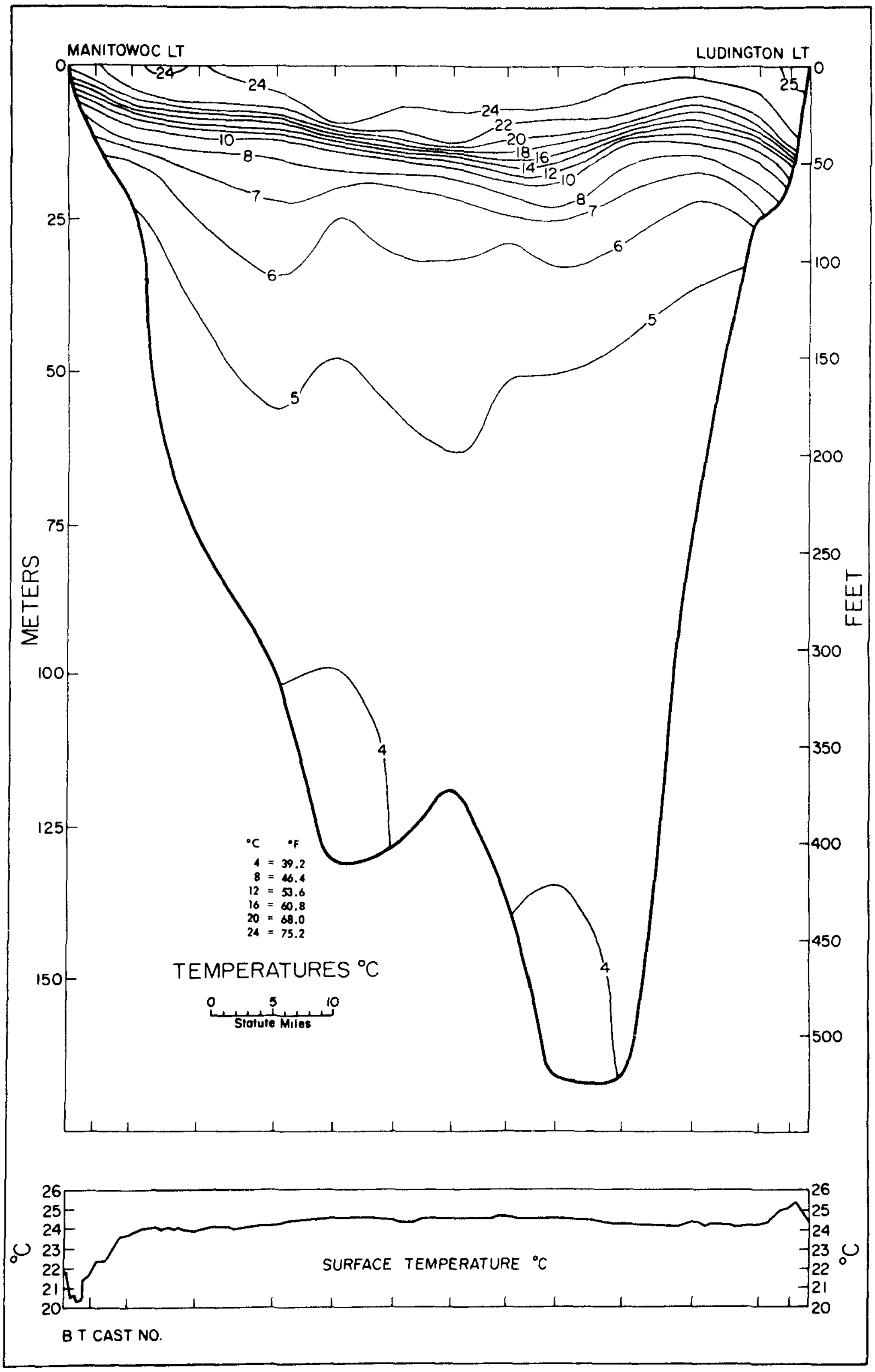


Figure 2.--Typical summer vertical temperature structure of Lake Michigan. Warm waters of 20° to 24°C (68.0-75°F) are in upper 10-20 meters, thermocline or zone of rapid temperature change is at 15-25 meters, and cold water of 4° to 8°C (39-46°F) at greater depths.

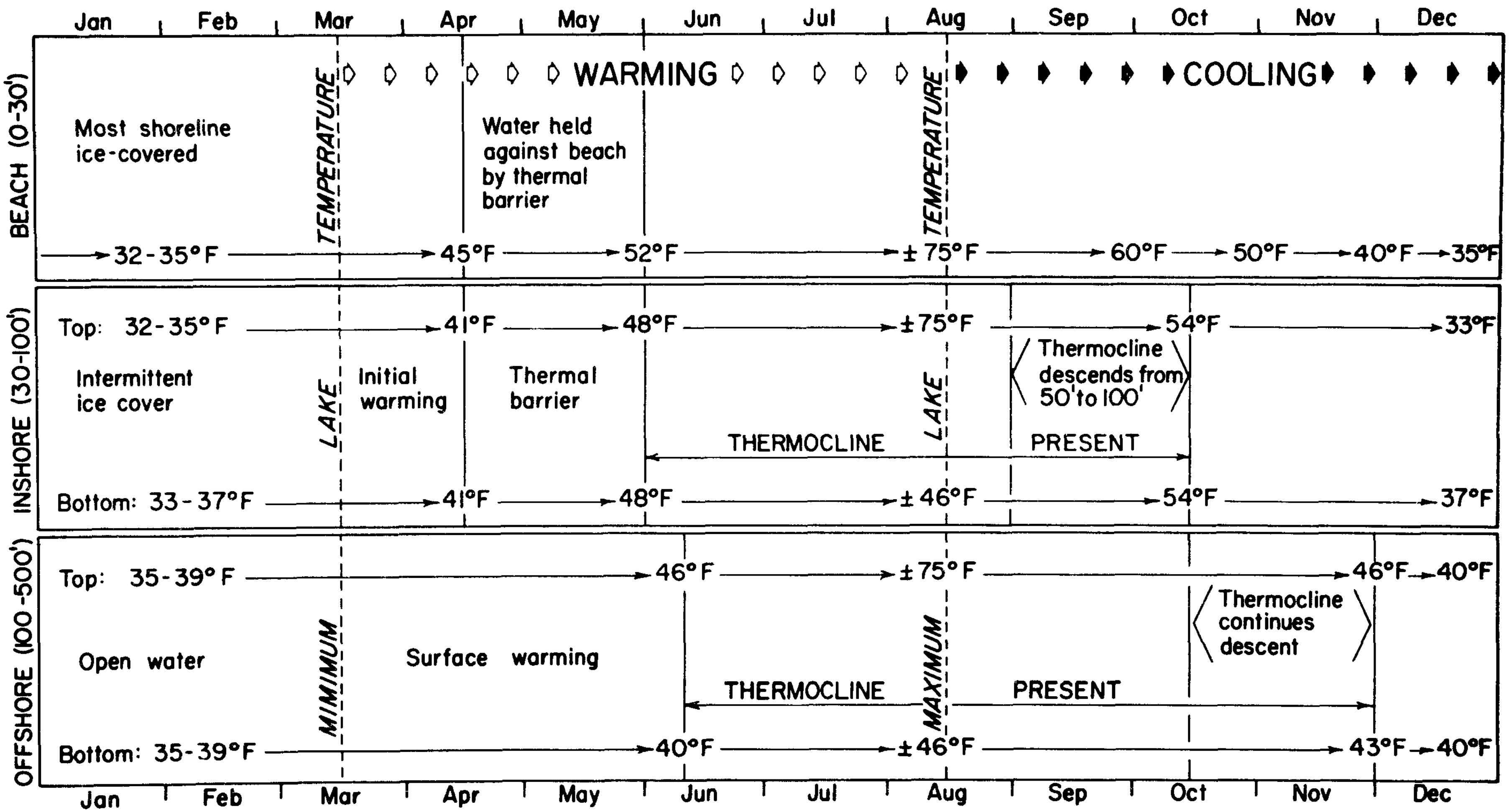


Figure 3.--Generalized annual temperature cycle in Lake Michigan by depth zones, with details of seasonal thermal characteristics.

For later consideration in this report, it is desirable to discuss the lake as two distinct, major zones, the inshore zone and the open lake. The inshore zone is defined as that volume of water which lies between the shoreline and the 100-foot depth contour. Within the inshore zone is the beach water zone, a sub-area that extends from the shoreline out to the 30-foot depth contour. The open lake zone lies beyond the 100-foot contour. Tables 1 and 2 present certain characteristics of these zones.

B. INSHORE WATERS

1. Importance of Inshore Zone

The inshore zone of Lake Michigan is probably the most important portion of the lake from the standpoint of man. Not only is it the zone that is most used by man (for example, as a source of water supply for domestic, industrial, and cooling water and as an area for fishing, boating, and swimming), but it is also the most biologically productive portion of the lake. The fishery productivity of the shallow and inshore waters of Lake Michigan has traditionally been the highest of any area in the lake. For example, within the State of Michigan waters of Lake Michigan, Green Bay constitutes less than 10 percent of the area but has contributed as much as 65 percent of the total annual commercial catch (Hile et al.,1953). Probably one of the basic reasons for the high productivity of the shallow water is the presence there of a substrate within the lighted surface zone where photosynthesis can take place. Also, nutrients are continually recycled from the bottom back into the water column due to strong vertical mixing processes.

Table 1.--Depth and volume characteristics of the major zones of Lake Michigan

Zone	Depth range (ft)	Area (sq mi)	Percentage of total area	Volume (cu mi)	Percentage of total volume
Open Lake	>100	17,360	77.5	1,122.0	95.5
Inshore Water	0 to 100	5,040	22.5	47.6	4.1
Beach water (subzone)	0 to 30	1,677	7.5	4.8	.4
Entire Lake	-	22,400	-	1,174.36	-

Table 2.--Lengths, widths, areas, and volumes of beach and inshore zones for four shoreline sections of Lake Michigan. The sections are analogous to those defined by Acres (1970).

Section of shoreline 1/	Length of shoreline (mi)	Beach zone			Inshore zone		
		Ave. width (mi)	Area (sq mi)	Volume (cu mi)	Ave. width (mi)	Area (sq mi)	Volume (cu mi)
Grand Traverse	327	0.35	378	1.07	1.04	339	3.21
Holland	207	.85	132	0.37	2.55	529	5.01
Chicago-Gary	103	2.05	143	0.41	6.21	640	6.06
Green Bay	1,024	1.06	1,024	2.90	3.45	3,532	33.40
Entire shoreline	1,661	0.96	1,677	4.76	3.03	5,040	47.68

1/ See Figure 2 for locations of sections.

The inshore and surface waters of Lake Michigan also are occupied by all species of fish (except chubs and sculpins) at one time or another during their life cycles. Some species such as yellow perch and catfish spend much of their life in shallow water; other species are present in the shallows only when immature or during migrations.

2. Extent of Inshore Water

The average width of the inshore water zone is 3 miles. The area is 5,040 square miles, or about 22 percent of the total area of the lake and three times the area of the beach water zone. The volume of water is 48 cubic miles--10 times that of the beach water zone but only 4.1 percent of the volume of the entire lake.

In contrast, the beach water zone has an average width of only 0.96 mile although the average is 2.05 miles for the Chicago-Gary sector. Its surface area is 1,677 square miles, or about 7 percent of the lake surface, including Green Bay. The volume is 4.5 cubic miles, or about 0.5 percent of that of the entire lake.

The approach of Acres (1970) has been followed in dividing the inshore zone of Lake Michigan into four sections (Figure 1). The physical dimensions of these segments are described in Table 2.

3. Thermal Trends in Inshore Waters

Seasonally, inshore water temperatures range from 32°F to as high as 82°F. They are lowest from January to mid-March, when the water is usually covered with ice. The initial period of warming generally begins in late March. Because of the high surface-to-volume ratio, the inshore areas warm more rapidly than the open lake.

By mid-April the beach waters are warmed to about 48°F, while the waters of the open lake remain below 38°F. This situation creates a strong temperature gradient between the inshore and open lake waters, and is an effective horizontal mixing barrier, which may persist as long as 6 weeks. During this time, pollutants introduced into inshore waters pose a potentially serious problem, because they are trapped there and progressively increase in concentration.

Inshore surface waters reach maximum temperatures in mid-August; bottom water temperatures are variable, however, due to vertical movements of the thermocline. During the summer, such movements are caused by wind-induced internal waves or seiches and cause bottom temperature changes as much as ± 18°F in less than 24 hours.

Changes in the wind direction over the lake induce large changes in the temperature of the entire inshore zone, at least several times each season. Wind shifts cause surface waters to be blown away from shore and deep, colder waters to upwell into the inshore zone. Figure 4 shows the vertical temperature structure of the lake during such event, including the very cold water along the eastern shore.

The net natural warming causes the top of the thermocline to descend below the 100-foot depth contour during September to mid-October. Cooling is rapid in the fall and is complete by late December.

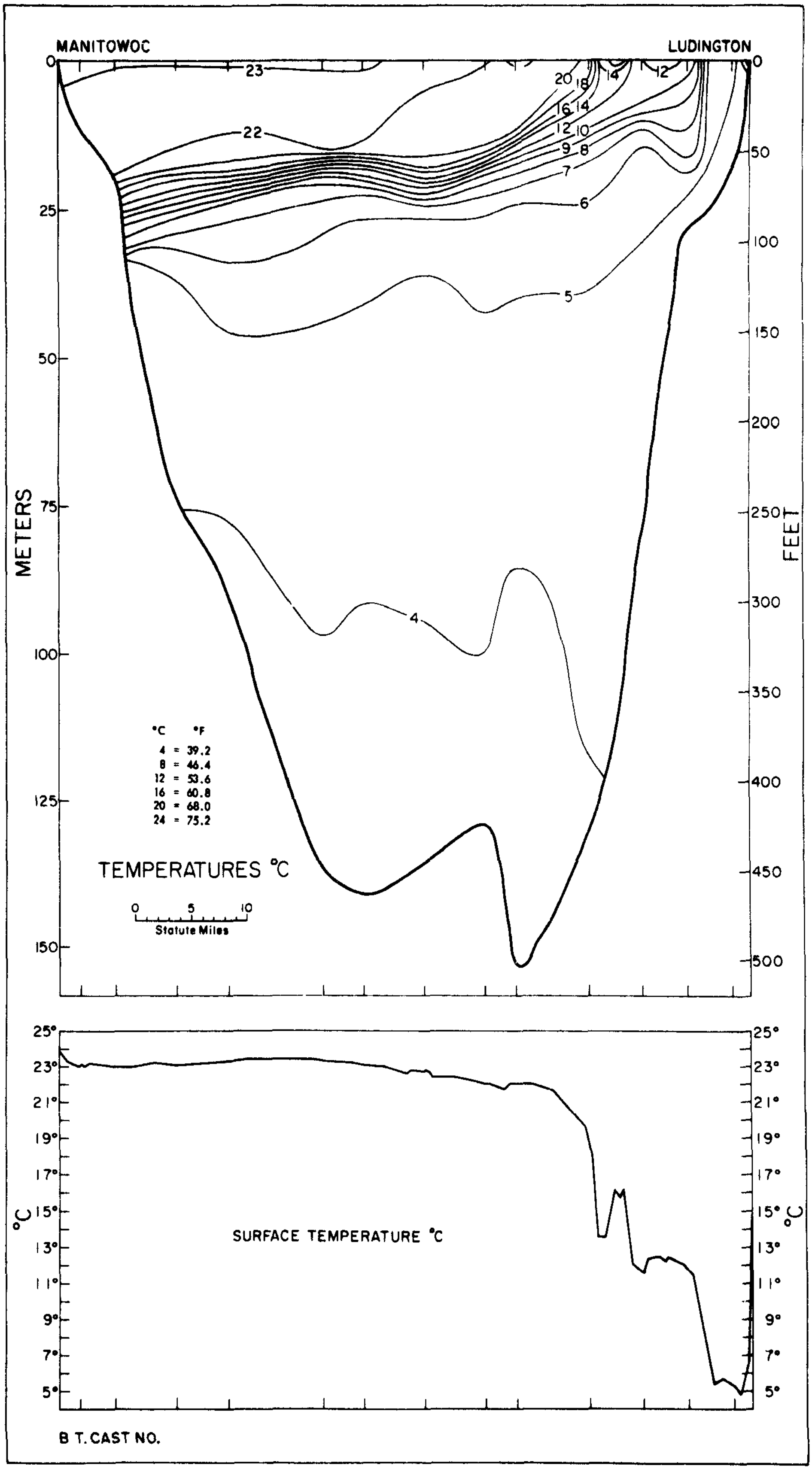


Figure 4.--Lake Michigan vertical temperature profile in mid-August, showing thermocline and a seiche-induced upwelling of cold water along the east shore.

4. Inshore Currents

The currents of the inshore waters are to some extent independent of the general system of lake-wide currents (which are discussed later). Inshore currents move parallel to the shoreline and with the prevailing winds, especially within the 30-foot depth contour (that is, a wind blowing from the north will cause the inshore waters to flow south).

Average current speeds at the 60-foot contour tend to be slower on the western shore of the lake (0.16 to 0.32 ft/sec) than on the eastern shore (0.38 to 0.45 ft/sec). Since winds throughout the region average 11 to 13 miles per hour (17 to 20 ft/sec), the currents average 1 to 3 percent of the wind speed.

5. Inshore Water Chemistry

Generally chemical concentrations are higher and the variation is greater in inshore waters than in the open waters of Lake Michigan (Table 3). The inshore waters receive municipal and industrial discharges and have in many locations been classified as being polluted (FWPCA, 1968).

Ammonia concentrations up to 1.4 mg per liter have been found near Calumet City, Illinois, and soluble phosphorus concentrations up to 1.5 mg per liter near Milwaukee, Wisconsin. Phenols and chlorides, both originating from industrial wastes, have been detected in high concentrations in inshore waters of the lake.

Table 3.--Chemical characteristics measured in inshore waters of Lake Michigan in 1962-63

[Values for average and range are in milligrams per liter unless otherwise indicated; ND - not detectable at sensitivity of test.]

Characteristic	Number of samples	Average	Range
Dissolved oxygen	2,541	10	3.7-16
Saturation (percent)	1,701	102	43-148
BOD	730	1.4	ND-8.6
NH_3-N	1,751	0.13	ND-1.4
NO_3-N	1,654	0.14	ND-0.90
Organic-N	529	0.21	0.01-0.70
Total PO_4	1,382	0.04	ND-5.0
SiO_2	645	1.7	0.4-4.4
Na	400	4.0	1.8-7.5
K	453	1.2	0.5-3.8
Dissolved solids	976	175	86-810
Specific conductance (micromhos per centimeter)	2,452	285	33-1130
pH (pH units)	2,113		6.4-9.3
Alkalinity	2,169	105	70-210
Ca	616	35	17-40
Mg	898	12	7-14
Cl	1,611	7.1	1.5-94
SO_4	1,547	20	10-76
Phenols (micrograms per liter)	1,033	2	ND-32

Dissolved oxygen is sometimes more depleted in the inshore waters than in deeper areas of the lake. Concentrations as low as 3.7 mg per liter (43 percent saturation) have been detected. Measured biochemical oxygen demands (BOD) have been as great as 6.7 mg per liter outside Milwaukee Harbor and 8.6 mg per liter near the mouth of the Grand River (off Grand Haven, Michigan).

Although levels of most chemical substances in the inshore waters are not now high enough to be considered critical for most water uses, they do show evidence of water quality degradation due to the large amounts of pollutants being discharged to Lake Michigan.

Control of these pollutants has been clearly recognized as a matter of great public concern; to date more than $1 billion has been spent by government (at all levels) and industry for sewage treatment facilities along the shore of Lake Michigan. It is estimated that several billion more dollars will be required to complete the job.

6. Fishery Resources

Nearly all of the most valuable and abundant native species of Lake Michigan live in the inshore region, but all of the important native species that lived in this zone have been greatly reduced or are now rare (Tables 4 and 5). All of these native species once migrated into tributary streams and rivers, usually to spawn; except for the runs of common suckers, these migrations have virtually vanished. The whitefish was once the most valuable fish of the lake, and whitefish and lake herring were extremely abundant in shore and tributary areas. Both species vanished from these areas, however, soon after mill dams,

Table 4.--Average annual production (thousands of pounds) of major[1/] species of Lake Michigan

Period	Native species								New species				[2/]	
	Sturgeon	Lake trout	Suckers	White-fish	Lake herring	Wall-eye	Yellow perch	Chubs	Carp	Smelt	Alewife	Coho salmon	Other species	Average
1879-1900[3/]	834	7,225	1,810	2,715	16,977	378	3,866	2,061	261	-	-	-	4/	35,149
1910-1919[3/]	13	6,763	4,035	1,670	8,642	189	2,411	3,525	247	-	-	-	4/	27,059
1920-1929[3/]	7	7,001	2,117	2,111	4,015	88	1,537	2,902	679	-	-	-	4/	20,477
1930-1934	5/	5,342	2,258	3,730	4,985	111	1,199	4,367	769	425	-	-	354	23,540
1935-1939	5/	5,038	2,280	1,201	4,621	78	2,406	5,295	1,605	1,462	-	-	234	24,220
1940-1944	5/	6,579	2,125	1,351	1,830	49	2,729	1,971	1,702	2,913	-	-	425	21,674
1945-1949	5/	2,675	1,901	3,756	6,044	506	1,446	5,435	1,319	765	-	-	560	24,407
1950-1954	3	14	882	1,436	8,000	605	1,963	10,482	1,170	4,384	-	-	243	29,182
1955-1959	1	6/	652	105	3,639	488	3,055	9,947	1,785	6,983	568	-	104	27,327
1960	1	6/	767	124	232	118	3,285	12,659	1,416	3,267	2,369	-	73	24,311
1961	2	6/	494	395	177	97	4,959	12,133	1,842	2,152	3,199	-	109	25,559
1962	1	6/	263	266	116	67	4,050	11,115	1,206	1,546	4,742	-	103	23,475
1963	3	26	299	285	41	61	4,872	7,460	1,277	1,203	5,396	-	98	21,021
1964	3	6/	215	777	34	35	5,835	5,172	1,320	969	11,744	-	97	26,201
1965	2	6/	168	995	46	27	1,296	7,440	2,016	927	14,007	-	70	26,994
1966	2	6/	404	1,422	49	24	736	7,228	2,714	1,110	29,004	-	71	42,764
1967	6/	1	391	875	30	16	1,265	9,089	2,542	1,225	41,396	1,484	137	58,951
1968	.2	73	465	893	53	10	631	10,183	2,352	1,789	27,194	1,999	166	45,810

1/ Species that have had an annual production greater than one million pounds.
2/ Includes species for which catches have always been less than one million pounds.
3/ Average for years of record.
4/ Incomplete data.
5/ Fishing prohibited in Michigan 1929-1950 and in other states after 1929.
6/ Less than 500 pounds.

Table 5.--Depth distribution and abundance of Lake Michigan fish in early period (at time of settlement) and recent period (last several decades)

[A = abundant; R = ruduced; VR = very rare]

Species	Inshore						Value and use
	Shallow		Intermediate		Open lake		
	Early	Recent	Early	Recent	Early	Recent	
Native shallow							
Emerald shiner	A	VR					Valuable forage
Lake herring	A	VR	A	VR			Valuable forage and food
Sturgeon	A	VR					Valuable food
Common sucker	A	R					Low value food
Sturgeon sucker			A	VR			Low value food
Yellow perch	A	R					Valuable food and recreation
Walleye	A	VR					Valuable food and recreation
Whitefish	A	VR	A	R			Valuable food
Native deep							
Burbot	A	VR	A	VR	A	VR	Low value food
Chubs (7 species)					A	R	Valuable forage and food
Deepwater sculpin					A	R	Valuable food
Lake trout	A	VR	A	R	A	R	Valuable food and recreation
Exotic							
Alewife		A		A		A	Nuisance, fish meal, valuable forage
Carp		A					Low value food
Coho salmon		A		A		A	Valuable food and recreation
Smelt		A		A			Valuable food and recreation

industrialization, and deforestation blocked movement or caused tributaries and shore areas to become warmer and more turbid. These factors may also have contributed to early elimination or reduction of runs of sturgeon, yellow perch, and walleye in many tributaries or shallow areas.

Populations of the larger native inshore species less affected by warming and turbidity (suckers and walleye) or that persisted at intermediate depths of the inshore region (lake herring and whitefish), were reduced greatly in the late 1940's and the 1950's by sea lamprey predation. The lake herring and remaining abundant inshore species (emerald shiner and yellow perch) were adversely influenced by competition during the explosive increase in dominance of the alewife during the late 1950's and 1960's. Before the alewife invasion, the lake herring was the most abundant species of the lake, and the emerald shiner was extremely abundant in rivers and harbors, where it often clogged water intakes. Both were major forage species for inshore predators such as yellow perch and walleyes.

All exotic species, including coho salmon, are very abundant in inshore areas during part of the year. Carp became abundant in shallow areas in the late 1800's and were particularly favored by the warmer and more turbid tributaries that resulted from forest removal and settlement. Smelt became abundant at the shallower depths during 1930-60 but were reduced substantially when the alewife became extremely abundant. The alewife has become the most conspicuously abundant inshore species because of spring dieoffs, but there is no evidence that its abundance equals the total of the previously very abundant species that it has replaced. The alewife is now the primary forage species for all major predators of the lake, but its objectionable characteristics have fostered management objectives aimed at reducing its abundance.

Other new inshore species which are not abundant, but which are important features of the present fishery restoration efforts on the Great Lakes, are the steelhead trout, brown trout, kokanee salmon and splake (lake trout-brook trout hybrid). Plantings of steelhead trout and brown trout have been started in Lake Michigan, and early results are promising.

Substantial amounts of money have been and are being spent on Lake Michigan fishery programs. Since 1967 the sea lamprey control program on Lake Michigan has involved an expenditure of $6 million (69 percent U.S., 31 percent Canadian), and the current annual lamprey control budget is $500,000. In addition, 11 million lake trout have been planted since 1965 by Federal and State governments at a cost of about $1 million. The States of Illinois, Indiana, Michigan, and Wisconsin all maintain fishery management programs on their Lake Michigan waters and place very substantial monetary values on the sport fishery, boating, and other recreational uses. Michigan, for example, is carrying a $90,000 management budget in fiscal year 1971 to conduct Lake Michigan fishery sampling and maintain a research station. The cost of the State's 1970 Lake Michigan stocking program--involving principally coho salmon--was $270,000. Michigan fishery statistics indicate that in 1969, 557,000 angler days were spent fishing for trout and salmon on Michigan waters of the lake, at an estimated expenditure of $16 per day, for a total angler expenditure of $9.5 million (Fish Division, Michigan Department of Natural Resources, personal communication).

C. OPEN LAKE

1. Definition and Extent

The maximum length of the open lake area is 307 miles; the average width is 118 miles. The surface area is 17,360 square miles--approximately 77 percent of the entire lake surface. The volume is 1,122 cubic miles--96 percent of the entire lake volume.

2. Thermal Trends in the Open Lake

Despite its great depth, Lake Michigan undergoes seasonal temperature changes similar to those in most inland lakes of temperate North America. The deep waters of the open lake remain close to 39°F, the temperature of maximum density, throughout the year, whereas surface (and shallow) waters undergo considerable thermal changes seasonally ranging from 32°F to as high as 82°F. (See Figure 3 for a generalized treatment of the temperature cycle in the open lake.)

The open lake remains ice-free except during extremely cold winters. During this period the water cools very slowly to the seasonal minimum in mid-March. Highest temperatures (35-39°F) at this time are in deep offshore waters.

Initial warming begins in late March. Thermal stratification is evident in the open lake by early June, but is not persistent and well established until late June. Depth of the upper limit of the thermocline is then about 50 feet. Surface temperatures rise rapidly over the entire lake until mid-July. Between mid-July and mid-September, surface temperatures remain nearly constant. Maximum lake temperatures usually are in mid-August. The upper limit of the thermocline descends from a depth of about 50 feet to about 100 feet during September to mid-October; it continues descent in the open lake during November and may reach 250 feet before it disintegrates. By late December, rapid cooling is complete and the lake is again nearly homothermous.

3. Currents in the Open Lake

Winds, water temperatures, bottom shape, rotation of the earth, and other factors all influence the currents of Lake Michigan. Seasonal temperature changes may be the predominant driving forces of net circulation (Huang, 1969). This recent theory contradicts an earlier one that winds are the primary driving force (Ayers et al., 1958). Huang's mathematical evidence demonstrated that net circulation can be maintained in southern Lake Michigan by thermal factors alone. Winds modify net circulation by causing surface-driven movements and by rocking the entire lake back and forth. Huang (1969) distinguished several different types of thermally induced circulations in Lake Michigan. All are based on the fact that fresh water is most dense at about 39°F. Water of higher or lower temperature is lighter and floats on 39°F water. Figure 5 summarizes Huang's theory and shows the annual cycle of water temperature in the lake.

During January to March the entire lake mixes together but as heating begins in April the inshore water heats most rapidly. A "thermal bar" develops and effectively isolates the inshore waters from the rest of the lake. As heating continues the "thermal bar" moves out into the lake and by June the lake becomes thermally stratified into a warm upper layer and a cold deep layer.

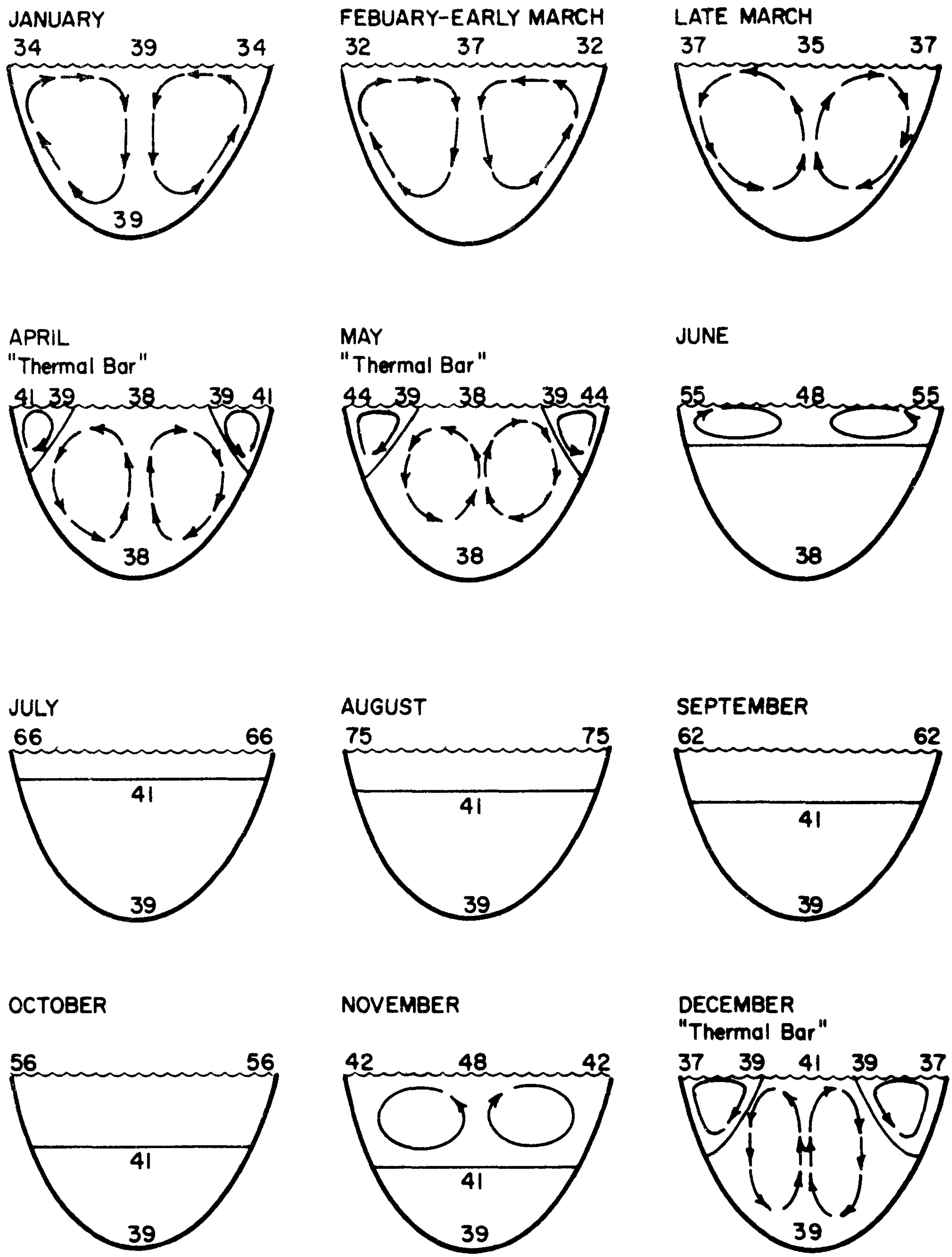


Figure 5.--Seasonal water temperatures and thermally induced circulations in southern Lake Michigan. (Numbers indicate approximate water temperature in °F. Circulation in July through October is primarily wind driven, and seiches are common. Figure adapted from Huang [1969], Rondy [1969], and others.)

After fall cooling, a second but weaker "thermal bar" occurs in December. Normally it is not observed, however, because of the weak temperature differences and the mixing of the strong winter winds.

4. Open Lake Chemistry

The open-lake waters of Lake Michigan are generally typical of oligotrophic lakes. Oxygen is always near saturation and the concentrations of nitrogen and phosphorus are low. Total dissolved solids average 158 mg per liter and the alkalinity is 110 mg per liter (Table 6).

5. Fishery Resources

Few native species have been abundant in the offshore region of Lake Michigan (Table 5). All of these are now reduced or very rare. The deepwater sculpin and seven species of chubs were extremely abundant in deep water where they lived during the entire year. These were the major forage of the two native deepwater predators--the lake trout and burbot. Larger chubs were also valuable food species and the two largest species were heavily exploited by the early fishery and became rare in the early 1900's. All other species of chubs have recently been reduced greatly by the combination of continued heavy exploitation, sea lamprey predation, and alewife competition.

Lake trout and burbot once lived in all depth zones of the lake. The adults were most abundant in deep water, and the young in shallower areas. Reports of the early fishery indicate, however, that adult lake trout were common in inshore areas and the larger rivers, as they were taken by fishermen in shore seines during the mid-1800's.

Table 6.-- Chemical characteristics measured in the open-lake portion of Lake Michigan in 1962-63

[Values for average and range are in milligrams per liter unless otherwise indicated; NS = not sampled; ND = not detectable at sensitivity of test.]

Characteristic	Number of samples	Average	Range
Dissolved oxygen	1,080	12	8.4-17
Saturation (percent)	497	102	73-152
BOD	NS	-	-
NH_3-N	429	0.06	ND-0.50
NO_3-N	595	0.13	ND-0.65
Organic-N	313	0.19	ND-0.52
Total Solids PO_4	388	0.02	ND-0.14
SiO_2	299	2.5	0.6-5.5
Na	321	3.9	2.7-6.5
K	325	1.1	0.4-2.0
Dissolved solids	417	155	100-240
Specific conductance (micromhos per centimeter)	918	260	185-345
pH (pH units)	1,040		7.5-8.9
Alkalinity	858	110	75-130
Ca	395	33	25-40
Mg	318	12	8-16
Cl	607	6.5	3.3-11
SO_4	561	20	12-30
Phenols (micrograms per liter)	NS	-	-

Large burbot may also have been taken in the early inshore fishery but not mentioned because of their low value as food fish. Lake trout and burbot were reduced to near extinction by sea lamprey predation in the late 1940's and early 1950's. Sea lamprey control measures and intensive lake trout stocking in the late 1960's have increased lake trout abundance substantially.

Of the exotic species that have been introduced into or have invaded Lake Michigan, the alewife and coho salmon live in the offshore region of the lake. Chinook salmon are also being stocked in Lake Michigan; their distribution is not clearly understood, although they appear to live in the offshore areas. Young coho salmon and alewives live throughout the lake most of the year and adults of both species live in the offshore area during the winter and much of the summer. Adult alewives concentrate to spawn near shore and in tributary streams in late spring and early summer; in some years they clog water intakes and die in large numbers, causing a major public nuisance. Coho salmon move to shore areas, and into streams to spawn during the fall and early winter. Alewives have become the most abundant fish in the lake and constitute the major forage supply for open-lake predators; all native forage species have been reduced greatly by various factors--including alewife competition.

III. THERMAL LOADING

A. PRESENT LOADING

Projections on thermal loading have been developed primarily from a recent Canadian publication here referred to as the "Acres Report" (Acres, 1970). These projections have the advantage of also providing data on heat discharges from the steel industry and municipalities. Current, but unpublished, Federal Power Commission projections are also available, and do not differ significantly from those in the Acres Report. The FPC projections have been inserted for decades not represented in the Acres Report. Tables 7 to 12 summarize the projections for megawatt capacity of power plants, waste heat from power plants and from other sources, cooling water requirements of power plants, and a breakdown of waste heat input by shoreline sector.

The primary source of Lake Michigan waste heat effluents is the power industry. In 1968 once-through cooling requirements for all Lake Michigan power installations were 6,643 cfs, which introduced an estimated 29.85 billion Btu's/hour of waste heat to the lake. As of early 1970, one nuclear and 23 fossil fuel power plants were operating on the lake, with a total capacity of 8,278 mw. Seven additional plants (five nuclear and two fossil fuel) were under construction and scheduled for operation by 1974, bringing the total on the lake to 31. In aggregate these plants will have a power capacity of 15,626 mw.

Table 7.--Projected 100 percent megawatt capacity for power plants on Lake Michigan, 1968 and 2000, by lake sector. 1/

Type of plant, and sector	Year			
	1968	1980	1990	2000
Fossil fuel plants				
Grand Traverse	72	82	82	82
Holland	1,484	1,484	1,484	1,484
Chicago-Gary	2,854	6,250	14,486	24,500
Green Bay	3,115	3,605	3,500	3,500
Nuclear plants				
Grand Traverse	75	138	286	918
Holland	0	2,046	5,281	12,516
Chicago-Gary	0	2,573	2,807	6,000
Green Bay	0	3,600	10,910	24,500
Combined (fossil fuel & nuclear)				
Grand Traverse	147	220	368	1,000
Holland	1,484	3,530	6,765	14,000
Chicago-Gary	2,854	8,823	17,293	30,500
Green Bay	3,115	7,205	14,410	28,000
Total projected capacity	7,600	19,778	38,836	73,500

1/ Data for 1968 and 2000 abstracted from Appendix J, Acres (1970); those for 1980 and 1990 prepared from unpublished data of the Federal Power Commission.

Table 8.--Projected waste heat addition (billions of Btu's/hr) to different sectors of Lake Michigan from power sources 1/

Type of plant, and sector	Year			
	1968	1980	1990	2000
Fossil fuel plants				
Grand Traverse	0.28	0.32	0.32	0.32
Holland	5.79	5.79	5.79	5.79
Chicago-Gary	11.13	24.38	56.50	95.55
Green Bay	12.15	14.06	13.65	13.65
Subtotal	29.35	44.55	76.26	115.31
Nuclear plants				
Grand Traverse	.50	.92	1.92	6.15
Holland	-	13.71	25.38	83.86
Chicago-Gary	-	17.24	18.81	40.20
Green Bay	-	24.12	73.10	169.15
Subtotal	.50	55.99	129.21	299.36
Combined (fossil fuel & nuclear)				
Grand Traverse	.78	1.24	2.24	6.47
Holland	5.79	19.50	41.17	89.65
Chicago-Gary	11.13	41.62	75.31	135.75
Green Bay	12.15	38.18	86.75	182.80
Total projected power industry heat addition	29.85	100.54	205.47	414.67

1/ Although based on power capacity projections from Acres (1970), the Btu figures were derived by assuming 100 percent capacity operation and a 20°F effluent rise. (Btu/hr estimates were obtained by multiplying megawatts of capacity by 0.0039×10^9 for fossil fuel and 0.0067×10^9 for nuclear fuel). Acres assumed average capacity operation.

Table 9.--Projected heat addition (billions of Btu's/hr) from the steel industry and municipal effluents to different sectors of Lake Michigan. 1/

Source and sector		Year	
		1968	2000
Steel industry			
Grand Traverse		0.00	-
Holland		0.00	-
Chicago-Gary		6.13	10.95
Green Bay		0.25	0.45
	Subtotal	6.38	11.40
Sewage effluents			
Grand Traverse		0.60	-
Holland		1.00	1.00
Chicago-Gary		1.00	1.40
Green Bay		1.60	2.30
	Subtotal	4.20	4.70
Combined steel and sewage effluent inputs		10.58	16.10

1/ Adapted from Acres (1970).

Table 10.--Principal present and projected waste heat addition (billions of Btu's/hr) to Lake Michigan.1/

Source	Year	
	1968	2000
Power industry		
Fossil fuel plants	29.35	115.31
Nuclear plants	.50	299.36
Steel industry	6.38	11.40
Municipal effluents	4.20	4.70
Total heat input	40.43	430.77

1/ Although based on power capacity projections from Acres (1970), the Btu figures were derived by assuming 100 percent capacity operation and a 20°F effluent rise. Btu/hr estimates were obtained by multiplying megawatts of capacity by 0.0039 x 10^9 for fossil fuel and 0.0067 x 10^9 for nuclear fuel. Acres assumed average capacity operation.

Table 11.--Present and projected cooling water (cubic feet per second) required by the power industry in different sectors of Lake Michigan. 1/

Type of plant, and sector		Year 1968	1980	1990	2000
Fossil fuel plants					
Grand Traverse		62	71	71	71
Holland		1,288	1,288	1,288	1,288
Chicago-Gary		2,477	5,425	12,574	21,267
Green Bay		2,704	3,129	3,038	3,038
	Subtotal	6,531	9,913	16,971	25,664
Nuclear plants					
Grand Traverse		112	205	426	1,368
Holland		-	3,051	7,875	18,664
Chicago-Gary		-	3,827	4,186	8,947
Green Bay		-	5,368	16,269	36,536
	Subtotal	112	12,451	28,756	65,515
Combined (fossil fuel & nuclear)					
Grand Traverse		174	276	497	1,439
Holland		1,288	4,339	9,163	19,952
Chicago-Gary		2,477	9,252	16,760	30,214
Green Bay		2,704	8,497	19,307	29,574
Total cooling water requirements		6,643	22,364	45,727	91,179

1/ As opposed to the average capacity requirements of Acres (1970), these estimates were developed by assuming operation at 100 percent capacity.

Table 12.--Calculation of the projected total waste heat input into Lake Michigan, by shore segments, in year 2000, including a comparison of waste heat input as a percentage of the maximum natural rate of heat input (1,750 $Btu/ft^2/day$) 1/

Sector of lake	Area of beach water in zone (sq mi)	Projected total thermal input in year 2000 (billions of Btu/hr)	Projected total thermal input in year 2000 per square foot of beach water ($Btu/ft^2/hr$)	Percentage of maximum rate of natural heat input
Grand Traverse	378	6.47	0.613	0.8
Holland	132	90.65	24.63	33.8
Chicago-Gary	143	148.10	37.15	50.9
Green Bay	1,024	185.55	6.49	8.9
Total beach zone	1,677	430.77	9.21	12.6

1/ Although based on power capacity projections from Acres (1970), the Btu figures were derived by assuming 100 percent capacity operation and a 20°F effluent rise. Btu/hr estimates were obtained by multiplying megawatts of capacity by 0.0039×10^9 for fossil fuel and 0.0067×10^9 for nuclear fuel. Acres assumed average capacity operation.

Although the power industry is the primary source of man-made heat addition to Lake Michigan, it should not be regarded as the only one. Certain industrial and municipal sources are also significant contributors of waste heat. The Acres Report projections indicate, for example, that in 1968 the steel industry contributed 16 percent of the man-made thermal input to Lake Michigan, or 6.38 billion Btu's/hour.

The combined power,steel industry, and municipal waste heat input to Lake Michigan in 1968 is estimated at some 40 billion Btu's/hour.

B. FUTURE LOADING (THROUGH YEAR 2000)

For the past 30 years, the Nation's electric power loads have grown at an average rate of 7 percent per year; consequently a doubling of electric power facilities has been required each decade. Forecasted load growth is the same through 1990 (Anonymous, 1968) and 2000 (Acres, 1970). More nuclear units will be installed in the Northeast and Midwest than in any other section of the United States. Nowhere are these plans for expansion more apparent that on Lake Michigan. Table 7 summarizes projections of growth in capacity.

The doubling of power capacity each decade shows the estimate of Lake Michigan megawatt capacity increasing at a geometric rate. Cooling water requirements will also increase at a similar rate (almost fourteenfold) from 6,643 cfs in 1968 to 91,179 cfs in 2000 (Table 11). Heat addition from steel and municipal sources is expected to increase to 17.30 billion Btu's/hour by 2000 (a 63 percent increase over that in 1968). In aggregate, it is estimated that waste heat addition to Lake Michigan from these sources will increase from 40 billion Btu's/hour in 1968 to about 431 billion in 2000.

C. WASTE HEAT DISSIPATION

1. Non-technical Overview

To consider both the immediate and eventual fates of waste heat in Lake Michigan, it is necessary to understand the process of addition of effluent heat to the water mass and its dissipation to the air. Recent findings tend to substantiate the theory that under normal conditions the principal amount of waste heat is passed to the water mass, and only a relatively small proportion is dissipated directly from the plume to the atmosphere. Csanady.(1970) advanced theoretical conclusions which indicate that heat dissipation is "diffusion-controlled." He concluded (though he did not fully discuss the important topic of atmospheric loss through back radiation) that excess temperature diffuses into the lake, if shoreline currents are normal and the water is moderately deep. He believed that his findings are supported by an empirical study by Palmer (1969). Hoops et al. (1968) concluded, on the basis of work at a Lake Monona (Wisconsin) power plant, that surface heat losses were about 5 percent of the heat discharged by the power plant; the remaining 95 percent was dissipated by dilution with lake water. Sundaram et al. (1969) concluded that the heated discharge of the proposed Bell Nuclear Station on Cayuga Lake (New York) would increase the average surface temperature of this 66.4-square mile lake about 0.7°F.

The size of the area affected by heat addition often can be predicted with some degree of confidence. However, the state of the art is not such that forecasts are completely accurate for any given heat source. The reasons for this deficiency are several, and they must be understood if an appreciation for the prediction is to be gained. It is also necessary to gain insight into the mechanics of heat dissipation in general. An attempt is made here to outline the theory, presupposing no special background in fluid mechanics or thermodynamics.

Heat, like mass, must be accounted for--and it can be accounted for through the idea of its conservation with time. Heat contained in a given parcel of water can be lost in several ways: (1) by absorption at the (lake) bottom, (2) by radiation back to the atmosphere when in contact or near-contact with the air, or (3) by evaporation and conduction to a colder air mass. If a mass of heated water is discharged to a lake and does not decrease in temperature as a result of these processes, it will naturally add its heat to the heat already in the lake. This process cannot, of course, continue indefinitely; it can, however, increase the temperature of the lake receiving water to that of the immediate discharge area if the lake is small enough. After a certain time, the entire lake comes to equilibrium and this equilibrium is maintained by exchange at the air-water interface.

A second process can be envisioned: Instead of following a body of water, consider a volume fixed in space in such a way that movement of water through the volume is allowed. Water of a certain temperature may then entirely displace a colder body of water mechanically. Such a process is due simply to the physical movement, or advection, of water into the volume.

A final process can be envisioned: Assume that half the water in the fixed volume is displaced by water of a different temperature. If the two bodies of water are allowed to mix completely, the result is a temperature midway between the two initial temperatures. This process can be roughly described as turbulent diffusion.

Thus, there are essentially four means by which a body of water can lose (or gain) heat: (1) by exchange at the air-water interface, (2) by advection, (3) by diffusion, and (4) by any combination of these three means. Analyses that are currently employed to evaluate temperature effects are based on these processes, although some of the mathematical tools that are employed are exceedingly sophisticated and the analyses are sometimes intractable. The intractability results from our lack of knowledge about such matters as lateral and vertical exchange processes (advection and turbulent diffusion), evaluation of background temperatures (or what the temperature would be if no heat sources were present), and hydrodynamics under the influence of bouyant jets.

If a dyed, heated, body of water is steadily discharged from a small orifice at a given velocity into a shallow, non-moving, clear, very large body of water, the dye decreases in intensity with increasing distance from the source and gradually becomes indistinguishable at a certain distance from the source. If the intensity of color down the midstream of the resultant plume could be measured, the intensity could be plotted on graph paper in the form of a simple curve that would describe the intensity-distance relationships. If the shallow receiving water body is replaced by a deep one, the plotted points will not fall on the same line. This simplified description differentiates between two-dimensional situations (i.e., in shallow water, where the dye is uniformly distributed with depth and the two dimensions are in the horizontal direction) and three-dimensional cases (i.e., in deeper water, where the dye distribution drops to zero at depth and has a different vertical distribution with distance from the source). The three-dimensional situation is extremely difficult to analyze theoretically; under field conditions it is even difficult to sample properly. Most engineering evaluations proceed from the two-dimensional case (in technical jargon the 'vertically integrated' assumption is made) to calculate the area which is of a higher temperature because of the heated water discharge.

In the three-dimensional situation, there is a region immediately near the discharge point (which is usually in shallow water) where the dye intensity remains essentially the same as that at the point of discharge. The surface area of this region may be rather small (a point to remember when considering loss of heat to the atmosphere). Adjacent to this region, "clear" water is brought into the dyed area in conjunction with a certain decrease in velocity; this clear water is said to be "entrained" and its magnitude is described by an "entrainment coefficient." In the entrainment region mixing occurs at the edges of the plume; little mixing takes place very near the source. This process is similar to the perhaps more familiar process of the building up of towering storm clouds. Here the vertical growth is effected by air being brought in from below (entrained) and moving upward. In the entrainment region, mixing occurs at the edge of the plume, whereas little mixing takes place very near the source. Another region can be described where the dye concentration is diminished by diffusion at the edges and loss in a vertical direction; the surface area traced by the edges of this region is relatively large (analogously with the heat loss phenomenon this is the region where loss to the atmosphere by evaporation, conduction and back radiation, accounts for a considerable amount. But, as it is in proportion to its differences in temperature above natural or "ambient," the total loss is actually rather small.)

Three main points evolve from the preceding description: (1) Although heat is lost to the atmosphere near the source because the temperature may substantially exceed the ambient temperature, the total amount lost is small because the surface area of this region (where losses take place in the absence of mixing) is small. (2) The bulk of the heat in the region near the source is simply added to the receiving water for a longer time. Further losses will occur in the next region, and the magnitude of loss to the atmosphere will depend on the surface area (greater than in the latter region) and the temperature difference between the regions and the ambient (smaller than in the latter regions). (3) In the final dissipative stages, heat is diffused and lost by surface cooling, but here the temperature does not greatly exceed the ambient temperature.

In total, therefore, most of the heat is retained in the volume of water near the discharge site and a rather large area can be expected to become heated.

Ayers et al. (1970), who made field observations near power plants in Michigan City, Indiana, and Waukegan, Illinois, did not list the condenser flows or discharge temperatures, nor give auxiliary data which could be used to make a 'jet release' analysis. They ascribed most of the temperature decrease with distance from the outfall to surface cooling. This explanation can hold, however, only if the discharge volume is small or the width of the discharge orifice is so great as to reduce the velocity of the jet to a small valve. To evaluate properly the heat buildup near an outfall, results from one survey cannot be extrapolated directly to another. Rather, a case-by-case evaluation is required and, at this stage of our knowledge, nothing less will suffice. Information required for the evaluation has been given in earlier paragraphs and includes such data as the dimensions of the outfall, volume of flow, and background or ambient temperatures. When the ambient temperature is not uniform in relation to distance from the shore, evaluation of what constitutes an "excess" temperature is doubtful at best; such conditions are likely to result periodically and, of course, during "thermal bar" conditions. The analysis by Ayers et al. (1970) is open to criticism because of their choice of ambient temperature; in fact, it is not clear from their illustrations whether an ambient temperature was indeed measured at all.

2. Studies of Model Plumes

Data from two evaluations of model plumes have been selected to provide some physical dimensions to the foregoing discussion. In one that was completed by Benedict (1970) specifically for the present report, the variables used were similar to those that might be expected for a Lake Michigan thermal plume. The assumed discharge volume (731 cfs) and temperature differential (25°F) are on the order of a conventional fossil fuel plant on Lake Michigan. The second evaluation is that of Pritchard-Carpenter Consultants (1970) for the proposed Davis-Besse Nuclear Power Station on Lake Erie. This study provides an example of the heat rejection potential of a Great Lakes nuclear installation of 1,500 cfs. (At least one larger plant is under construction on Lake Michigan--the Donald C. Cook Plant, near Benton Harbor, Michigan, at 3,500 cfs.)

a. Lake Michigan Surface Jet Model

Benedict's shoreline discharge model, which simulates a Lake Michigan discharge on the order of the Campbell Plant (a conventional power plant near Port Sheldon, Michigan), assumes zero lake currents, an ambient temperature of 65°F, once-through cooling, a 25°F rise over the condensers, an effluent of 731 cfs, and a plume depth of 5 feet. There is no allowance for surface heat loss. Since the theoretical plume, under conditions of no current, would generate symmetrically outward from the discharge, it is possible to examine the thermal characteristics in terms of distance that waste heat isotherms extend (Table 13).

Evaluation of the isotherms was carried to the 0.5°F limit only for illustrative purposes since under normal conditions natural processes would distort the plume shape and diffuse the heat to depths greater than 5 feet. However, under the conditions of the model and at equilibrium, the thermal influence would extend along the plume center line a substantial distance (4.8 miles to the 1.0°F isotherm and 20 miles to the 0.5°F isotherm) and thus cover a rather extensive area.

b. Lake Erie Nuclear Model

Pritchard-Carpenter Consultants (1969, 1970) computed and analyzed plume distributions for the Toledo Edison Compnay, as part of that company's evaluation of the proposed Davis-Besse Nuclear Power Station on Lake Erie.[1] Analyses were carried out for two conditions--no lake current and with shoreline current. Only the shoreline-current condition is discussed here, since it is the more typical in Lake Michigan. In this situation, the plume is bent in the direction

[1]The Toledo Edison Company kindly consented to use of these data in the present report.

Table 13.--Distance (miles) from source of excess temperature isotherms calculated from a Lake Michigan surface jet model.

Waste heat isotherm (°F)	Distance (miles) from plume source at centerline
20	.052
15	.057
10	.062
5	.234
2.5	.717
1.0	4.80
0.5	20.17

of the current. Although the proposed plant is to be situated on Lake Erie, the calculations provide interesting summary statistics on plume dimensions as they apply to the large flows required by nuclear power plants.

In general, an onshore wind causes currents that are parallel to the coast in the nearshore region. When the plume is bent so that it is directed along the coast, entrainment (and thus, dilution) can be effected only on one side of the plume. The result is that the rate of decrease of temperature is less than if the plume had been directed straight out into the lake.

Calculations of the plume dimensions were based on assumptions of an 18°F temperature rise, 1,526 cfs of cooling water, 70°F ambient temperature, a 10 mph wind, and a longshore current directed towards the southeast at a rate of 0.67 fps. Estimates were made of the plume certerline length, width, and area (Table 14).

The 1°F excess temperature isotherms were about 52 and 8 miles from the source for the two conditions of dilution only and dilution plus cooling, respectively, and the respective areas affected were about 374 and 13 square miles.

c. Application of results from Model Studies

The Lake Michigan jet and Lake Erie "dilution only" examples approximate situations in which atmospheric and lake conditions do not permit rapid dissipation of waste heat to the atmosphere. Under conditions when such atmospheric losses would occur, the lake volume

Table 14.--Dimensions (in miles and square miles) of excess temperature isotherms in a bent jet thermal plume discharge from the Davis-Besse Nuclear Power Station for the case of an ambient transverse current of 0.67 $ft.sec^{-1}$, and a jet discharge velocity of 6.7 $ft.sec^{-1}$. (Converted from report by Pritchard-Carpenter Consultants, 1970). 1/

Excess temperature isotherm(°F)	Dilution only			Dulution plus cooling		
	Length (mi)	Width (mi)	Area (sq mi)	Length (mi)	Width (mi)	Area (sq mi)
14	0.051	0.018	0.002	0.051	0.019	0.001
12	.095	.036	.003	.095	.036	.003
10	.197	.074	.014	.197	.074	.014
8	.479	.180	.086	.437	.177	.083
6	1.458	.714	1.040	1.184	.679	.807
4	3.276	.941	3.081	2.537	.850	2.155
2	13.125	2.178	28.588	5.946	1.275	7.569
1	52.462	7.083	373.048	8.181	1.555	12.697

1/ Length = length of the area within the specified isotherm along the axis of the thermal plume; width = width of the area within the specified isotherm; area = area contained within the specified isotherms.

affected by waste heat would diminish. However, from the earlier discussion of heat dissipation, it appears that, at best the percentage of the total waste heat rapidly lost to the atmosphere is sufficiently small that the assumption of little or no waste heat loss to the atmosphere is reasonable, at least during a great deal of the annual temperature cycle. It follows that the assumption of moderate or no waste heat loss to the atmosphere is reasonable during a good deal of the annual temperature cycle--recognizing of course that short-term loss to the air occurs and that nearly all of the waste heat will be removed during the fall overturn and winter. The "dilution plus mixing" example of the Davis-Besse plume evaluation appears to be very conservative in describing the actual area and volume of thermal influence; and the "dilution only" assumption of the other two examples is the more applicable. It is concluded that large percentages (at times virtually 100 percent) of the discharged waste heat will be diluted into the water mass and that the heating effect of one plume can cover many areal miles of the lake.

3. Magnitude of Projected Waste Heat Addition

It has been advanced that at times most waste heat would be diffused into the water mass for an ecologically significant time period. Waste heat production is projected to be 431 billion Btu/hr on Lake Michigan in year 2000; and to assess the potential ecological impact of this waste heat addition, it is desirable to place dimensions on the physical characteristics of waste heat distribution. Existing information on this topic is very limited; the following discussion is intended to provide at least a limited amount of insight into the situation, as projected.

Acres (1970) estimated that 0.52 Btu/ft^2/day of waste heat would be added to Lake Michigan in year 2000--an increase of 0.47 over the 1968 value of 0.05 Btu/ft^2/day (based on estimtates of average power capacity operation and the waste heat additions from other sources). This estimate applies to the entire lake surface, however, and does not allow for the likelihood that the waste heat release would occur in the inshore waters.

Table 12 presents estimates of waste heat inputs to the 1,677 square miles of beachwater zone (0-30 foot depth) by shoreline sector for the entire lake. The last column of the table presents the projected waste heat input, expressed as a percentage of the maximum natural rate of heat input. (The natural input estimate for nearshore waters of Lake Michigan [based on unpublished data of the Bureau of Commercial Fisheries] is supported by estimates for Lake Ontario of 1,735 Btu/ft^2/day [Rodgers, 1968] and for Lake Cayuga of 2,000 Btu/ft^2/day [Sundaram et al., 1969].) This very general statistic indicates that the rate of waste heat input would in the year 2000 approximate 13 percent of the natural maximum heat input (For the Chicago-Gary Sector, this statistic is 51 percent and for the Holland Sector, 34 percent).

The basis of the statistic is subject to criticism, since some of the waste heat will diffuse beyond the 30-foot contour (average width, 1 mile), some will be lost to the air, and, of course, the concentration of waste heat near the discharges will cause great variability in the actual value of the statistic. However, available studies indicate that Lake Michigan thermal plumes hug the shoreline, and it follows that the principal ecological impact would occur in the shallower waters; and it is this fact that makes the general use of the statistic valid. Furthermore, during certain periods the "thermal bar" lies entirely within the inshore zone, preventing transfer of heat to deeper water.

Substantial refinement of the assumptions is both desirable and needed, and other approaches to the problem can be taken. The existing calculations are sufficient, however, to permit the conclusion that projected waste heat production would add to the beach water sector of Lake Michigan an artificial thermal load that is equal to a significant percentage of the natural rate of heat input. This conclusion has ecological significance in terms of both eutrophication and fishery effects.

IV. EFFECTS OF TEMPERATURE FLUCTUATIONS ON LAKE MICHIGAN FISH

A. INTRODUCTION

Increased demand in recent years for the use of natural surface waters for cooling has caused widespread concern that the addition of artificial heat to these waters will be harmful to aquatic life. As a consequence the effects of temperature on aquatic life are under intensive study and some of the results are now being published. Extensive bibliographies by V. S. Kennedy and J. A. Mihursky (1967) and E. C. Raney and B. W. Menzel (1969) list over 1,200 references that cover the early literature as well as some of the more recent publications. Excellent review articles describing the thermal requirements of fishes were published by J. R. Brett (1956, 1960) and R. E. Burrows (1963). A book edited by P. A. Krenkel and F. L. Parker (1969) and the published Proceedings of the Second Thermal Workshop of the U. S. International Biological Program (J. A. Mihursky and J. B. Pearce, eds; 1969) deal with the biological aspects of thermal pollution for major groups of aquatic plants and animals. Although the present section is limited to a discussion of the effects of temperature changes on fish and other organisms in Lake Michigan, references are made to the published literature when necessary, to describe thermobiological principles and to fill gaps in the knowledge of the specific thermal requirements of Lake Michigan aquatic organisms.

The factors that determine the growth, survival, distribution, and abundance of fishes and other coldblooded aquatic organisms in nature are complex and incompletely known, but the role of temperature is firmly established as a major one. All available information indicates that each organism has specific thermal tolerances or limits that reflect the thermal requirements for each of the important metabolic functions in the individual; these functions and thermal tolerances vary from life stage to life stage. When the limits are exceeded the organism functions at reduced efficiency, and may ultimately die. The rate at which individuals, populations, or species are lost depends on the degree to which the thermal limits are exceeded, the duration of exposure to thermal stress, and the indirect effects of these thermal conditions (e.g., effects on the abundance of organisms suitable as food).

The temperatures that are rapidly lethal have well defined limits and these have been thoroughly described for many species, including some found in Lake Michigan and the other Great Lakes. Less well known but equally important are the temperature limits for successful survival in other situations where unfavorable temperatures reduce the ability of the organisms to move about, escape predation, compete with other species for food, and otherwise successfully complete all of the vital life processes and stages (including reproduction).

The use of inshore waters of Lake Michigan for waste heat disposal would have a serious impact on fishes that must complete their early life stages (especially egg incubation and early growth) in the inshore and beach water zones. Fishes are least mobile in these life stages and therefore least able to avoid unfavorable thermal conditions. Also affected adversely would be the highly mobile adults that require these shallow-water areas for spawning and the anadromous fishes that need to pass through the inshore and beach zones to spawn in tributary streams or to enter Lake Michigan as young from the tributary streams to complete the growth phase of their life cycle. Shallow-water organisms other than fishes, many of which are required as food for fishes or are otherwise important to man, would also be affected by the use of inshore lake waters for waste heat disposal.

B. EFFECTS ON ADULTS AND JUVENILES

Most organisms cannot live at temperatures much higher or lower than those to which they are accustomed (Kinne, 1963), and a general relation can be demonstrated between the temperatures that are lethal for adult fishes and the temperatures of the natural environment in which these fishes occur. In natural populations the temperatures that are lethal for adult fishes usually exceed the natural temperature extremes by only 9 to 12°F (Brett, 1969).

The lethal limit for juvenile coho salmon is 77°F (Brett, 1952) and adults die in about 60 minutes at 77°F (Coutant, 1969). Coho salmon must pass through the beach zone waters as juveniles descending to Lake Michigan and as adults ascending tributary streams to spawn. When adult coho salmon concentrate off stream mouths in late summer and early fall before entering these streams to spawn, average bottom water temperatures in the beach zone range from 69°F (August) to 58°F (end of September), and one year in three the temperatures can be as much as 10-11°F higher than the average values (Figure 6). In mid-August of an average year a rise of only 8°F would increase bottom water temperatures in the beach zone beyond the lethal limits, and in one year of three an even smaller increase

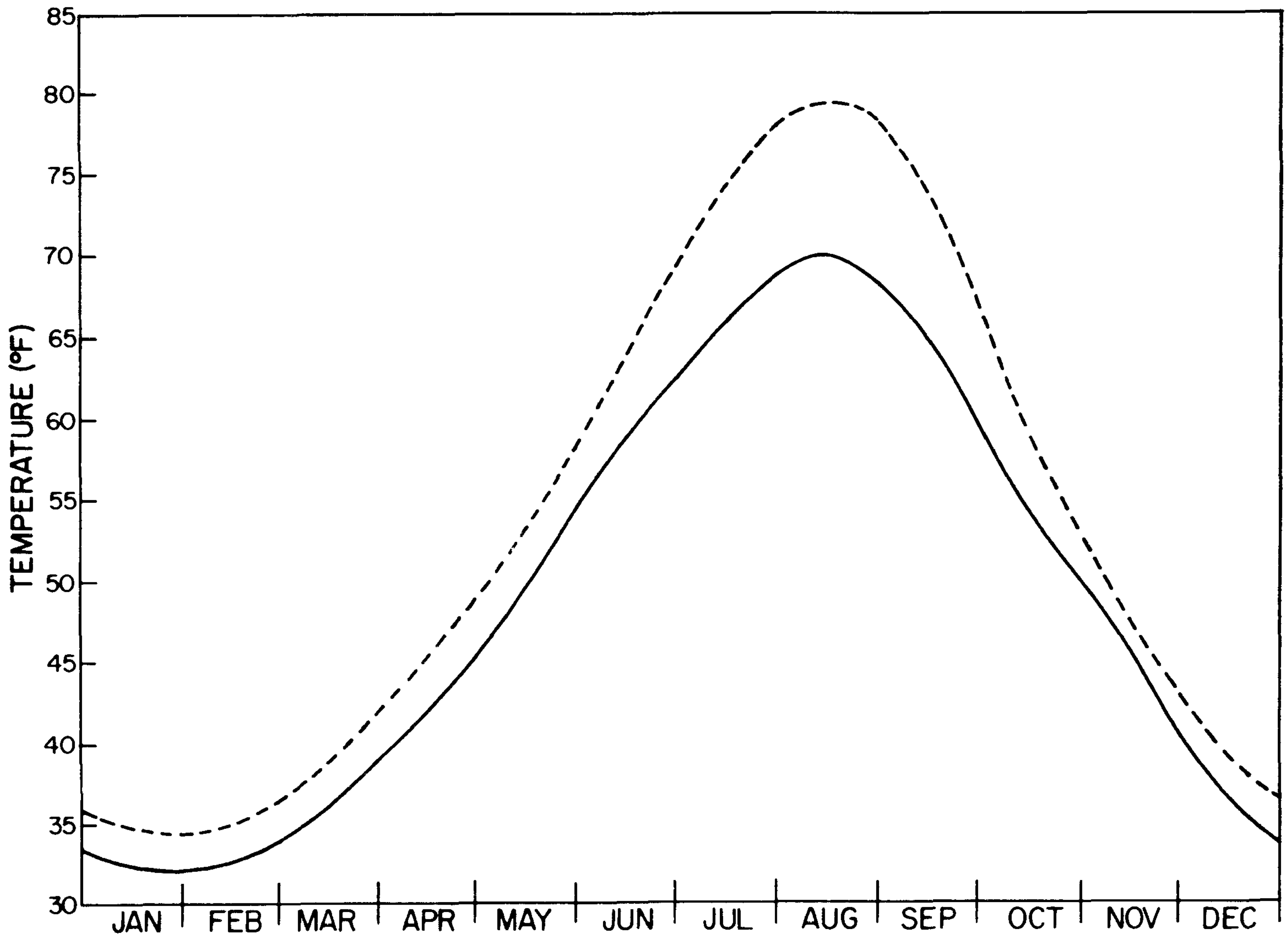


Figure 6.--Average Lake Michigan beach zone water temperatures. Temperatures were measured on the bottom at 18 to 36 feet; dashed line indicates one standard deviation above the average (1/3 of all temperatures fell between the two lines). Data compiled from Church (1941 and 1942), Chicago Municipal Water Treatment Facilities (1966; unpublished records), and the Bureau of Commercial Fisheries (1954, 1955, and 1969; unpublished).

would exceed 77°F. By the end of September a rise of 19°F would exceed the lethal level. Although surface water temperature data are not available for the beach zone, the surface temperatures would be higher than those of the bottom waters used to construct the curve in Figure 6; the migrants must pass through these surface waters to enter the stream mouths.

In addition to fish mortalities that occur when temperatures exceed the upper temperature tolerance limit of fishes, mortalities may also result when fish acclimated to high temperatures are suddenly exposed to sharply dropping temperatures.

Emery (1970) described a mortality that occurred as a result of a natural upwelling of cold offshore bottom water in Georgian Bay, Lake Huron. The upwelling suddenly lowered beach zone bottom water temperatures from 65.3°F to 44.6°F in about 11 hours; recovery was rapid, however, and by the 15th hour bottom water temperatures in the affected area had risen to 64.9°F. The more mobile fishes left the area when the temperature dropped but crawfish and sculpins could not; these ceased feeding and many died.

Low temperature mortalities may also occur in Lake Michigan as a result of the use of lake water for cooling. In a report of a fish kill on Lake Michigan at the Consumers Power Company Campbell Plant at Port Sheldon on August 29, 1968, the Michigan Water Resources Commission concluded that a sharp drop in water temperature (from 71 to 57°F) at the intake of the Port Sheldon installation gave fish in the discharge water a low temperature shock to which they were unable to adjust (Robinson, 1969). Species found dying or in distress at the time of the investigation were channel catfish, carp, suckers, and gizzard shad--all generally considered to be intolerant of low temperatures or of low temperature shock.

Although the fish kill at Port Sheldon was due in part to the invasion of the shallow beach zone by cold offshore water, the high temperature of the effluent water to which the fish had become acclimated was also a contributing factor. Fish mortalities caused by low temperature shock are also likely to occur in the absence of coldwater upwellings when effluent water temperatures fall--as when a power plant goes "off line" or its level of operation is greatly reduced. Little information is available on the thermal tolerance of the alewife but a recently completed manuscript entitled "Effects of temperature on electrolyte balance and osmoregulation in the alewife (*Alosa pseudoharengus*) in fresh and sea water" by J. G. Stanley and P. J. Colby, indicates that the alewife is very intolerant of low temperature shock. When alewives acclimated at 62.6°F were subjected to an 18°F temperature decrease in 2 hours, 13 of 21 (62 percent) died. This information suggests that severe mortalities of alewives could be caused in effluent waters by low temperature shock when a power plant reduces its level of operation. The effect would be most severe during the spring when the lake water is cold and alewives concentrate near shore before spawning.

Sublethal temperature shock has also been shown to affect adversely the well being and survival of juvenile salmonids. According to the temperatures of Figure 6 and the lethal temperatures of juvenile coho salmon (Brett, 1952), a temperature rise of 15 to 35°F in the beach zone waters at stream mouths would be required to kill young downstream migrants. Coutant (1969), however, has shown that heat doses only 25 percent as large as those required to cause loss of equilibrium (the dose required to cause equilibrium loss is less than that required to cause death) measurably increases the susceptibility of juvenile chinook salmon and rainbow trout to predation.

The heat doses required to cause harm to juvenile and adult Lake Michigan fishes are not known but there is little doubt that sub-lethal temperature shock and increased susceptibility of affected fishes to predation would be important consequences of discharging heated effluents into Lake Michigan.

Even more restrictive than the lethal temperature limits are the limits for the efficient function of the complex of vital life processes that ensure the continued successful existence of the individual, population, and species. The temperature requirements for these vital processes are known for only a few species, but the available information indicates that the general form of the relations may be similar for most fishes native to the temperate waters of North America. Among these fishes the swimming ability, feeding rate, food conversion efficiency, and growth rate typically are low at low natural environmental temperatures, rise with rising temperature to some maximum (at the "optimum temperature"), and then decline sharply with further temperature increases as the upper lethal temperature is approached. Figure 7 shows the effect of temperature on the food intake, growth, and conversion efficiency of coho salmon. The curve of Figure 7 marked "ration" describes the voluntary rate of food intake at the various temperatures. Intake was low at low temperatures, rose with temperature to a maximum at about 59-64°F, and then declined sharply at higher temperatures. Growth followed a trend similar to that of intake. Growth rate was most rapid at 59°F and fell off at higher and lower temperatures. Extension of the ends of the growth curve indicates that growth rate was nil at about 39 and 70°F.

Conversion efficiency which is defined as,

$$100 \times \frac{\text{growth in weight}}{\text{weight of food eaten}}$$

gives the percentage of the food eaten that is converted into growth. When no growth occurs the conversion efficiency cannot exceed zero percent; according to Figure 7 this occurs at about 39°F and at 69-70°F.

Where the problem has been studied intensively (for sockeye salmon; Brett, 1969), the evidence indicated that the successful natural range of the species coincides with areas in which water temperatures do not exceed the "optimum" for food conversion efficiency by more than a few degrees and where food conversion efficiency is not reduced to less than 80 percent of the maximum. According to Figure 7, the food conversion efficiency of coho salmon--a close relative of the sockeye--reached a maximum at about 54.5°F and fell below 80 percent of maximum at 62°F. Temperatures higher than 62°F during the growth phase of the coho salmon can be expected to reduce the population success of this species.

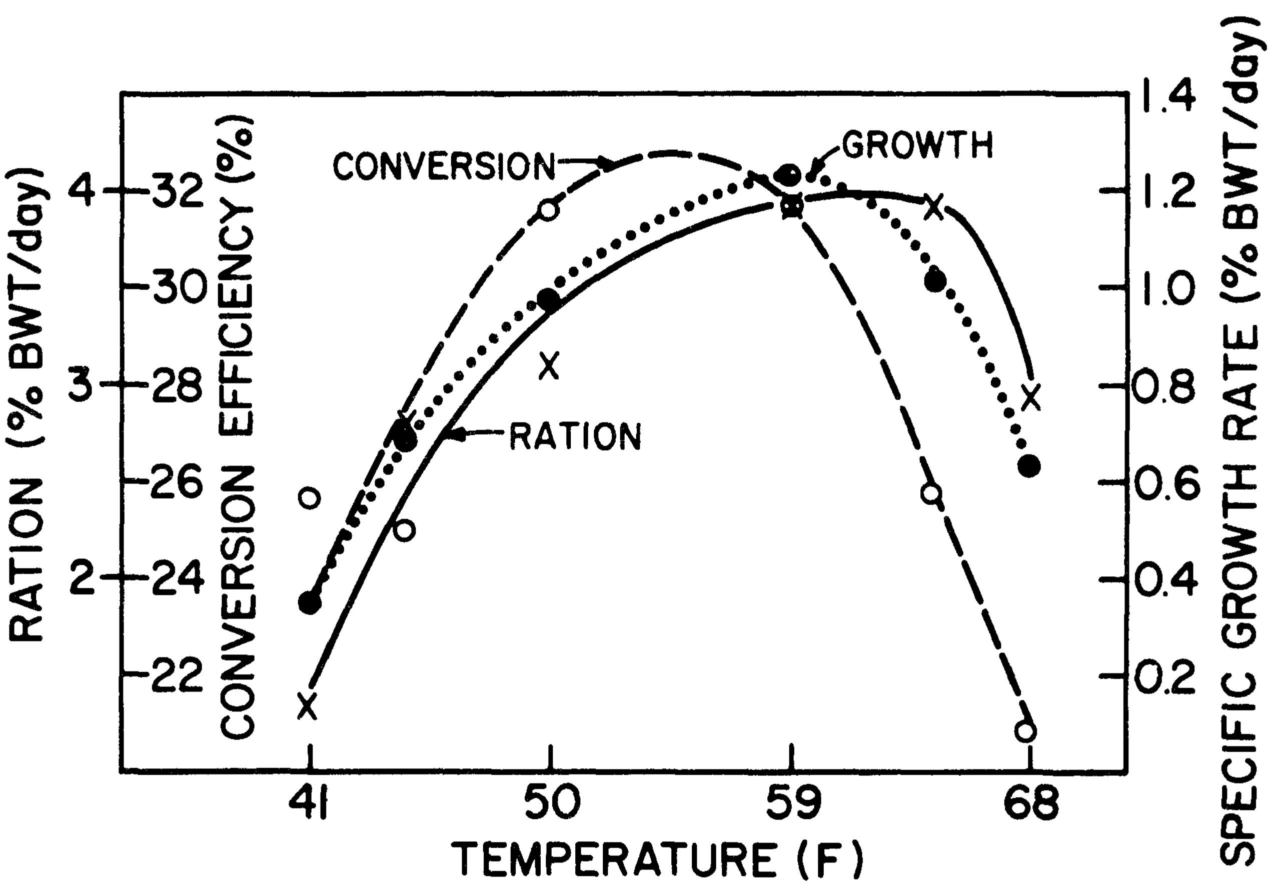


Figure 7.--The effect of temperature on the food intake, growth, and conversion efficiency of juvenile (0.5-pound) coho salmon held in fresh water and fed unrestricted amounts of alewives from Lake Michgian (T. Edsall, unpublished data).

In addition to its effect on the growth, survival, and general well being of fishes, temperature is also important because it directly affects the availability of coho salmon (and other fishes) to the angler. The temperature range for optimum feeding rate of juvenile coho salmon fed unlimited amounts of alewives is 59-64°F; elevation of temperature above 64°F reduces feeding rate (Figure 7). An even lower optimum temperature for feeding in nature (where food availability is restricted) is predicted from data on optimum temperature for growth and conversion efficiency of coho salmon whose food intake was restricted to levels approaching those in nature (T. Edsall, unpublished data)--and indeed the optimum feeding temperature for adult coho salmon in Lake Michigan is about 50-55°F (Borgeson, 1970). When adult coho salmon in Lake Michigan concentrate off stream mouths before ascending the streams to spawn, lake water temperatures average 69 to 56 (August to end of September) and one year in three range from 69 to 79°F in mid-August and from 58 to 69°F at the end of September (Figure 6). According to Figure 7 elevation of inshore water temperatures at this time, when the major portion of the catch of coho salmon is usually made in Michigan waters of Lake Michigan, will sharply lower the feeding rate and consequently reduce angler success.

Elevation of beach zone water temperature may also delay the start of the upstream migration, thereby shortening the duration of the stream fishery for salmon. In 1969 about one-half of the Lake Michigan salmon caught by anglers were taken in tributary streams.

Although temperature data for the beach zone waters at the time of the salmon runs are not available for Lake Michigan, the 1968 run of coho salmon "jacks" (precocious males) in the Chagrin River, a tributary of Lake Erie, did not begin until beach zone water temperatures fell below 65°F, and in 1969 the first run of adult coho salmon seen in Lake Erie entered the Chagrin River on September 13, after the beach zone water temperatures had dropped to 66°F; furthermore, the peak of the 1969 run did not occur until October 24-26 when temperatures were 58-62°F (Russel Scholle, Ohio Division of Wildlife, personal communication).

C. EFFECTS ON MATURATION AND SPAWNING REQUIREMENTS

1. Maturation

The environmental requirements for normal maturation of the sex products within the gonads of adult fishes have been studied for only a few species (see Welch and Wojtalik, 1968, for a review). Most studies show that both temperature and light cycles are important. Recently the FWQA Laboratory, Duluth, Minnesota, has shown that water temperatures must be 43°F or lower for 5 months to ensure normal maturation of the eggs of yellow perch; higher temperatures upset the natural temperature and photoperiod cycles and significantly reduce both the number and viability of the eggs that are spawned. The average water temperature in Lake Michigan drops below 43°F on about November 20 and rises above 43°F again on about April 20--a period of 5 months; any delay in cooling in the fall or acceleration of warming in the spring will shorten the time available for maturation to a period less than that required. Although water colder than 43°F will still be available to perch, there is evidence that they may not avoid, or may be attracted to, the warmer waters when they are available (Weatherly, 1963; Ferguson, 1958).

2. Spawning

In general, the discharge of heated effluents in shallow water can be expected to have its most serious effects on Lake Michigan fishes during spawning and egg incubation. The available information suggests that most Great Lakes fishes that spawn in shallow water have preferred spawning sites, and that in years of low population abundance these areas are used to the exclusion of other areas. During years of high abundance, however, spawning is much more widespread. Spawning areas of most shallow-water spawners in Lake Michigan are not precisely known, but the distribution of the whitefish fishery during the spawning season, as indicated by past records, indicates that whitefish spawned in the shallow shoreline waters of the entire lake in times of high abundance (S. H. Smith, Bureau of Commercial Fisheries, personal communication). Although populations of whitefish in Lake Michigan are now at an all-time low, and their spawning may be restricted to a few local areas, population increases that should result from current fishery management programs will increase the number of spawning areas used; consequently, all potential spawning sites must be protected. Similar protection may also be required for the inshore spawning areas of yellow perch, smelt, lake herring, and lake trout.

There is mounting evidence supporting the hypothesis that coregonid fishes have narrow temperature limits for spawning. Monti (1929) found that whitefish did not spawn in Italian lakes where winter temperatures remained above 45-46°F. Whitefish in the Great Lakes spawn in November and December when the lake is cooling, and a drop to 42°F is required to stimulate spawning (Louella E. Cable, Bureau of Commercial Fisheries, manuscript in preparation). Temperatures above 42°F will presumably exclude whitefish from their preferred spawning grounds. Lake herring spawn later than whitefish--from mid-November to mid-December, when the temperature drops from 39 to 37°F (Smith, 1956). Several other investigators (Stone, 1938; Washburn, 1944; Brown and Moffett, 1942; P. J. Colby and L. T. Brooke, manuscript in preparation) observed that lake herring spawn when the temperature falls below 39°F. Cahn (1927) found that ripe female lake herring in laboratory tanks would not spawn at 40°F, but would do so only after the temperature had dropped to 38.5°F or lower. John (1956) reported that lake herring will spawn--later than usual--when temperatures are above 39°F during late autumn, but suggested that the delay may reduce egg survival. Pokrovskii (1960), as cited by Lawler (1965), wrote that the temperature of the water at the time of spawning exercises an influence on the abundance of year-classes of certain whitefishes and on their yield; in some years the quantity of fertile eggs reached 80-100 percent, in others it decreased to 30-50 percent, and in one instance only 10 percent of the eggs deposited were fertile. Such low fertility was attributed to long drawn-out autumns in which the males leave the spawning grounds before the optimum spawning temperature for females is reached.

Yellow perch spawn in the spring during rising temperatures. Optimum spawning temperatures are 46-54°F; at 61°F spawning is reduced and at temperatures above 62°F eggs are aborted without being fertilized (unpublished data, FWQA, Duluth). The spawning season for perch in Lake Michigan begins about May 15 and ends about July 1 (L. Wells, Bureau of Commercial Fisheries, personal communication). Water temperatures average 49°F on May 15 (one year in three this average may be as high as 53°F) and 62°F on July 1 (in one year in three this average may be as high as 69°F; Figure 6). Thus, in one year in three, the addition of heat to the spawning areas at the start of the spawning season (May 15) would cause the optimum temperature for spawning to be exceeded, and the addition of heat towards the end of the spawning season would cause the females to abort their eggs.

Lake Michigan alewives spawn from early June, when temperatures in spawning areas rise above 60°F, through mid-August, if temperatures remain below 82°F (Edsall, 1970). Although most Lake Michigan alewives spawn in flowing water in tributary streams, spawning is common in the sheltered areas of Green Bay in northwestern Lake Michigan, and occurs occasionally along the unprotected shoreline of Lake Michigan proper when the lake water is warm enough. The warming of lake waters by heated effluents will facilitate lake spawning by alewives where spawning now occurs only infrequently.

Any increase in the abundance of alewives that is likely to result from an increase in the spawning areas, however, is contrary to present management objectives (see section on fishery resources) for Lake Michigan.

D. EFFECTS ON INCUBATION REQUIREMENTS

The available evidence suggests that a normal self-sustaining fish population may continue to exist successfully only in areas where temperatures are in the range that permit the production of viable fry from at least 50 percent of the eggs that are spawned (Alderdice and Forrester, 1968). Information on the effects of temperature on survival and development of eggs and fry of Great Lakes coregonid fishes is scanty; published work is limited to only a few studies on the influence of temperature on early survival and development. Lawler (1965) found that year classes of whitefish in Lake Erie were strong only when suitable temperatures prevailed; fall temperatures must drop early to 43°F, the decrease to the optimum temperatures for development must be steady, and spring temperatures must increase slowly and late in the season to provide prolonged incubation near the optimum developmental temperatures. Christie (1963) found production of larger year classes of whitefish in Lake Ontario to be associated with cold Novembers followed by warm Aprils. Price (1940), who incubated whitefish eggs at constant temperatures from 32 to 54°F, found that the optimum hatching temperature was 33°F and at temperatures above 43.2°F the hatch of viable fry fell below 50 percent. Colby and Brooke (1970), who incubated lake herring eggs at constant temperatures ranging from

32 to 54°F, demonstrated that the highest temperature at which 50 percent of the eggs produced viable fry was 44.6°F, and that the optimum temperature was about 42°F. Most of the mortalities occurred during the early stages of development (gastrulation and organogenesis) when the eggs were most sensitive to adverse temperatures. According to the data of Price (1940), Colby and Brooke (1970), and Figure 6, lake temperatures are already at the maximum tolerable for the successful incubation of whitefish and cisco eggs and the addition of heat to the lake in the fall in areas where the eggs of whitefish or ciscoes are incubating will reduce the viable hatch below the 50 percent level.

It is obvious that a 10°F rise over natural maximum tolerable temperatures during spawning (from 42 to 52°F for whitefish and from 39 to 49°F for lake herring) would cause high mortality among eggs during the critical period of early embryo development. A 5°F rise over natural temperatures (to 47°F) would kill whitefish eggs or increase the incidence of abnormalities, and a 3.6°F rise shortens the incubation period of lake herring by at least 29 days (Colby and Brooke, U. S. Bureau of Commercial Fisheries, manuscript in preparation), causing the fish to hatch in a potentially hostile environment in which light may not be of the right intensity, or food may not be of the proper kind (species), size, or density to ensure survival. Braum (1967) reported that <u>Coregonus</u> eggs incubated at 39°F hatched after 65 days. Eggs spawned in December hatched at the end of February, when plankton is scarce. Modern German hatcheries incubate eggs at 34°F to delay hatching until April, after 120 days of incubation, to take advantage of the larger plankton population than available. Einsele (1966) stated that it is now firmly established that in the Austrian Alpine lakes only 1 to 10 adults will result from 10,000 naturally spawned coregonid eggs. In the laboratory, however, survival can be varied from nearly 100 percent to nil by varying food density and light intensity. Einsele suggested that the feeding conditions for fry improve as the year proceeds from March to the end of April and early May, when the light intensity may rise above 100 lux and the number of copepodites per liter may increase to 20 or more. Fry stocked at this time would most likely have the best chance of survival. He also pointed out that in Alpine lakes the feeding situation for coregonid fry does not improve continuously as the year proceeds, but that there is a turning point towards the end of May when diurnal plankton migration begins and crustacean plankton moves down to 10-20 meters during the daytime. The light intensity for fry may be critical at 5 meters and is certainly too low below 10 meters. Also, at this time the many zooplankters may not be in the appropriate size range for food of fry. Einsele also stated that stocking fry from hatcheries in January and February had little or no effect on the fish population.

Although factors governing egg and fry survival in Lake Michigan have not been studied intensively at the Great Lakes Fishery Laboratory, evidence from a local field study in progress suggests that shortening the incubation period could be potentially deleterious to the fish stocks.

Preliminary investigations of lake herring feeding habits by the Great Lakes Fishery Laboratory show that they have some specific food requirements. Fry begin feeding about 6 days after hatching, which is well before the yolk-sac is absorbed. The diet is composed primarily of Crustaceans of the order Eucopepoda - suborders Cyclopodia and Calanoida for the first 2 to 3 weeks (or until they reach a total length of 15 mm) at which time species of the suborder Harpacticoida are found in their gut. The range of mean total length of food eaten (to 0.6 mm) by fry 12 to 18 mm long is less than the mean total lengths of the preferred food available (0.6 to 1.mm). Thus fry are selecting food organisms that are small enough for them to ingest or that have swimming speeds or behavior patterns that enable the fry to capture them. In either case the food organisms ingested are not adults but rather juveniles of a stock that has recently reproduced. Evidence from a food selectivity study shows an increase in abundance of cyclopoid juveniles coinciding with the hatching and appearance of lake herring (cisco) fry. At this time the stock of calanoids is increasing in density but decreasing in average size, indicating a younger population. This population is increasingly fed upon by the lake herring fry as the density of cyclopoids drop (P. J. Colby, Bureau of Commerical Fisheries, manuscript in preparation).

The timing of these natural events is no doubt essential for the perpetuation of these fish stocks and has evolved as a result of natural selection, e.g., fish which spawned earlier or later were selected against by the environment. Any heat discharge which would interfere with this natural timing (e.g., cause the fry to hatch when the natural preferred foods are lacking or scarce) would jeopardize the survival of that stock.

Temperatures above 64°F will cause mortality in excess of 50 percent of the eggs of yellow perch during the first 24 hours after the eggs are spawned (FWQA, Duluth; unpublished data). According to Figure 6 the average temperatures on May 15 (the start of the spawning season), June 1, and June 15 (the end of the spawning season), were 49, 53, and 58°F respectively; and in one year of three they might be as high as 53, 58, and 64°F. Temperature elevations of 15°F on May 15, 11°F on June 1, and 6°F on June 15 would bring the water temperature to 64°F, the lethal limit. In one year of three temperature rises of 11 and 6°F could bring lake temperatures to 64°F on May 15 and June 1; on June 15 the temperature may already equal the lethal limit.

Although 50 percent of the eggs spawned may hatch at temperatures below 64°F, the most viable fry are produced only from eggs incubated at temperatures below 61°F (FWQA, Duluth, unpublished data). Temperature rises of 12, 8, and 3°F on May 15, June 1, and June 15, respectively, could bring the average water temperature to 61°F (Figure 6). In one year of three temperature rises of only 8°F on May 15 and 3°F on June 1 might bring the temperature to 61°F, and after June 7 the temperature may already exceed that value.

E. EFFECTS ON FRY REQUIREMENTS

Fry of whitefish, lake herring (cisco), smelt, alewife, and yellow perch occupy inshore waters during at least the early stages of their development; limited evidence suggests that those which move into deeper water later in the fry stage inhabit upper levels.

Hart (1930) found that whitefish in the Bay of Quinte (Lake Ontario) spawned mostly in water 8-15 feet deep, and that the eggs began hatching in about mid-April. The newly hatched fry remained near the surface, and about 2 weeks after hatching began to school and concentrate in water less than 18 inches deep. About 4 weeks after hatching they moved into water 3 or 4 feet deep, but always remained near the surface. Reckan (1970) found whitefish fry in South Bay, Lake Huron, in shallow areas (less than 3 feet deep) in late June and early July. Studies of the early life history of whitefish now being conducted by the University of Wisconsin-Milwaukee in Green Bay and northwestern portions of Lake Michigan have shown that Lake Michigan whitefish also use the inshore areas for egg incubation and nursery grounds; about 90 percent of the larvae were at water depths of 10 feet or less (Walter Hogman, University of Wisconsin, personal communication).

Pritchard (1930) reported that cisco spawning in the Bay of Quinte took place in water 8-10 feet deep, and that the eggs hatched in late April and early May. The fry ranged in shallow water with whitefish fry until they were about 1 month old, when they moved into deeper water. Cisco fry have also been observed in shallow water in Lake Huron (Faber, 1970). The cisco fry were often present in the upper 8 inches of water very near shore (e.g., around docks); small numbers, however, were regularly taken in surface collections over deep water.

Smelt spawn in early spring in tributary streams and along shore in Lake Michigan (as evidenced by the concentrations of sport fishermen during smelt spawning time). How long the fry remain in the shallow water is not known, but Wells (1968) demonstrated that most remain in the warm upper strata until late summer. In eastern Lake Erie young smelt frequent shallow epilimnial waters and at times are heavily concentrated near shore (Ferguson, 1965).

Alewives spawn in late spring and early summer in tributary streams (and along shore in some areas) in Lake Michigan (Edsall, 1970). Soon after hatching, which is primarily in June and July, the young are mostly in the upper few feet of water very near shore, but as they grow older some rapidly disperse into the upper warm levels over deeper areas, and may be found in midlake by late summer (BCF, unpublished data; Wells, 1968).

Yellow perch spawning areas in Lake Michigan are not completely known but most apparently spawn among weeds or on rocky shoals. These areas provide substrates to which the ribbon-like egg masses can cling. Hatching occurs mostly in June, at least in southeastern Lake Michigan. Largest catches of fry by BCF have been in water about 16 feet deep, and few fry have been caught in water deeper than 33 feet. Sampling has been extremely limited in water shallower than 16 feet, but on the basis of perch fry distribution in other lakes, it seems extremely likely that the fry in Lake Michigan are most abundant in water shallower than that depth.

Although the distribution of the fry of a number of other species is poorly known, some undoubtedly occupy inshore areas of Lake Michigan. The larvae of burbot and deepwater sculpins (both present in Lake Michigan), for example, have been observed in association with whitefish fry in very shallow water in Lake Huron (Faber, 1970). Two common Lake Michigan forage species, trout-perch and spottail shiners, are mostly in water less than 30 feet deep when they are in spawning condition in early summer (Bureau of Commercial Fisheries, unpublished data; Wells, 1968).

Published information on the thermal tolerance of larval fishes, including coregonids, is almost totally lacking. Recent studies in which newly hatched cisco fry acclimated at 38°F were subjected to temperature shock showed that 100 percent of the fry were immobilized in about 700 minutes at 73°F, 55 minutes at 77°F, and 5 minutes at 81°F (T. Edsall, unpublished data). Studies by Coutant (1969) on the effect of acute sublethal temperature shock on juvenile salmonids revealed that heat doses only 25 percent as large as those required to cause loss of equilibrium caused a significant increase in the susceptibility of the shocked fish to predation. No records were made of the heat doses required to produce loss of equilibrium in cisco fry, but they were considerably lower than those required to produce immobilization (T. Edsall, unpublished data). Although studies of the susceptibility of cisco fry to predation were not made, the available information suggests that cisco fry that hatch in middle to lake April and are subjected to temperatures of less than 10°F above the average for that date (Figure 6) have an increased susceptibility to predation.

F. OTHER EFFECTS

1. Effects on Fish

Historically, there is little doubt that increased temperatures and lower flows in tributary streams following deforestation and settlement were important factors associated with the reduction or elimination of stocks of whitefish, lake herring, and lake trout that spawned in rivers and shallow areas of the Great Lakes. Heavy exploitation, mill dams, and pollution were also suspected of being contributing causes; however, even after these factors were eliminated as influences, the stocks did not recover while the temperature increases persisted (forests were not replanted, and industries and cities that caused aquatic warming grew larger).

Increased temperature is still considered today the most likely cause for the reduction in numbers of whitefish, lake herring, and lake trout from tributaries and shallow areas of all of the Great Lakes, and the virtual elimination of all of these species from the St. Clair River, Lake St. Clair, the Detroit River, and Lake Erie, where they were once abundant. Lakes St. Clair and Erie recovered to some degree from this loss because they are shallow and thus are favorable for members of the perch family (walleyes, blue pike, saugers, and yellow perch), which can tolerate warmer waters. These species cannot, however, live in the cold, deep water of the other Great Lakes, nor can other species--as is illustrated by Lake Ontario, where all large lake species (including those of the perch family) are greatly reduced or absent. Fish are very scarce in Lake Ontario throughout the offshore region, which includes some 70 or 80 percent of the area of the lake.

Crossman (1969) noted that, although the increase of 2°F in average water temperature in Lake Erie since the period 1918-27 does not seem large, it is actually equivalent to moving the lake 50 miles to the south--and many of the prime species, such as lake trout, whitefish, and ciscoes (lake herring) were already at the southern limit of their temperature tolerance in Lake Erie before settlement. He also stated that, for whitefishes, temperatures only slightly above a critical level during incubation seriously reduce the number of eggs that hatch and the number of young fish that will be added to the population.

Several studies and observations support the hypothesis that temperature is presently limiting the natural distribution of coregonid fishes in the Great Lakes area (Frey, 1955; Lawler, 1965; Colby and Brooke, 1969; Crossman, 1969; Edsall and Colby, 1970).

Some of the potential insidious effects of heated effluents on the spawning grounds in Lake Michigan include the changing of the ecology of this critical habitat. Milner (1874) reported that lake trout in Lake Superior spawn in 7 to 90 feet of water, and James Reckahn (Ontario Department of Lands and Forests, personal communication) has noted that whitefish spawn over water from a few inches to 20 feet deep.

Hart (1930) found whitefish eggs in crevices and under stones. They were observed most commonly at a depth of about 8 feet and none were observed below a depth of about 15 feet. Whitefish and lake trout both spawn over suitable bottom areas where wave action and currents keep the bottom swept clean. The observations of Merriman (1935), Royce (1936), and Royce (1951) show that lake trout spawning areas are restricted to bottoms of clean gravel or rubble, free of sand and mud. Royce (1951) stated: "As the fish make no effort to bury the eggs, the bottom must have crevices into which the eggs can fall, if eggs and larvae are to be protected." Because crevices and interstices are required for protection of eggs of whitefish, lake herring, and lake trout in shallow water, any heat addition that will accelerate production and deposition of organic matter, prolong decomposition reactions and contribute decomposition products to these confined microhabitats will have deleterious effects on egg survival. These subtle changes may already be taking place in the Great Lakes; research on the problem is much needed. It is important that water quality in the bottom-water interface does not approach conditions described over fiber deposits by Colby and Smith (1967) if fish survival is to be ensured. Anoxic conditions, with associated production of bacteria similar to those over fiber beds, could occur in areas of increased heat in the presence of adequate nutrient sources. Such a situation could result where a sewage treatment plant and a power plant discharge effluents in the same vicinity.

2. Mortality of Water Birds

Multiplication of bacteria is encouraged by increasing summer lake temperatures. One particular organism of concern is *Clostridium botulinum* type E, the bacterium which has caused dieoffs of fish-eating birds on Lake Michigan and has caused human mortalities. Although this organism readily grows at low temperatures, it has an optimum range of about 68-86°F. Since it becomes most common in areas of high localized temperatures, any increase in temperature within this range will stimulate both multiplication of the organism and production of its toxin.

3. Intake Damage

Although the major share of attention so far has been focused on the thermal effects of cooling water discharges on the metabolism of Lake Michigan fish, several other consequences of using the lake waters for cooling also merit serious consideration.

Thermal shocking of aquatic organisms pulled into a power plant is an important consideration when judging intake damage. Just as important are the physical jarring and smashing to which organisms (adult fish, fish fry, and plankton) are subjected when they are brought up against the fish screens and internal piping of the intake structures. Assuming a use rate of 91,000 cfs (by the year 2000), about 1.1 percent of the total volume of the water inside the 30-foot depth contour (where the eggs, larvae and juveniles of many important Lake Michigan fishes are most abundant) will be passed through the cooling systems of power generating plants daily; and in one year a water volume equal to several times the entire water mass inside the 30-foot contour would pass through these cooling systems. Available information on the effect of thermal shock on larval fishes (see the section of fry requirements for information on the thermal tolerance of larval lake herring) indicates that the expected temperature rise alone experienced by these fishes while passing through the cooling system would be very injurious or immediately lethal. Similar undesirable effects are anticipated for other important aquatic organisms, including phytoplankton (Morgan and Stross, 1969) that serve as food for Lake Michigan fishes.

4. Discharge Damage

The addition of chemicals to clean cooling systems may also cause damage to Lake Michigan fishes and food organisms. Chlorine is generally used to limit the growth of algae on condenser surfaces. The amount of chlorine used depends on the installation but chlorination to 0.1 mg/liter for about one-half hour, three times daily, is typical. Although the amount of chlorine introduced to the lake will not significantly increase the chloride content of the lake, the

the chlorine will have a bactericidal and algicidal effect on organisms in the treated water. Preliminary data obtained to determine the potential of chlorine for use as a fish toxicant indicate that even short exposures to concentrations of less than 0.1 mg/liter are lethal to young coho salmon in natural Michigan surface waters (L. Allison, Michigan Department of Natural Resources, personal communication). Other toxicants such as chromates and copper sulfate (used to combat algal problems in cooling facilities) may also be present in the discharge water and have a serious effect on the aquatic environment.

Heated effluents from power plant cooling systems will be saturated or supersaturated with dissolved gases and will cause the formation of emboli in fishes that will damage gills, eyes, epidermis and other tissues and may be lethal. Newly hatched whitefish and lake herring larvae are highly susceptible to damage from supersaturation (T. Edsall, Bureau of Commercial Fisheries, personal communication; J. Reckahn, personal communication). Larvae of other Lake Michigan fishes are probably also susceptible.

V. EUTROPHICATION

The general effects of increased water temperature on the phytoplankton and other algae are known, but are not well delineated--particularly with respect to lakes. Patrick (1969) stated: "Blue-green algae will increase due to increased organic load and/or to rise in temperature . . .. In general, the blue-green algae have more species that prefer temperatures from 35°C [95°F] upward, whereas the green algae have a relatively large number of species that grow best in temperatures ranging up to 35°C [95°F] although some can grow at higher temperatures. Most of the diatom species prefer lower temperatures--that is, temperatures below 30°C [86°F]. The natural succession of species which we find is largely due to the fact that species can outcompete each other under varying temperature conditions. Of course, other ecological conditions also control the kinds of species which we find present at various seasons of the year. These conditions are light, nutrients, and so forth." The synergistic effect of increased temperature and increased nutrient concentration suggested by Dr. Patrick may be of particular concern with respect to present and projected conditions in Lake Michigan.

In Lake Erie, the most eutrophic of the Great Lakes, a succession of algal pulses occurs each year. Diatoms appear first in late winter or early spring when temperatures begin to rise above freezing, following the winter period of relatively little algal activity. Diatoms reach their maximum at temperatures of 35°F to

50°F. When the temperature rises above 50°F, green algae become dominant and remain dominant until the temperature nears its maximum of about 75°F. Above 75°F blue-green algae appear, and as the lake begins to cool, very large blooms frequently occur.

The algal succession as described above for Lake Erie has not been generally observed in Lake Michigan, even though temperature ranges are similar. The reason for the difference is that Lake Erie is richer and more variable in nutrient content; algal succession is not due to temperature alone, but is the result of temperature and adequate nutrient supply. The response in Lake Erie to artificial heat rise could be expected to be a change in the time of the algal succession during the warming season. Pulses of diatoms, green algae, and blue-green algae would probably occur earlier than would be expected naturally. In addition, artificial warming would lengthen the period of dominance of blue-green algae by simply sustaining temperatures above 70°F for a longer period.

In Lake Michigan, however, indications are that nutrients in the inshore waters are approaching levels commonly found in the central basin of Lake Erie. Lake Michigan inshore waters receive a substantial and increasing load of nutrients in the form of nitrogen, phosphorus, and other fertilizing agents from domestic effluents and agricultural runoff. Therefore, it can be expected that the inshore waters of Lake Michigan, if nutrients are not sufficiently controlled, will attain conditions of algal production similar to those in Lake Erie. When these conditions are reached, temperature becomes a very important factor. Dominance of green and blue-green algae will become more frequent and persistent. Blue-green algae, which are especially responsive to higher temperatures, will become more prolific in direct proportion to temperature increase. Stoermer and Yand (1969) reported that, although the dominant phytoplankters in Lake Michigan are still diatoms, the numbers of taxa that are associated with degradation of water quality have increased, and that a number of species which were able to thrive only in the naturally enriched areas near shore and in estuaries are now found in some areas of the open lake. They stated: "Consideration of distribution and relative abundance of the major components of the plankton flora leads one to the conclusion that Lake Michigan is probably at the present time about at the 'break point' between rather moderate and transient algal nuisances, largely confined to the inshore waters, and drastic and most likely irreversible changes in the entire ecosystem." Temperature increases, whatever the amount, will tend to promote these undesirable changes, especially in inshore waters.

C. L. Schelske and Stoermer, in the abstract of a paper entitled "Depletion of Silicon and Accelerated Eutrophication in Lake Michigan," presented at the meetings of the American Society of Limnology and Oceanography in August 1970, have commented further on this. They stated: "During the past 30 years, the relative abundance of diatom species commonly associated with degradation of water quality has increased. In the summer of 1969, the plankton diatoms comprised less than 10 percent of the phytoplankton in samples from the southern part of the lake, which was a significant deviation from previous years when the diatoms comprised at least 65 percent of the phytoplankton. . . . . The evidence compared with data from Lake Erie and Lake Superior suggests that accelerated eutrophication in Lake Michigan is rapidly approaching the point of a severe environmental change in which the diatom flora will be reduced or replaced by green and blue-green algae." The overall effect of heated discharges will be to reinforce an increase in warmwater algal species at the expense of more desirable coldwater species.

Hawkes (1969) cited the work of Poltoracka-Sosnowska (1967) in which the phytoplankton was compared among three Polish lakes having different temperature ranges:

"Lichen Lake received thermal discharges from the electricity-generating stations at Konin and had a temperature range of 7.4°C [45.3°F] to 27.5°C [81.5°F]. Slesin Lake was not influenced by thermal discharges and had a temperature range of 0.8°C [33.4°F] to 20.7°C [69.3°F]. The third lake was only slightly influenced by thermal water. It was found that Lichen Lake, the warmest lake, supported the richest phytoplankton flora: 285 forms; and Slesin Lake, the least number: 198. In contrast with the other lakes, the phytoplankton flora of Lake Lichen was comparatively constant. It was observed that, as the temperature of Lichen Lake rose, the numbers of phytoplankton species increased. The characteristic dominant forms in Lichen Lake were the diatom Melosira granulata and the blue-green alga, Microcystis aeroginosa. These two algae are characteristic of eutrophic situations. In the cold water of Lake Slesin, the diatom Stephanodiscus astraea (an oligotrophic form) was dominant.

"Patalas (1967) compared the productivity of Lichen Lake with that of a natural cold-water lake in the same lake system. It was found that the primary productivity of the heated lake (7.3 $g/m^2/d$) was almost twice that of the cold lake, 3.75 $g/m^2/d$. Secondary productivity in the form of phytophagous crustacea and rotifers was 4.5 $g/m^2/d$ in the heated lake, compared with 1.06 $g/m^2/d$ in the unheated lake."

The rate of eutrophication is controlled primarily by nutrient supply and water temperature. Either can be a limiting factor to productivity. Nutrient control measures are being undertaken at municipal and industrial effluent outfalls on a lake-wide basis; however, many diffuse sources of nutrients are not now amenable to control (e.g., agricultural and urban runoff and sediment erosion). Waste heat inputs, on the other hand, are entirely "point" sources and, on an overall basis, can be controlled much more efficiently that can nutrients. Thus, the control of waste heat provides greater assurance that the expensive productivity-limiting objectives of nutrient control will be attained.

VI. ECOLOGICAL RAMIFICATIONS OF THE ADDITION OF WASTE HEAT TO LAKE MICHIGAN

A. INTRODUCTION

Details of the resource, the mechanism and projected magnitude of waste heat input, and pertinent interactions of aquatic life and temperature have been reviewed in earlier sections. It is the purpose of the present section to examine the ecological ramifications of waste heat addition to Lake Michigan. The effects of individual plumes on aquatic life at specific sites are discussed, as well as the broader lake-wide aggregate effects of the projected waste heat rejection that would result from once-through cooling in coming decades.

B. GENERALIZED PLUME IMPACT

Unless a discharge is located sufficiently far from shore and in deep water, waste heat will under normal lake current conditions frequently be carried to the beach water zone, where the ecological impact will be essentially the same as that of a shoreline discharge. For this reason, attention is focused primarily on shoreline point and jet discharges.

A single plume, depending principally on effluent volume and temperature, will exert a thermal influence over a significant lake area. For example, the "dilution only" model study for the Davis-Besse Nuclear Plant indicated that the plume for an 18°F temperature rise would at equilibrium cover 28 square miles to the 2°F isotherm and 373 square miles to the 1°F isotherm (Table 14). Thus, organisms in substantial areas of the inshore waters would be exposed to the biological influence of the unnaturally warmed water.

A more extensive variation of a single plume ecological effect is the situation where two or more waste heat discharges are close enough to interact. An additive effect will cause the thermal ecological impacts from the interaction to be more intense than if only one heat source existed.

The once-through cooling process will thermally shock and physically jar adult fish, fry, and plankton. Physical damage occurs against fish screens, internal piping, and intake structures. Industrial and power operations also frequently add algicides to cooling water with resultant adverse effects on organisms. It is desirable to relate this once-through cooling damage to the large volume of water required for a single plant. A 600 cfs effluent would require 142 billion gallons of lake water per year and a 3500 cfs effluent, 826 billion gallons. In the course of an operational year, a proportionately large amount of plankton would be destroyed or placed under unnatural stress.

There will frequently be a sector which will exhibit temperatures sufficiently higher than ambient lake temperatures to be lethal or immobilizing to nearly all species in Lake Michigan. The size of the sector so affected depends, among other things, upon the discharge temperature and velocity, lake current velocity, and tolerances of specific organisms. Intolerant organisms of all life stages must avoid this sector or suffer stress or mortality; thus they are prevented from normal habitation or utilization of this zone.

There will also be a heated sector adjacent to the one nearest the outfall that is not lethal, but from time to time actually attracts certain species of fish. Angling success is reputedly sometimes improved in such sectors. The vicinity of the plant outfall will from time to time be "flushed" by storms and upwellings; the frequency of such occurrences is discussed in section II. The physical dynamics are not clearly understood but the mixing will predictably occur--sometimes with great rapidity and accompanied by sharp drops in temperature in the area of the thermal discharge. At such times, fish attracted by the warm water and acclimated to it are exposed to stress. Such stress can be sufficient to cause fish mortalities, as happened at the Campbell Plant near Port Sheldon, Michigan, in August 1968. It is suspected that a similar stress condition might occur when the heat source is shut off, as when a power plant goes off line.

An unnatural, three-dimensional continuum of temperature decrease extends from the warmest water at the discharge out to where the lake mass exhibits ambient temperatures. Within this continuum of thermal influence of the plume, the waste heat will directly and indirectly influence life processes of fishes, including feeding rate, maturation, growth, spawning, incubation, vulnerability to predation, hatching, and larval development.

Adverse physiological effects will result when optimum thermal limits for a particular life process are exceeded in the plume; these influences will generally increase in subtlety with distance from the discharge. Evidence discussed in section II indicates that only slightly elevated temperatures, properly timed and sufficiently long, can be critical in the various life history stages of Lake Michigan species. The evidence also indicates that adverse thermal limits are already approached by existing water temperature regimes; and that in warmer years, the lake temperatures may for several species already exceed these limits. For example, Lake Michigan temperature regimes may now be at borderline limits for optimum growth, reproduction, and/or survival of yellow perch, whitefish, lake trout, lake herring, alewives, and coho salmon. Thus, it appears that artificial heating would aggravate and intensify existing critical adverse effects and perhaps create new ones. Particularly in warmer years, temperature increases induced by waste heat would detrimentally affect these species or reduce their habitat in the area influenced by the plume.

An extensive zone of thermal influence would affect the species composition of algae and bacteria, in favor of species preferring higher temperature; for example, green and blue-green algae would be favored over diatoms. Such a localized eutrophication effect is particularly important in lake zones where nutrient concentrations are high.

In addition to "flushing" in the actual vicinity of the discharge, the entire area influenced by waste heat will also be purged from time to time with colder lake water. Since the addition of waste heat serves to "inflate" local natural temperatures in the shallow water environment, one resultant net effect is to exaggerate the natural temperature extremes caused by the flushing out process and thereby complicate ecological adjustments to the extremes.

C. POTENTIAL IMPACT OF CUMULATIVE WASTE HEAT

Assuming the once-through cooling technique, the projected year 2000 situation in which 431 billion Btu/hr of waste heat would be discharged to Lake Michigan requires a more general approach to ecological evaluation. The number of discharges under such a situation is unknown, although estimates as high as 100 have been advanced. Several definite impacts are recognizable, if not quantifiable.

It has been demonstrated that waste heat addition in coming decades could significantly raise the temperature in extensive areas of the inshore waters, particularly the beach water zone. Waste heat from individual shore discharges are capable of thermally influencing many miles of lake shore. As the frequency of discharges along the shore increases, many plumes would eventually be so close together that their effects would merge. With the magnitude of projected waste heat, it is not difficult to envision a very sizable proportion of the beach water zone and certain adjacent waters physically affected by artificial temperature increases.

The aggregate influence of waste heat from increasing numbers of plants around the perimeter of the lake would proportionately magnify the unnatural effects on fish and other aquatic organisms caused by a single plume. Where several plants would exist in proximity, ecological problems would be intensified with interaction of their thermal zones of influence.

Under such warmed conditions and in those areas where nutrients are approaching critical levels, changes toward increased eutrophication would be expected. The increased eutrophication would be evidenced by dramatic increases in blue-green algae.

Extensive areas of waste heat influence would also favor species of bacteria tolerant of relatively high temperatures. Under certain conditions, the warming influence would assist in proliferating both the abundance and toxin production of _Clostridium botulinum_ type E during summer and fall, and increase the probability and magnitude of mass dieoffs of shore and water birds.

Finally, projected once-through cooling water requirements of 91,000 cfs for year 2000 would require a volume of lake water equal to roughly 1 percent of the beach water zone daily, or 2.15 trillion gallons per year. On the basis of shear volume of water used, thermal and physical damage to aquatic organisms by once-through cooling could be expected to reach considerable ecological significance.

VII. CONCLUSIONS

(1) The inshore zone is in many respects the most important portion of Lake Michigan. It is the most used by man and is the most biologically productive.

(2) At times very large percentages (up to virtually 100 percent) of the waste heat discharged to the lake are diffused into the beach water zone; and studies of model plumes indicate that the influence of the heated water from a single discharge can cover many areal miles of the lake.

(3) Assuming that once-through cooling water requirements in the year 2000 will result in the discharge on the magnitude of 431 billion Btu/hr of waste heat into Lake Michigan, a significant artificial thermal load would be added to the beach water zone. Since this waste heat load would equal a significant percentage of the natural rate of heat input, it is not difficult to envision resultant physical warming of a large proportion of the beach water zone and certain adjacent waters.

(4) Heated plumes alter the natural habits of fish, exclude them from discrete areas of heated water near shore, and produce the hazard of stress and mortality in the event of rapid cooling. The plumes also create a broad area of thermal influence in inshore waters, which in an unnatural manner influences critical life history stages of fish and other aquatic organisms in the vicinity of the discharge. Evidence indicates that for several fish species,

critical life history stages are adversely affected. Furthermore, during warmer seasons, the waste heat accelerates the eutrophication process over and probably outside the discharge vicinity, which is an undesirable effect in oligotrophic Lake Michigan. The added heat also alters the normal species composition of algae during cooler seasons, and improves conditions for the development of *Clostridium botulinum* type E bacteria during warmer seasons.

(5) On the basis of available evidence, the practice of once-through cooling, regardless of any temperature standard (except virtually no heat addition), will impart the bulk of waste heat to the lake mass for an ecologically significant period of time. In other words, a 1,000-cfs discharge 5°F above the ambient temperature will transmit essentially the same amount of heat into the lake as a 250-cfs discharge with a 20°F rise, and for essentially the same length of time. It follows that, regardless of any number standard, the magnitude of ecological impact of the heat would be on the same order (disregarding more direct effects, such as fish mortalities near the discharge, which may perhaps be avoided by more thoroughly diluting the effluent).

(6) If the projected amount of waste heat is an amount sufficient to impart ecological damage to the lake, the only available alternative is to restrict the addition of waste heat to that level which will minimize or avoid damage.

(7) The timing of natural events is essential for the perpetuation of Lake Michigan coldwater aquatic life that has evolved as a result of natural selection. Any waste heat influence which would interfere with this natural timing places the survival of this aquatic life in jeopardy. Evidence presented in this report indicates that only slightly elevated temperatures, if properly timed and sufficiently long, can be critical in the life history stages of Lake Michigan species.

(8) Assuming the projected year 2000 cooling water requirement of 91,000 cfs and once-through cooling, an amazing water volume equal to 1.1 percent of the beach water zone volume would be passed through the cooling systems of power generating plants daily (4.4 percent per day for the Chicago-Gary sector). An unquantified, but significant, amount of physical and thermal damage would occur to plankton, eggs, larvae and juvenile fish. Prevention of this damage can be achieved by simply avoiding the technique of once-through cooling. Such an objective can be readily achieved by the use of closed cooling systems.

(9) Rate of eutrophication is controlled primarily by nutrient supply and water temperature, either of which may limit productivity. Since nutrient levels in certain areas of Lake Michigan are now approaching critical levels, a lake-wide shallow water warming influence would contribute to accelerating eutrophication. Therefore, the careful control of waste heat provides greater

assurance that the productivity-limiting objectives of the immensely expensive lake-wide pollution control program will be attained.

(10) Environmental influences in Lake Michigan which are detrimental to the species characteristics of large northern lakes pose a serious threat to the United States-Canadian sea lamprey control program, the State-Federal lake trout restoration program, the coho and chinook salmon sport fisheries, alewife control, and other fishery programs. Potential lake-wide effects of waste heat discussed in this report are considered to constitute such a detrimental environmental influence.

(11) On the basis of the above points, it is concluded for ecological reasons that no significant discharge of waste heat into Lake Michigan should be permitted.

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