CONTROL OF THE SEA LAMPREY *(PETROMYZON MARINUS)* IN LAKE SUPERIOR, 1953-70

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ABSTRACT

The sea lamprey (Petromyzon *marinus)* gained entrance into Lake Superior in the early 1940's, and began making drastic inroads on the fish stocks by the early 1950's. Serious efforts to control the parasite began in 1953 with the installation of electrical' barriers in streams to block spawning runs. Control measures became much more effective after 1958, when a selective toxicant, the lampricide 3-trifluoromethyl-4-nitrophenol (TFM), was used to destroy larval lampreys in streams.

A unique methodology was developed for stream treatments which included surveys to find sea lamprey larvae, bioassays to determine effective lampricide concentrations, analytical techniques to monitor concentrations of lampricide throughout the treatment, and feeder systems to apply the toxicant in controlled amounts. Evidence of successful control was indicated first by reduced sea lamprey spawning runs, as measured by the numbers of adults taken at electrical barriers. The runs declined in 1962 by about 86%; periodic re-treatments of lamprey-infested streams held the population at a low level in 1963-70. Other indicators of success were decreases in the incidence of sea lamprey wounds on lake trout *(Salvelinus namaycush),* in the numbers of sea lamprey larvae in streams, and in the number of streams regularly used by sea lampreys for spawning.

Although sea lamprey control and heavy plantings of hatchery-reared stock had restored lake trout abundance to prelamprey levels in many areas by 1970, the trout had not yet become self-sustaining. Additional effort will be required to further reduce the effects of lamprey predation.

INTRODUCTION

The invasion of the upper Great Lakes by sea lamprey (Petromyzon marinus) in the late 1930's created widespread apprehension among conservation agencies and the fishing industry. This concern was well founded, for by 1950 the lake trout (Salvelinus namaycush) was all but eliminated in Lakes Huron and Michigan by sea lamprey-predation.

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1 Contribution 481 of the Great Lakes Fishery Laboratory, U.S. Fish and Wildlife Service, Ann Arbor, Michigan 48107. This study, which is part of a program conducted by the Service under contract with the Great Lakes Fishery Commission, was largely completed while the senior author was a member of the Laboratory staff.

The first confirmed record of this parasite in Lake Superior was an adult, 240 mm long, taken near the eastern end of Isle Royale in August 1946 (Applegate 1950). An adult female (490 mm) was reported from Whitefish Point (eastern Lake Superior) in December of the same year (Creaser 1947). The relatively small size of the first specimen and the distance of the collection locality from Lakes Michigan and Huron (about 403 km [250 miles]) suggest that it may have been produced in a tributary of Lake Superior; thus sea lampreys may have been present in the early 1940's. In 1947 and 1948, migrating or spawning lampreys were observed in four tributaries of Lake Superior (Applegate 1950).

The sea lamprey must have invaded Lake Superior by passing through the rapids or locks in the St. Marys River, either by swimming or while attached to migrating fish or upbound ships. That passage on ships' hulls is likely was clearly demonstrated in 1956 and 1957 when divers who examined 125 ships passing through the Canadian locks at Sault Ste. Marie found 18 sea lampreys attached to the hulls. This habit of hitching on ships no doubt greatly increased the rate of infestation of Lake Superior.

The invasion of the upper Great Lakes by the sea lamprey led to an extensive program of research and control in which United States and Canadian agencies cooperated. Early efforts to coordinate investigations of the sea lamprey's distribution, life history, and destructiveness in Lake Superior and the other Great Lakes led to the formation of the Great Lakes Sea Lamprey Committee in 1946. This committee and the Great Lakes Lake Trout Committee were combined in 1952 to form the Great Lakes Lake Trout and Sea Lamprey Committee, which was renamed in 1953 and functioned as the Great Lakes Fishery Committee in 1953-57. Delegates from the United States Fish and Wildlife Service, the Ontario Department of Lands and Forests, and each State bordering the Great Lakes, were represented on these successive committees. In 1953 the Great Lakes Federal-Provincial Fisheries Research Committee, consisting of representatives from the Department of Fisheries of Canada and the Ontario Department of Lands and Forests, was formed to investigate the sea lamprey problem in Canadian waters of the Great Lakes.

The Great Lakes Fishery Commission was established in 1955 by the Governments of the United States and Canada and began its official functions of formulating and implementing sea lamprey control and coordinating fishery research in the Great Lakes in 1956. The Commission's agents responsible for sea lamprey control and research were the United States Fish and Wildlife Service, with field headquarters at Marquette, Michigan (Fig. 1), and the Fisheries Research Board of Canada, with field headquarters at London, Ontario.. In 1966 the Canadian responsibility for lamprey control was transferred from the Fisheries Research Board to the Department of Fisheries, with field headquarters at Sault Ste. Marie (Fig. 2).

Sea lamprey control began in Lake Superior in 1953 with the installation of a network of mechanical traps and electric barriers. The development of a selective lampricide brought about a change in control procedures in 1958. We document here the history, development, progress, and results of sea lamprey control in Lake Superior from 1953 to 1970.

Fig. 1. United States Fish and Wildlife Service Sea Lamprey Control Station, Marquette, Michigan.

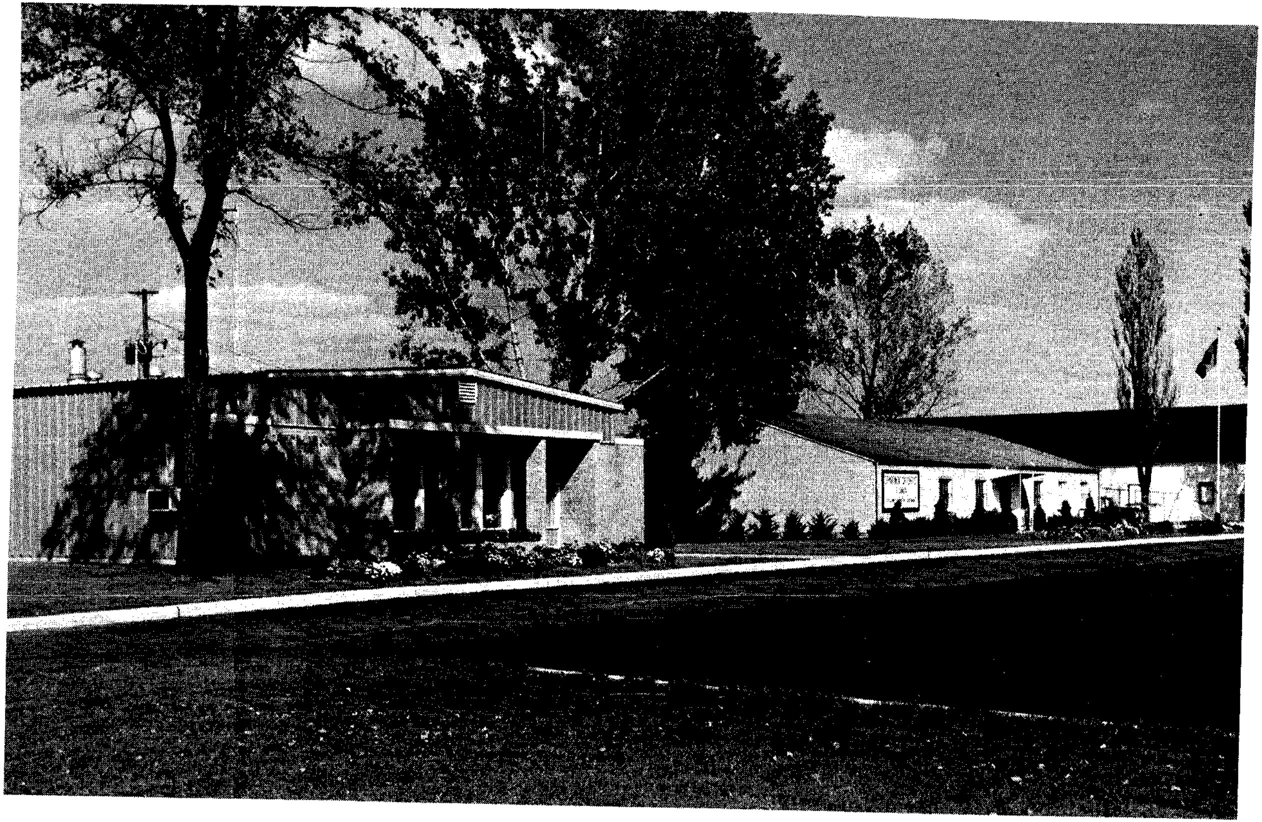

Fig. 2. Canadian Sea Lamprey Control Centre, Sault Ste. Marie, Ontario.

LIFE CYCLE OF THE SEA LAMPREY AND REQUIREMENTS FOR REPRODUCTION

The life history of the sea lamprey in the Great Lakes was described by Applegate (1950). In the Lake Superior drainage, adult sea lampreys (Fig. 3) ascend certain tributary streams in spring or early summer (April-July). Spawning begins when stream temperatures reach or exceed 10 C (50 F). The female deposits her eggs (average, about 68,000) in a nest constructed in gravel (Fig. 4), usually in an area with rapid current. The lampreys die after spawning. The eggs hatch in 10 to 13 days and the larvae (or ammocetes) remain in the nest 18 to 21 days. Upon emerging from the nest, they are carried downstream to areas of reduced current-eddies, backwaters, sloughs, or near banks (especially along inside bends) where they burrow into the soft bottom. Larval lampreys are most abundant in substrates composed of mud and silt that include some sand and often undecomposed organic detritus. Ammocetes have been found in practically all stream environments-including pockets of sand and silt behind rocks and areas with a hard bottom-but in general their abundance decreases progressively from soft to hard bottom (Stauffer and Hansen 1958).

During the nonparasitic phase of their life, sea lampreys feed on microscopic organisms; the most prevalent are diatoms and desmids (Creaser and Hann 1929). The consumption of any particular organism is probably dictated by availability, preference of the ammocetes, and selectivity of the feeding apparatus (Schroll 1959; Manion 1967).

The larval stage lasts from 3 to at least 10 years-probably longer in some streams (Manion and McLain 1971). At the end of this period, the larvae metamorphose to the adult parasitic form, taking on well-developed eyes, a circular suctorial mouth with teeth, and a blue and silver coloration. The young transformed lampreys (average length about 145 mm [5.7 inches]) migrate downstream during fall or spring (primarily fall in Lake Superior) during periods of fluctuating water levels. Upon reaching the lake, they begin to feed on fish. They grow rapidly and generally reach lengths of 305 to 610 mm (12 to 24 inches) in 12 to 20 months. In the late fall they move inshore, probably toward the mouths of the rivers they will ascend to spawn in the spring (Johnson 1969).

At least three physical factors in the stream environment are essential for successful sea lamprey spawning (Applegate 1950). First, for nest building a suitable substrate of gravel is required that includes at least a small amount of sand or other fine material to which the eggs can adhere, thereby increasing the probability of their retention in the nest. Second, current must be flowing unidirectionally over the nest. Although sea lampreys confined in pens in an area of changing currents in the Root River, Ontario, built nests, and the eggs developed to the two-cell stage before the experiment was destroyed by a flood (Scott 1957), the many unconfined lampreys that have been observed attempting to construct nests in areas where the direction of flow was changing have invariably failed; the absence of a steady current may be the major “reason why successful spawning has not been observed along the lakeshore when other conditions appeared to be satisfactory. Third, water temperatures must be suitable. Experiments on the effects of different

Fig. 3. Adult sea lamprey, *Petromyzon marinus*, from the Chocolay River, Michigan, June 1970. Length, 470 mm (18.5 inches).

Fig. 4. Sea lampreys spawning in the Big Garlic River, Michigan, July 10, 1967 (water flow is from right to left).

constant temperatures on the early embryological development of the sea lamprey (Piavis 1961) demonstrated that burrowing larvae were produced only at temperatures of 15.6-21.1 C (60-70 F). The optimum temperature was 18.3 C (65 F).

The restraints imposed by these requirements, and the presence of physical barriers such as dams and falls, limit the number of Lake Superior streams in which sea lampreys can reproduce. Even if a stream satisfies the required conditions, however, it does not necessarily follow that lampreys will spawn in it or, if they spawn, that a population of ammocetes will develop. Some streams that appear suitable are known not to be used, and adult lampreys have been observed in a few streams in which an ammocete population has never developed.

Of 1,293 United States tributaries of Lake Superior surveyed in 1950-52 to determine suitability for lamprey production, only 267 met the physical requirements described above (Loeb and Hall 1952; Loeb 1953). Of the 622 known tributaries of Lake Superior along the Canadian shore, most of which had been at least cursorily inspected by 1954, 157 were considered to be potential lamprey-producing streams (Lawrie 1954).

BUILDUP OF THE SEA LAMPREY, 1953-61

A continuous evaluation of the increase in abundance of sea lampreys in Lake Superior was made possible by the observation of catches at electrical barriers and of the incidence of lamprey wounds and scars on lake trout and other fish.

Evaluation by electric barriers

Initial attempts to control sea lampreys in Lake Superior were concentrated on the blocking of streams inhabited by lampreys, to prevent adults from reaching spawning grounds. Electric barriers were constructed on streams that appeared to be used most extensively by spawning lampreys,

The barriers were composed of parallel electrode arrays, stretched across a river to establish an electric field from one bank to the other. The electrodes were energized with 115-volt alternating current. In streams where fish mortality was excessive, direct-current diversion devices that diverted fish into a bypass trap were installed in conjunction with the alternating-current barriers. The diversion devices caused no major change from the basic principle of preventing sea lampreys access to spawning areas (Lenson and Lawrie 1959; McLain et al. 1965).

Electric barriers were installed progressively from east to west in tributaries on both the Canadian and United States shores of Lake Superior between 1953 and 1957. (Examples are shown in Figs. 5 and 6). A total of 97 streams were eventually included in the barrier program-60 in the United States and 37 in Canada. Some were operated only long enough (usually 1 or 2 years) to assess the importance of the stream for lamprey spawning, and then discontinued if the stream was not used. Others were operated for 8 years, from 1953 to 1960, as a means of decreasing the sea lamprey

Fig. 5. Electric barrier on the Garden River of North Channel, Lake Huron. This horizontal rack-type installation, consisting of pipe electrodes and wooden separators, is typical of barriers used in Canadian waters of Lake Superior.

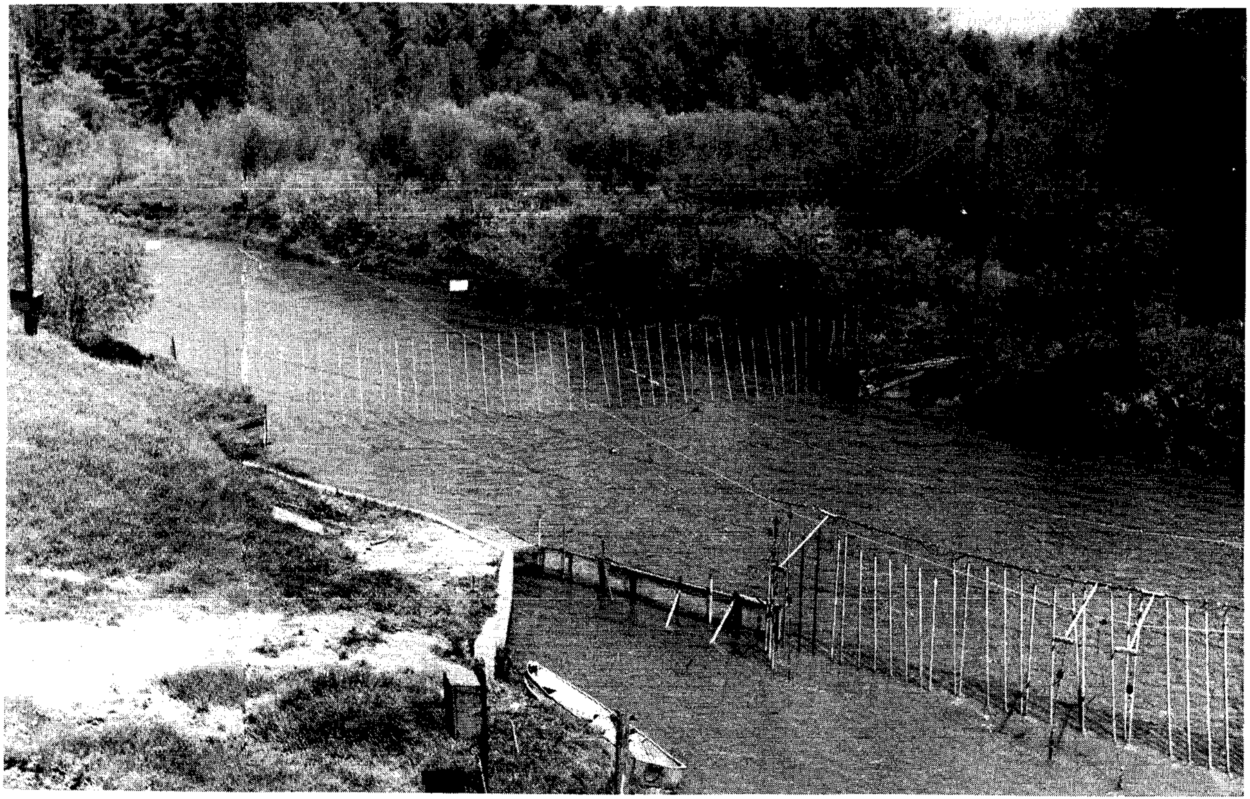

Fig. 6. Electric sea lamprey barrier and trap above the mouth of the Brule River, Wisconsin, June 1965. Water flow is from left to right. The direct-current electrodes at lower right, which extend across the river, lead fish into the trap near the stream bank (left center).

population. After the adoption of chemical control methods, 24 barriers were operated during 1961-67 as assessment devices to measure changes in the numbers of spawning migrants from year to year; this number was reduced to 16, all in the United States, in 196870.

Increases in abundance of sea lampreys

The growth of the sea lamprey population in Lake Superior during the 1950's and early 1960's has been inferred from counts of upstream migrating adults at electric barriers (Table 1) and from the increase in the incidence of scarred fish. (The numbers of adult sea lampreys collected at barriers operated in 1958-70 to assess the effectiveness of lamprey control are listed later, in Table 6.) Sea lamprey abundance apparently increased from 1953 to a first peak in 1958, decreased slightly in 1959 and 1960, and then reached an all-time high in 1961. Stream surveys have shown that populations were not established in some tributaries in the western end of Lake Superior until the 1960's. Observations on the Amnicon River, however, confirmed that this stream was being heavily used by sea lampreys for spawning as early as 1956.

Reports by commercial fishermen of the incidence of lamprey wounds and scars on lake trout, as part of their monthly reports of catch statistics to State agencies, yielded further information on the increase in lamprey numbers over the years. In 1946 up to 10% of the lake trout in individual catches were lamprey scarred, but the average was less than 1% (Shetter 1949). By 1951 the average had reached 5% in State of Michigan waters. Scarring rates continued to increase in most areas of the lake until a peak was reached in 1959 and 1960, when in some areas the proportion of lake trout bearing scars was more than 90% at certain times of the year. The incidence of scarring on lake trout examined during spawn-taking operations in the Apostle Islands area by the Wisconsin Department of Natural Resources indicated a large and growing population of feeding sea lampreys in that area of the lake in the middle and late 1950's; scarring increased from 10% in 1952 to 91% in 1960.

Effects of sea lamprey predation on fish stocks

The effect of lamprey predation (combined with high fishing intensity) on fish stocks in Lake Superior was dramatically illustrated by the decline in lake trout production from about 2,041 metric tons (4.5 million pounds) in 1950 to 227 metric tons (0.5 million pounds) in 1960 (Fig. 7). During this period, 277,531 adult sea lampreys were captured at the barriers.

Parker and Lennon (1956) reported that sea lampreys held in captivity until they reached an average length of 320 mm (12.6 inches) killed an average of 8.4 kg (18.5 pounds) of fish. Inasmuch as lampreys in the Great Lakes reach much larger average lengths, these authors believed that the **"average fish-kill by wild lampreys exceeds, and could be approximately** double, the 18.5 pounds recorded for laboratory animals." If wild Lake Superior lampreys killed an average of 13.6 kg (30 pounds) of fish during their parasitic life, the lampreys captured at the barriers alone destroyed more than 3,629 metric tons (8 million pounds) of fish in 1953-60. Since barriers

Table 1. Numbers of sea lampreys taken at electric barriers operated in tributaries of Lake Superior, 195 3-61
[Dash indicates that barrier was not in operation.]

Stream	1953	1954	1955	1956	1957	1958	1959	1960	1961
United States									
Waiska River		32	47	71	55	70	43	127	87
Pendills Creek	23	40	45	42	47	17	40	33	74
Halfaday Creek	-	12	3	14	4	2	-	-	-
Ankodosh Creek	-	0		-		-	-	-	-
Betsy River	221	567	569	1,517	786	1,092	1,006	705	1,366
Little Two Hearted River			-	-	739	460	461	715	558
Two Hearted River	371	638	600	1,766	7,899	3,477	4,141	4,508	7,498
Dead Sucker River	0	0				-	-	-	-
Sucker River	750	1,309	1,713	4,400	3,597	1,842	2,522	4,980	3,209
Hurricane River		8	25	99	188	29	65	80	96
Beaver Lake Outlet	8	19	19		49	18	-	-	
Miners River	64	53	148	96	427	91	159	411	220
Furnace Creek	18	47	66	209	274		396	2,293	1,012
Au Train River	204	350	486	613	739	348	168		181
Rock River		-	1,633	3,407	3,102	1,488	1,250	2,646	3,660
Laughing Whitefish River	-9	25	16	19	37	11	28	42	267
Sand River		0					-	-	
Chocolay River	356	1,227	3,350	6,888	8,096	6,221	3,500	4,216	4,201
Carp River	-	0	2	1	4	0	5	5	-
Harlow Creek	-	1	1	0	3	3	31	14	22
Little Garlic River	-	0	0		-	-		-	-
Big Garlic River	-	54	89	154	270	262	247	87	
Iron River	-	67	206	335	737	428	266	342	2,430
Salmon Trout River		1	0	0		-	68	5	12
Pine River	-	10	12	18	34	22	43	28	70
Little Huron River	-	0	-			-	-	-	-
Huron River	-	147	472	1,628	2,868	3,526	1,492	1,377	4,825
Ravine River		1	4	2	10	5	23	8	6
Slate River		0	-		-	-	-	-	-
Silver River		247	786	963	2,810	2,152	878	1,386	5,052

Table 1 . - Cont'd

Stream	1953	1954	1955	1956	1957	1958	1959	1960	1961
Sturgeon River	-	1	1	4	31	28	544	161	427
Otter River	-	0	0	1	0	0	-	-	-
Pilgrim River	-	0	-	-	-	-	-	-	-
Trap Rock River	-	0	0	-	-	-	-	-	-
Traverse River	-	3	4	37	45	76	598	-	-
Tobacco River	-	0	-			-	-	-	-
Little Gratiot River	-	0	1	4	-9	1	11	-	-
Gratiot River	-	1	0	4	2	31	11	-	-
Boston-Lily Creek	-	0	-	-	-	-	-	-	-
Schlotz Creek	-	0	-	-	-	-	-	-	-
Graveraet River	-	0	-	-	-			-	
Elm River	-	0	7	7	7	-2	-8	12	-9
South Branch Elm River	-	0	0	-	-	-			
Misery River	-		183	571	868	896	2,581	761	962
Firesteel River	-	60	150	229	1,039	1,546	2,084	276	1,118
Flintsteel River	-	2	1	1	2	2	0	0	-
Union River	-	0	0	-	-		-	-	-
Bad River	-	-	-	685	2,652	6,203	4,468	-	-
White River	-	-	-	219	412	231	552	233	-
Fish Creek	-	-	-	-	520	251	428	354	
Cranberry River	-	-	-	-	-	0	14	50	12
Iron River	-	-	-	-	-	0	-	-	-
Fish Creek	-	-	-	-	-	0	-	-	-
Reefer Creek	-	-	-	-	-	1	-	-	-
Brule River	-	-	-	-	3,988	22,842	19,389	9,755	22,478
Poplar River	-	-	-	-	126	580	8	58	103
Middle River	-	-	-	-	4,289	4,853	3,645	2,839	3,502
Amnicon River	-	-	-	-	11,055	7,670	986	1,165	4,741
Black River	-	-	-	-	-	4	13	21	-
Nemadji River	-	-	-	-	-	3	1	10	-
Subtotal	2,024	4,922	10,639	24,084	57,820	66,931	52,173	39,783	68,198

Table 1. - Cont'd

Stream	1953	1954	1955	1956	1957	1958	1959	1960	1961
				Canada					
East Davignon Creek	-	-	1	3	-	-	-	-	-
West Davignon Creek	-		0	0	-	-	-	-	-
Little Carp River	-	-	20	24	26	5	5	-	-
Big Carp River	-	-	5	27	28	19	15	20	6
Cranberry Creek	-	-	6	11	18	6	-		-
Goulais River	-	-	46	62	820	682	395	760	-
Haviland Creek	-		0	3	-	-	-	-	-
Stokeley Creek	-	49	11	58	5	2	0	-	-
Harmony River	-	19	29	29	16	6	8	19	14
Jones Landing Creek	-	-	0	0	-	-	-	-	-
Downey Creek	-	-	0	0	-	-	-	-	-
Chippewa River	-	-	807	839	359	220	296	1,051	453
Batchawana River	-		608	421	427	358	482	629	561
Sable River	-	39	43	65	76	47	142	246	88
Pancake River	-	-	555	717	1,073	809	816	1,306	931
Agawa River	-	-	-	0	26	19	18	-	-
Coldwater Creek	-	-	-	-	0	-	-	-	-
Baldhead River	-	-	-	-	0	-	-	-	-
Gargantua River	-	-	-	-	0	-	-	-	-
Old Woman River	-	-	-	-	0		-	-	-
Michipicoten River	-	-	-	53	372	641	371	143	-
Dog River	-	-	-	-	9	0	10	-	-
Swallow River	-	-	-	-	0	-	-	-	-
White Gravel River	-	-	-	-	0	-	-	-	-
Willow River	-	-	-	-		-	-	-	-
Little Pic River	-	-	-	0	8	-	-	-	-
Prairie River	-	-	-	0	0	0	-	-	-
Steel River	-	-	-	1	0	-	-	-	-
Hewitson Creek	-	-	-	0	1	1	-	-	-
McLeans Creek	-	-	-	0	0	-	-	-	-

Table 1. - Cont'd

Stream	1953	1954	1955	1956	1957	1958	1959	1960	1961
Pays Plat River	-	-	-	6	3	4	32	10	31
Big Gravel River	-	-	-	5	99	154	541	626	799
Little Gravel River	-	-	-	0	2	0	0	-	-
Cypress River	-	-	-	1	3	5			
Jackfish River	-	-	-	0	0	64	240	--	--
McIntyre River	-	-	-	-	0	2	2	-	-
Neebing River	-	-	-	-	1	0	0	-	-
Subtotal	-	107	2,131	2,325	3,364	3,044	3,374	4,810	2,883
Total	2,024	5,029	12,770	26,409	61,184	69,975	55,547	44,593	71,081

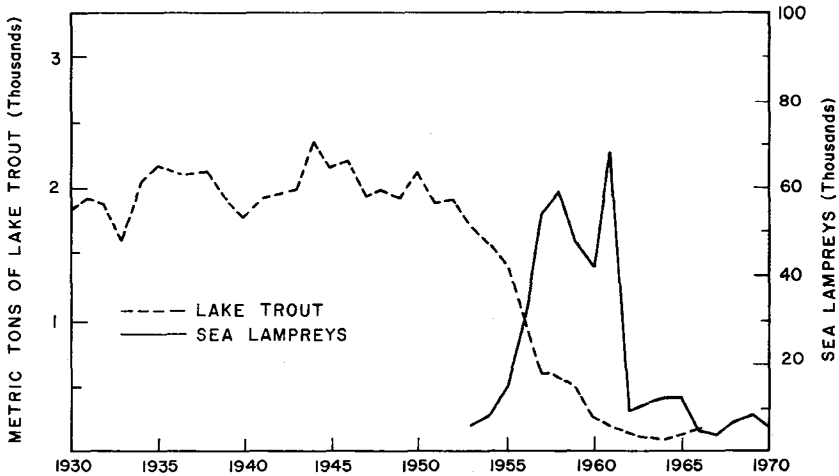

Fig. 7. Production of lake trout and numbers of sea lampreys caught in 24 index streams of Lake Superior. Catches of lampreys in 1953-56, while barriers were being built in index streams, are not strictly comparable with those in 1957-70. The numbers of index barriers in full operation in the earlier years were as follows: 1953, 6; 1954, 13; 1955, 19; and 1956, 21. In 1968-70, the number was reduced to 16 (the 8 Canadian barriers were discontinued).

were not present in some of the largest streams used by spawning lampreys, the catch did not represent the total population in the lake; thus losses to lampreys were unquestionably far greater.

An increase in sea lamprey predation on rainbow trout or steelhead (Salmo gairdneri) was reflected by numbers of lamprey-scarred fish recorded at nine electric barriers along the south shore of Lake Superior. In 1956, when observations were begun, 1.5% of 1,300 mature rainbow trout captured in the traps were marked by lampreys; in 1960, 13.6% of 1,078 fish were scarred.

Although records for other fish are less detailed than those for lake trout and rainbow trout, many species are known to have been adversely affected by the sea lamprey. The burbot (Lota lota) declined concurrently with the lake trout, even though few burbot were taken in the commercial fishery. Reports of high scarring rates on whitefish (Coregonus clupeaformis) were common from 1954 to 1960. Information on other species is sparse, but sea lampreys have been observed feeding on, or wounds have been found on, almost all of the fishes in Lake Superior, ranging in size from rainbow smelt *(Osmerus mordax)* to lake sturgeon *(Acipenser fulvescens).*

DISTRIBUTION OF SEA LAMPREY AMMOCETES

The development of a chemical method for the control of sea lamprey larvae in streams (Applegate et al. 1958) prompted intensive surveys to determine the presence and distribution of ammocetes in streams and other waters.

Most stream surveys were carried out with electroshockers, consisting of a source of electricity-usually a portable gasoline-powered generator (Fig. 8) or battery-and a pair of electrodes that conduct pulses of electricity into the water and the stream bottom. As the electrodes are passed slowly over suitable habitat, the irritated larvae emerge from their burrows. The lampreys were collected with dip nets and preserved in 5% formalin for subsequent examination to separate sea lamprey larvae from those of endemic species and to collect other biological data. In the early years, electrical power was supplied by generators but by the mid-1950's more easily portable back-pack units were developed for use in remote and inaccessible areas; in these units, 6- and 12-volt battery-powered converters supplied 110-volt alternating current to the collecting nets (Tibbles 1959; Braem and Ebel 1961). In the late 1960's, efficiency was increased by the development of a transistorized model of the back-pack shocker that yields pulsed direct current (Fig. 9).

The development in 1966 of a formulation of a molluscicide (Bayer 73 [2-aminoethanol salt of 2', 5-dichloro4'-nitrosalicylanilide] as 5% active ingredient on silica sand) provided a most useful means for surveying streams where the effectiveness of electroshockers was limited by low conductivity. or by the deep water over larval habitat. The sand granules coated with chemical are spread evenly on the water surface and then sink to the stream bottom. Ammocetes in the substrate soon emerge from their burrows to escape the chemical and are available for collection.

Distribution in streams

The Michigan Department of Natural Resources found sea lamprey larvae in 21 of 60 river systems surveyed with direct-current electric shockers in 1957 (Stauffer and Hansen 1958). Subsequent surveys by the United States Fish and Wildlife Service increased the list of sea lamprey streams to 80 along the United States shore of Lake Superior (Fig. 10, Table 2).

First surveys of Canadian tributaries of Lake Superior by the Ontario Department of Lands and Forests and the Fisheries Research Board of Canada were largely in inaccessible areas and produced only limited information on ammocete distribution. Later, more detailed examination by improved techniques led to the collection of sea lamprey ammocetes in 39 Canadian tributaries of Lake Superior (Fig. 10, Table 2).

Distribution in bays, estuaries, and lakes

Some ammocetes drift downstream into bays, estuaries, and lakes in river systems. One such area, East Bay near the mouth of the Sucker River, Alger County, Michigan, was surveyed by the Michigan Department of Natural Resources in 1960 (Wagner and Stauffer 1962). An orange-peel dredge was used to collect larvae, and the larval population was estimated by the area-density method (Rounsefell and Everhart 1953). The population of sea lamprey ammocetes in this 31.6-ha (78-acre) area was estimated to be 96,300 ± 20,500. Inasmuch as the study required 5 weeks, an inspection of all

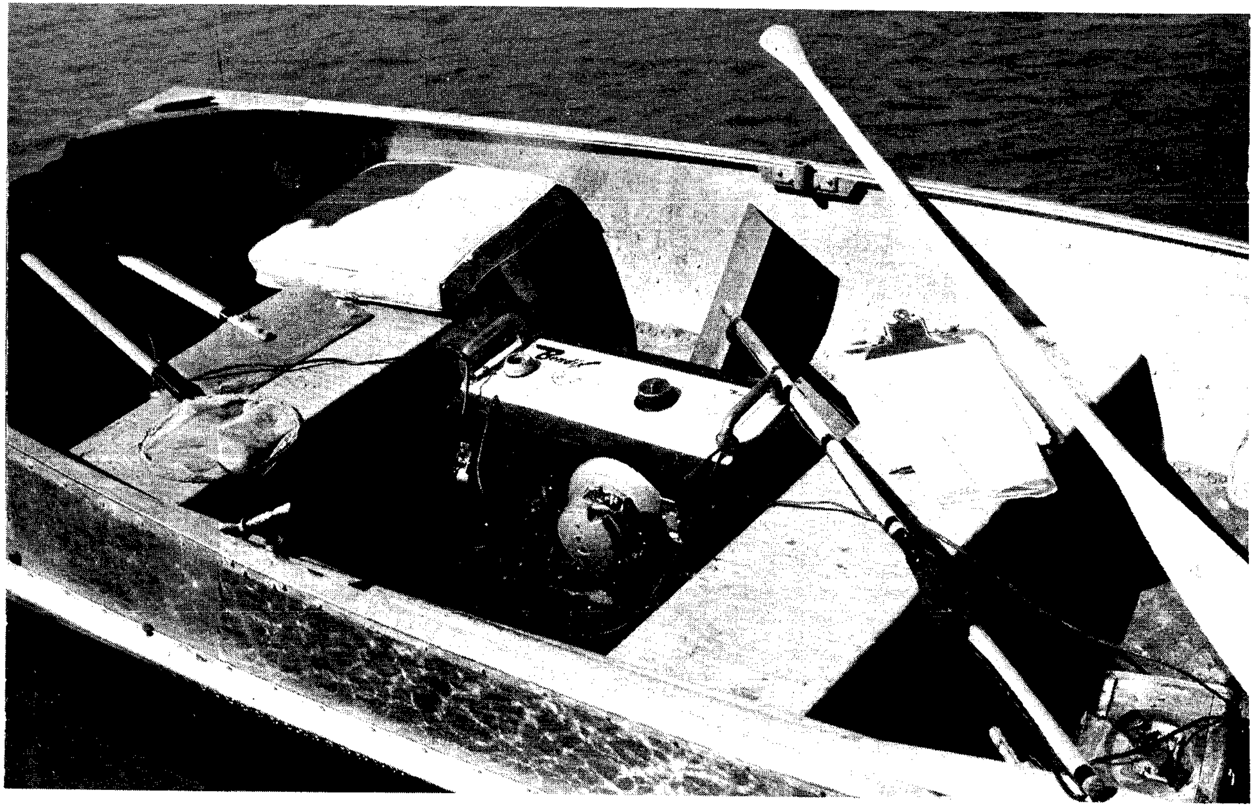

Fig. 8. Equipment developed in 1958 for collecting ammocetes from Canadian tributaries of the Great Lakes. Note the compact, gasoline-powered electric generator; two galvanized steel electrodes on wooden dowels (one with micro switch sealed in a rubber cover); and a dip net for collecting specimens.

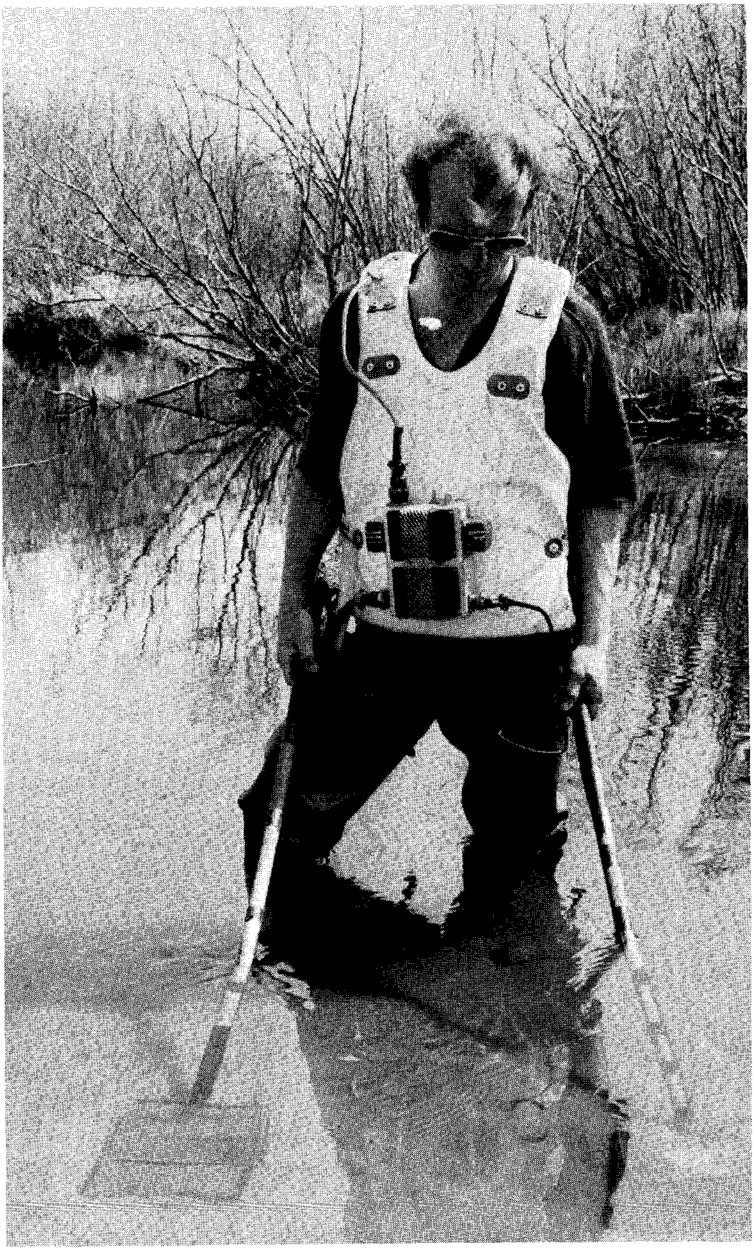

Fig. 9. Collecting ammocetes with a transistorized back-pack shocker.

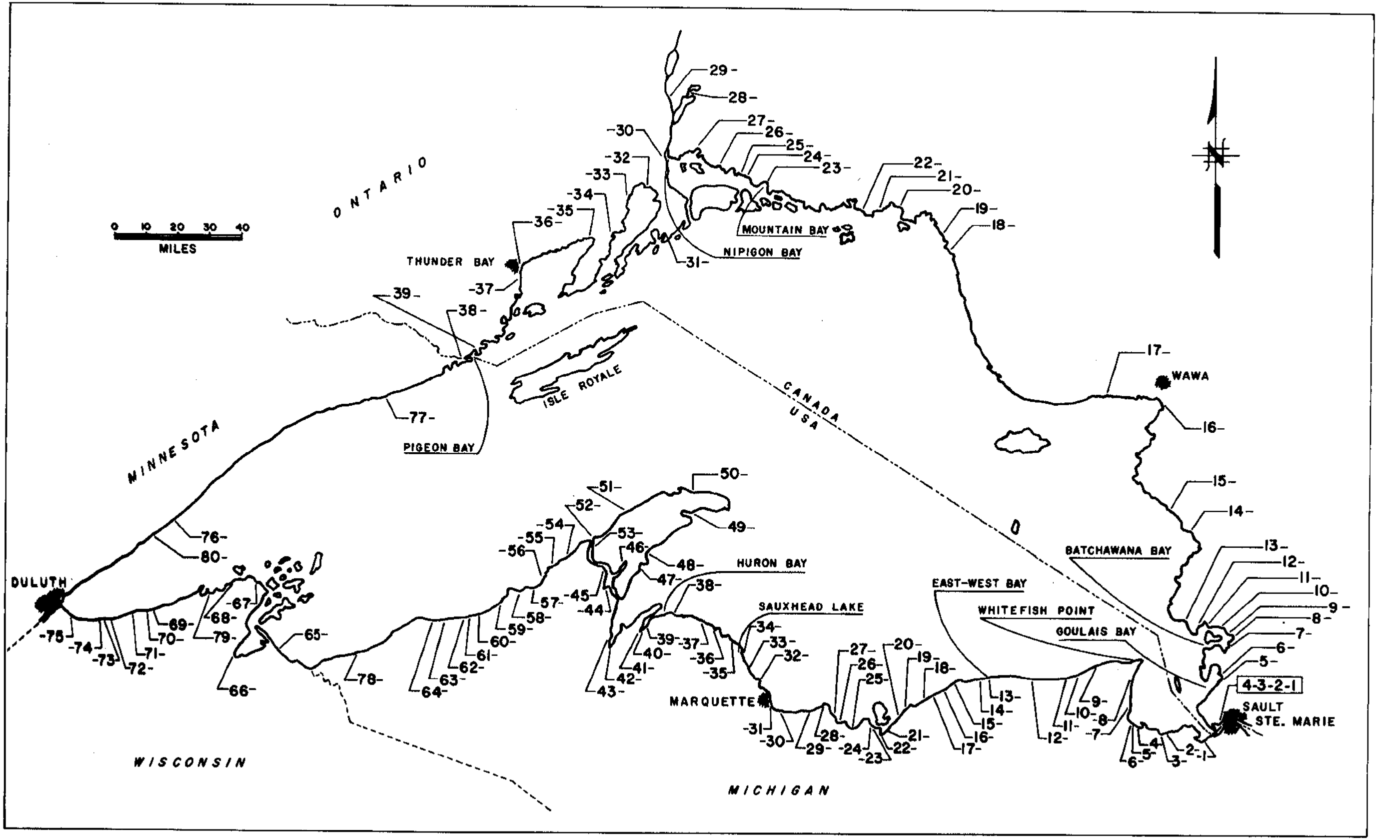

Fig. 10. Lake Superior, showing location of 80 U.S. streams and 39 Canadian streams in which sea lamprey ammocetes have been collected (see Table 2 for names of streams).

Table 2. Streams tributary to Lake Superior that have contained sea lamprey ammocetes

[Stream number corresponds to location in Fig. 10. "Current lamprey production group" indicates capacity of streams to produce sea lampreys; group l-heavy and consistent; 2-medium; 3-light or very light (includes five large, complex Canadian streams [marked by asterisks] in which ammocetes have been scarce and which have been treated only if surveys indicated a danger that the streams might produce parasitic-phase lampreys)]

Location, number and stream		Stream flow (cfs)	Current lamprey production group
United States (county and state)			
Chippewa, Michigan			
1	Waiska River	30	2
2	Pendills Creek	25	3
3	Grants Creek	3	3
4	Naomikong Creek	7	3
	Ankodosh Creek	5	3
2	Galloway Creek	5	3
7	Tahquamenon River	60	1
8	Betsy River	70	2
Luce, Michigan			
9	Three Mile Creek	3	3
10	Little Two Hearted River	50	2
11	Two Hearted River	200	1
12	Dead Sucker River	30	3
Alger, Michigan			
13	Sucker River	100	1
14	Sable Creek	10	3
15	Hurricane River	10	3
16	Sullivans Creek	5	3
17	Seven Mile Creek	17	3
18	Beaver Lake Outlet	25	3
19	Mosquito River	25	3
20	Miners River	60	3
21	Munising Falls Creek	2	3
22	Anna River	50	3
23	Furnace Creek	30	3
24	Five Mile Creek	5	3
25	Au Train River	250	2
26	Rock River	25	2
27	Deer Lake Outlet	30	3
28	Laughing Whitefish River	30	2
29	Sand River	30	2
Marquette, Michigan			
30	Chocolay River	150	1
31	Carp River	15	3
32	Harlow Creek	10	3
33	Little Garlic River	20	2
34	Big Garlic River	20	2
35	Iron River	65	2
36	Salmon Trout River	50	2
31	Pine River	30	3
38	Huron River	70	1

Table 2 - Cont'd

Location, number and stream		Stream flow (cfs)	Current lamprey production group
Baraga, Michigan			
39	Ravine River	20	3
40	Slate River	10	3
41	Silver River	40	1
42	Falls River	50	3
43	Six Mile Creek	24	3
Houghton, Michigan			
44	Sturgeon River	1,000	1
45	Pilgrim River	15	3
46	McCallum Creek	1	3
47	Mud Lake Outlet	20	3
48	Traverse River	40	1
52	Smith Creek	9	3
53	Boston-Lily Creek		3
54	Salmon Trout River	3:	3
55	Graveraet River	15	3
56	Elm River	15	3
Keweenaw, Michigan			
49	Little Gratiot River	75	3
50	Eliza Creek	3	3
51	Gratiot River	14	3
Ontonagon, Michigan			
57	Misery River	60	2
58	East Sleeping River		2
59	Firesteel River	60	2
	Ontonagon River	700	1
61	Potato River		2
62	Cranberry River	40	2
63	Little Iron River	40	3
64	Union River	11	3
Gogebic, Michigan			
78	Black River	300	3
Ashland, Wisconsin			
65	Bad River	700	1
Bayfield, Wisconsin			
66	Fish Creek	85	2
67	Raspberry River	2	3
68	Sand River	5	3
69	Reefer Creek	4	3
70	Fish Creek	1	3
79	Cranberry River	30	3
Douglas, Wisconsin			
71	Brule River	210	1
72	Poplar River	15	3
73	Middle River	20	2
74	Amnicon River	50	1
75	Nemadji River	250	2

Table 2 - Cont'd

Location, number and stream		Stream flow (cfs)	Current lamprey production group
Lake, Minnesota			
76	Splitrock River	15	3
80	Gooseberry River	100	3
Cook, Minnesota			
77	Arrowhead River	200	3
Canada (district and province)			
Algoma, Ontario			
1	Past Davignon Creek	10	3
2	West Davignon Creek	15	3
3	Little Carp River	20	2
4	Big Carp River	20	2
	Cranberry Creek	25	3
6	Goulais River	800	1
1	Stokeley River		3
8	Harmony River	25	3
9	Sawmill Creek	5	3
10	Chippewa River	190	2
11	Batchawana River	210	1
12	Sable River	45	2
13	Pancake River	60	2
14	Agawa River	500	3*
15	Sand River	200	3
16	Michipicoten River	2,200	2
17	Dog River	200	3
Thunder Bay, Ontario			
18	White River	350	2
19	Big Pic River	500	3*
20	Little Pic River	450	3*
21	Prairie River	100	3
	Steel River	750	3*
23	Pays Plat River	220	3
24	Big Gravel River	160	1
25	Little Gravel River	95	3
26	Cypress River	25	2
27	Jackfish River	50	2
28	Cashe Creek	30	
29	Nipigon River	3,800	3*
30	Otter Cove Creek	5	3
31	Stillwater Creek		2
32	Black Sturgeon River	650	1
33	Wolf River	150	1
34	Pearl River	50	3
35	Blende Creek	10	3
36	McIntyre River	80	3
37	Kaministikwia River	1,150	1
38	Pigeon River	400	2
39	Cloud River	5	3

such areas in this manner was obviously impractical. In 1961 the United States Fish and Wildlife Service developed an electrified beam trawl to collect ammocetes in areas where other methods were not practical (McLain and Dahl 1968). This trawl was used extensively in Batchawana Bay just north of Sault Ste. Marie to corroborate information on populations sampled originally by means of a specially designed dredge (Thomas 1960). Sand granules coated with Bayer 73 have also been spread on the bottom in deep water areas off the mouths of streams to collect ammocetes.

An attempt was made during 1959 and 1960 to delineate the distribution and measure the density of ammocete populations in four areas (see Fig. 10 for locations)-Goulais Bay, Batchawana Bay, Mountain Bay (the part of Nipigon Bay adjacent to the Gravel River), and Pigeon Bay-by electroshocking in shallow water, dredging in deep water, and making spot applications of rotenone to the bottom, under inverted trays. Batchawana Bay received the most thorough study because it contained the only population of obvious significance. Here the average density of sea lamprey ammocetes in 1959 and 1960 was 1.7 per 836 m^2 (1,000 square yards), but no areal limits could be established for the population. Individuals were found as far as 4 km (2.5 miles) from the nearest parent stream but concentrations were greatest near the mouths of the Chippewa, Batchawana, and Sable Rivers.

Sea lamprey ammocetes present in lakes within river systems were difficult to assess. Beaver and Furnace Lakes in Alger County, Harlow and Saux Head Lakes in Marquette County, and Otter Lake in Baraga County all contained lamprey populations of unknown magnitude. Each of these areas was surveyed in several ways but only estimates of relative abundance were obtained.

Sea lamprey larvae have been found off the mouths of 12 Lake Superior streams. The greatest numbers have been collected in the bays at the mouths of the Silver, Sucker, Batchawana, Chippewa, and Sable Rivers.

METHODOLOGY FOR CHEMICAL CONTROL OF LARVAL SEA LAMPREYS

Development of a selective lampricide completely changed the emphasis of the sea lamprey control program in 1958. The task of introducing precisely controlled amounts of chemical into streams necessitated the development of new methods and equipment in a short time. The development of the lampricide, the preparations needed before the lampricide is introduced into a stream, and the methods of applying the material are described here.

Development of a selective lampricide

The first measures to control sea lampreys were aimed at preventing migration of adults to spawning grounds in all streams with suitable spawning and larval habitat. After streams were blocked with barriers, however, the five or more year classes of larvae already in the streams could be expected to continue contributing to the parasitic population in the lake for as long as 10 years (or even longer).

The desire to eliminate this extreme delay in achieving control prompted a search, beginning in 1953, for a chemical that would kill lampreys in streams before they migrated to the lake. About 6,000 chemicals were tested at the Hammond Bay (Lake Huron) Biological Station of the United States Fish and Wildlife Service (listed in part by Applegate et al. 1957). Six closely related halogenated mononitrophenols were found that demonstrated differential toxic effects on larval lampreys and fishes. Subsequently, four additional compounds in this chemical group were discovered. All 10 compounds displayed selective toxicity, but some were better adapted than others to field application because of their physical and chemical properties and cost. One compound, 3-trifluoromethyl-4-nitrophenol (TFM), was adopted for use in the field. Its application in early experimental treatments was described by Applegate et al. (1961).

Pretreatment preparations

Stream surveys

Application of lampricide to a stream is preceded by an intensive survey with electric shockers, and occasionally chemicals (TFM or Bayer 73) to determine lamprey distribution. From the survey a detailed map showing the location of sea lamprey ammocetes and information on their size and density is prepared. Water discharges of the main stream and each tributary are determined, fish species are recorded, and sections of the stream that might be difficult to treat by routine methods are identified. Such problem areas may include beaver ponds, lakes within the system, extensive springs or seepage areas, isolated oxbows, or large estuaries. Stream survey reports include a map showing recommended application points, access roads, trails, and land ownership. The survey, which is completed in advance of a scheduled treatment, is the basis for determining the need for treatment and for planning application of lampricide.

Standards for decision on stream treatment

For the first few years in which TFM was used, treatment of a tributary of Lake Superior was based on only one criterion: If a single sea lamprey ammocete was found, the stream was treated and scheduled for re-treatment in 4 years. Posttreatment surveys and studies of reestablished sea lamprey populations, however, soon demonstrated the need for more flexible scheduling. In a few streams where sea lampreys spawned and larvae were produced, ammocetes disappeared before reaching metamorphosis. In other streams, only small numbers became reestablished. In some streams ammocetes reached the parasitic phase in 3 years, whereas in other streams 10 or more years were required. These wide differences in lamprey life history from stream to stream dictated the need for additional guidelines to determine whether or not a stream should be treated.

The first consideration for determining whether a stream is to be treated is the size of the ammocetes present. In most tributaries of Lake Superior, sea lampreys do not metamorphose until they are at least 120 mm (4.7 inches) long. Therefore, if the largest larvae in a population are less than 100 mm (3.9 inches) long in midsummer, treatment usually may be safely postponed for at least a year. Growth rate must also be taken into account, however, in estimating the time required for larvae to reach transformation; in a few rivers where ammocetes grow rapidly, treatment becomes necessary when the largest ammocetes are 80 to 90 mm (3.1 to 3.5 inches) long.

A second important consideration is the scheduling of treatments in the presence of problem areas within a stream system. Because it is difficult or impossible to kill all ammocetes in lakes, beaver ponds, or estuaries by normal treatment procedures, it is sometimes more efficient to destroy the larvae before they reach these areas than to try to kill them later. For example, the Sucker River, Alger County, Michigan, was treated every-other year in 1961-69 to prevent contamination of East Bay, the 31.6-ha (78-acre) “lake” near the mouth; and the three major tributaries of Batchawana Bay were treated annually in 1961-68 to reduce the population of ammocetes in the bay.

Other problem areas in streams are springs, and seepage areas in which the lampricide used in a routine treatment is diluted enough to allow some lampreys to survive. These rivers are also usually treated more frequently than most others, to try to eliminate the surviving lampreys before they migrate to Lake Superior.

Occasionally, to complete all treatments in a given area, field crews treat a small stream earlier than is required on the basis of the size of the lamprey larvae if the cost is less than that of returning to treat the single stream later.

Bioassays

Although surveys may be completed well in advance of a chemical treatment, other procedures must be carried out immediately before the application of lampricide. The most important is a bioassay to determine the minimum concentration needed to kill ail lamprey larvae and the maximum concentration that can be used without causing significant mortalities of other fish (Fig. 11). Depending on its complexity and size, an individual stream system may require several bioassays because chemical properties that alter the effect of the lampricide may differ in different parts of the system. Bioassay procedures used in the United States were described by Howell and Marquette (1962). Essentially, solutions of TFM in stream water, in a range of concentrations (in equal increments), are tested and the time to death of ammocetes and fish at each concentration is recorded over a 24-hour period. When completed the bioassay delineates the minimum concentration required to kill lampreys and the maximum concentration that does not harm fish.

The fish used in the bioassay, usually rainbow trout in the United States and brook trout *(Salvelinus fontinalis)* in Canada, are provided by the States and the Province of Ontario. When warm-water species are present in the stream to be treated, small suckers (usually white suckers, *Catostomus commersoni)* are sometimes used as test fish. Ammocetes for use in the bioassay are collected from naturally occurring populations in the Great Lakes watershed, generally from an area near the treatment site. Larvae of all species of lampreys are usually used, since sea lamprey ammocetes are apparently

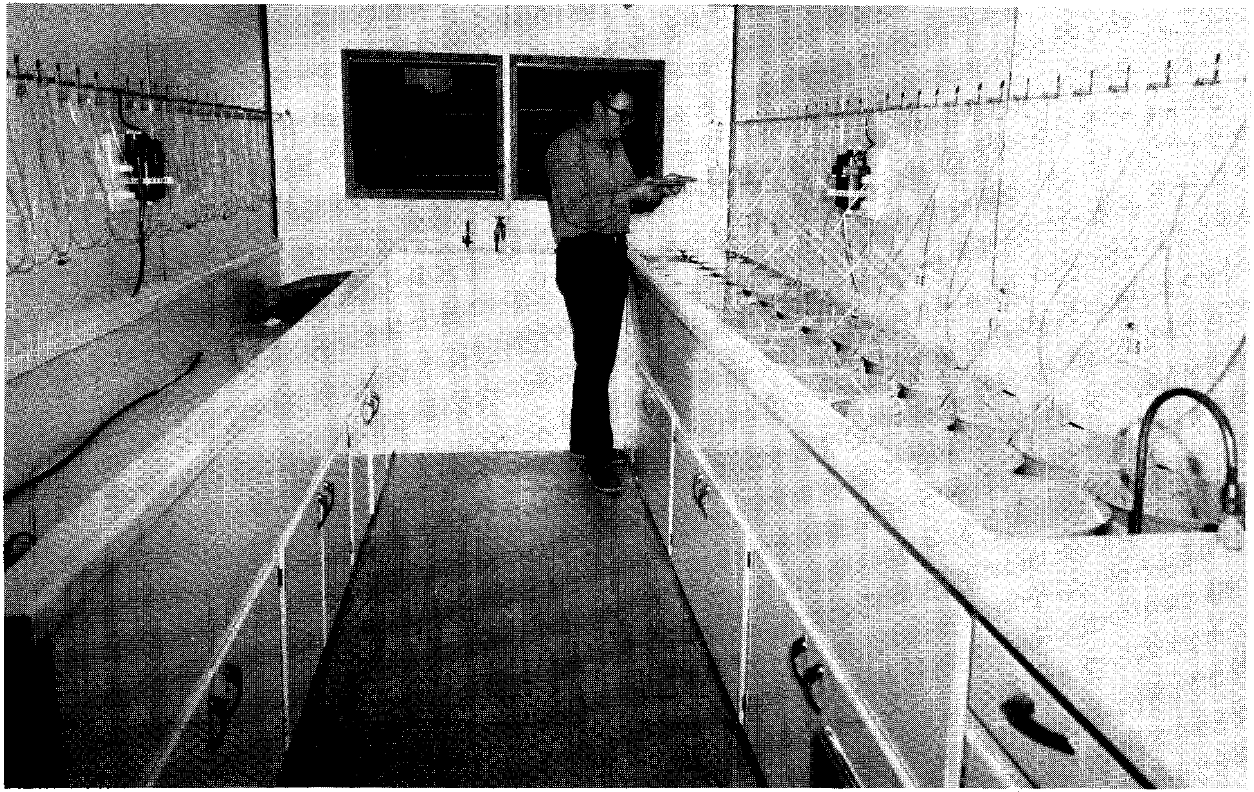

Fig. 11. Mobile bioassay laboratory. Lamprey ammocetes and fingerling rainbow trout are placed in the test containers and exposed to a range of lampricide concentrations. The time to death at each concentration is noted.

only slightly more susceptible than the endemic species (Davis 1970). Because of this slightly greater susceptibility, however, only sea lampreys (when available) are used for the bioassay of large rivers, to keep the amounts of lampricide used to the minimum required. for effective treatment. The selectivity of TFM between ammocetes and other fish may vary from stream to stream, between tributaries within a system, and also with the seasons of the year (Howell and Marquette 1962). Generally, the concentrations required to kill lampreys increase as conductivity and alkalinity increase (Kanayama 1963). The range in effective concentrations for tributaries of Lake Superior is not large; the minimum lethal concentration usually is between 1 and 5 ppm and the maximum allowable between 1.5 and 13.

The difference between the maximum allowable and minimum lethal concentrations of lampricide defines the so-called working range. The most significant figure obtained from a bioassay is not the range itself but the ratio of the working range to the minimum lethal concentration. The ratio is usually expressed in terms of the amount by which the volume of flow can increase in a stream treated at the maximum allowable concentration before the minimum lethal concentration is reached. For example, if the bioassay test shows the maximum allowable and minimum lethal concentrations to be 6 and 2 ppm, respectively, the ratio of the working range (4 ppm) to the minimum lethal concentration (2 ppm) is 2, and the flow can increase to double that at the point of application before the concentration in the stream becomes critically low.

In bioassays of Lake Superior streams, determination of the concentration to be used is usually based on a 6- to 9-hour exposure of test animals. In stream treatments, however, the application time is lengthened to allow the lampricide to penetrate into areas in which the current is slow.

In Canada the bioassay procedures have been modified and are described here in detail.[2]

> The first modification was to replace the arithmetic intervals of concentration with a geometric series, and to make a similar transformation in the intervals between observations. This change had the advantage not only of making successive intervals of dose and exposure more nearly proportional to the response of the test animals, but also of simplifying the results by permitting rapid transformation of the data for graphical presentation.
>
> A further modification of the original procedure was the application of probability theory to the interpretation of bioassay test results. It was observed from an analysis of earlier work that probit kill is proportional to the logarithms of concentration and of time. Thus, when for equally spaced intervals of probit kill the corresponding logarithms of exposure time and of concentration are plotted on arithmetic paper, the points fall along equally spaced parallel lines. It is possible, therefore, to determine from the time-concentration coefficients of a point on the appropriate line the values of exposure and dose necessary to produce any desired level of expected kill. The foregoing observations were found to be valid for other fish as well as lampreys, but the mortality line for other fish was steeper than that for lampreys.
>
> In Canadian bioassays, the cube root of 2 (1.26) was chosen as the ratio between successive concentrations, and the square root of 2 (1.41) as the ratio between successive observations. Kills of 99.9% of the lampreys and 25% of the

[2]G. F. M. Smith of the Fisheries Research Board of Canada, Ottawa, developed the statistical and experimental design of these bioassay procedures.

other fish were arbitrarily chosen as the minimum effective and maximum permissible levels, respectively, for a successful treatment. For extrapolation of the observed lamprey kill to higher percentages, equally spaced intervals on the probit scale were chosen. One series of such intervals corresponds approximately to the percentages 50, 78, 94, 99, and 99.9. Since the permissible fish kill (25%) falls within the observable figures, extrapolation is unnecessary.

At the end of a test period, the numbers of dead lampreys recorded at each observation are totaled for each concentration, as are the numbers of dead fish. The actual values of the exposure times and concentrations are replaced by their coded logarithms: the numbers 1, 2, 3, . . 10. The coded log times to death for 50, 78 and 94% lamprey mortality are calculated at each concentration, by use of arithmetic interpolation where necessary. These coded log times are plotted against the coded log concentrations on arithmetic paper, with time as the ordinate (Fig. 12). A line, fitted by inspection, is drawn to pass above all, or nearly all, of the points plotted for the times to death for 50% of the lampreys. The average difference between coded log times to death in successive mortality levels (i.e., between 50 and 78% and between 78 and 94%) is calculated. Two more lines corresponding to the 78 and 94% mortality levels are drawn parallel to the first line and spaced from it by vertical distances equal to the average difference in the

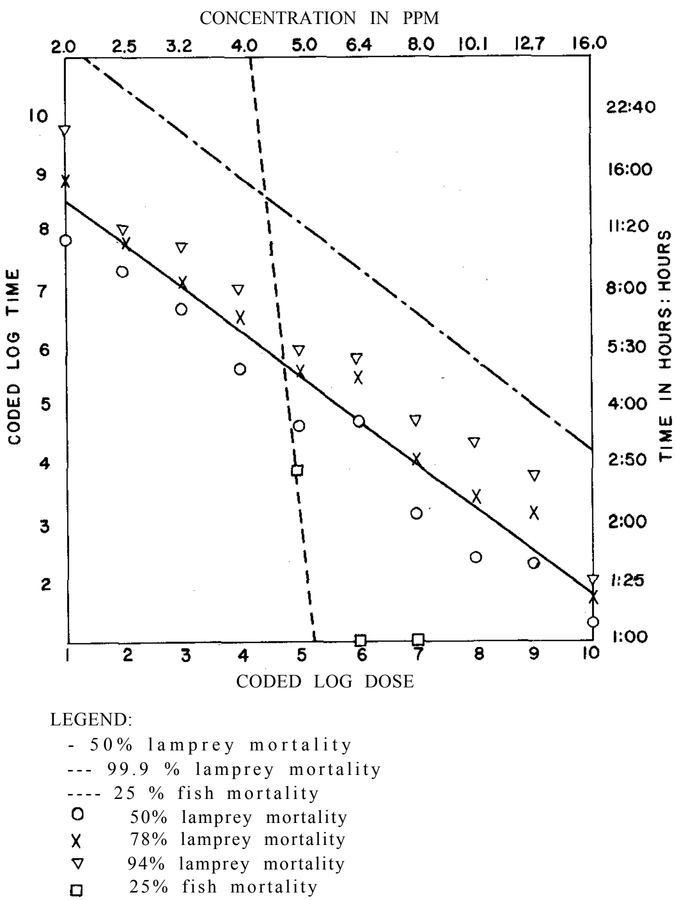

Fig. 12. Chart of probit bioassay (see text for explanation).

coded times to death, and to twice this difference, respectively. These lines should pass above all, or nearly all, of the plotted points; otherwise the 50% mortality line must be redrawn. Finally a fourth line is drawn representing the 99.9% level of lamprey mortality, at a distance from the 50% line equal to four times the average difference in the coded times to death. The coordinates of any point on this line (if taken within the range of the experimental values) represent, in terms of coded log time and coded log concentration, the exposure and dose required to cause a 99.9.% kill of ammocetes in the water that was tested. Actual values of time and concentration may be read by aligning logarithmic scales with the known quantities represented by the code numbers -on the ordinate and abscissa, respectively.

For the line of 25% fish mortality, the coded log times to death for 25% of the fish are calculated as above, by use of arithmetic interpolation where necessary. These values are plotted against the corresponding coded log concentrations on the same sheet of graph paper with the lamprey data. A line of best fit is drawn through the points by inspection. This line usually intersects the 99.9% lamprey mortality line in the highest part of the concentration range. In the area of the paper to the left of the line drawn for the fish and above that drawn for 99.9% lamprey mortality, any pair of time-concentration coordinates are, in theory, values of exposure and dose that will produce a mortality of at least 99.9% of the ammocetes and not more than 25% of the fish in the water that was tested.

Although the experimental design and the analysis of the results differ from those described by Howell and Marquette (1962) the conclusions reached with regard to the lampricide levels required to treat a given stream are nearly the same, and thus the two methods are probably equally valid.

Other pretreatment work

Other pretreatment preparations include the measurement at various points throughout a stream system of flow in cubic feet per second, with a Price or Watt current meter, according to the standard stream-gaging procedures of the United States Geological Survey (Corbett and others 1943). In a short simple stream, measurements may be required only at the lampricide application point and near the mouth, to determine the difference in volume. In a more complicated river system, measurements may be needed at each application site, at the mouth of each tributary, and near the confluence of the stream with the lake. These measurements are used to calculate the amount of lampricide required to maintain the proper concentration in each section of the stream. Lampricide is applied at a concentration below the maximum allowable, as determined from the bioassay test, for a sufficient time to ensure that, even in a long watershed, the block of chemical will maintain its identity and will generally be of uniform concentration from bank to bank and surface to bottom of the stream. Unless affected by some extraneous factor, water containing the desired concentration of chemical will reach the mouth without the application of additional lampricide.

In addition to volume of flow, the speed of flow must be ascertained throughout each stream section to estimate the travel time of the block of chemically treated water. The intervals between starting times of multiple applications may vary from a few minutes to several hours at various points in a system, depending on the time required for the treated water in each branch to reach the main stream. Rate of flow also is important in selecting sampling stations for chemical analysis to monitor the concentrations in the blocks of lampricide as they move downstream. Velocity is usually measured by timing the passage of the green fluorescent dye, fluorescein, between different points in the watershed.

When all of the other pretreatment preparations are completed, a map is prepared for the stream system, showing the location of feeder sites and the precise starting times for applying the toxicant to ensure that each block of treated water will reach the main stream at the proper time. “Boosting” sites may be selected where lampricide is to be added to prevent dilution of the concentration below the lethal minimum. Since it is essential to have a precise means of determining the concentration at any point in the stream, analysis stations are selected for monitoring the concentrations in the treated water as it moves downstream. Variations in concentration of TFM caused by changes in volume during treatment can be detected by colorimetric analysis, based on the natural color of nitrophenols (Smith et al. 1960). Samples of water are taken at each of these stations and “blank” values (the colorimetric value of the stream water recorded when the colorimeter has been calibrated with distilled water) are ascertained. For each station with blank values that are significantly different from those of the other stations, a set of chemical standards is prepared with stream water and appropriate concentrations of TFM.

Given the volume of flow, previously measured, and the desired concentration as determined from the bioassay results, the rate at which TFM must be applied can be calculated by the following formula:

$$F' = \frac{C \times F}{0.03713 \times C'}$$

where F’ = rate of pumping lampricide in U.S. gallons per hour,

F = volume of flow of the stream in cubic feet per second at the point of introduction of the lampricide,

C’ = concentration of stock solution in grams per liter,

C = concentration of TFM in parts per million desired in the stream at point of introduction, and

0.037 13 = conversion factor.

When the strength of the commercial formulation of TFM is expressed in percentage active ingredient, the following formula is used:

$$F' = \frac{CXF}{K}$$

where K = a conversion factor whose value is determined by the strength of the lampricide.

Sites are selected for collection of lamprey larvae and observation of fish that might be affected by the lampricide.

Application of lampricide in streams

The lampricide is introduced into the stream at the predetermined times and amounts by accurately controllable pumping systems. In rivers with large volumes of flow, the lampricide is usually introduced by positive-displacement piston-type pumps (Fig. 13) as described by Applegate et al. (1961). In

Fig. 13. Introduction of undiluted lampricide TFM from a storage tank with a constant feed chemical proportioning pump to the Kaministikwia River (near Kakabeka Falls), Ontario.

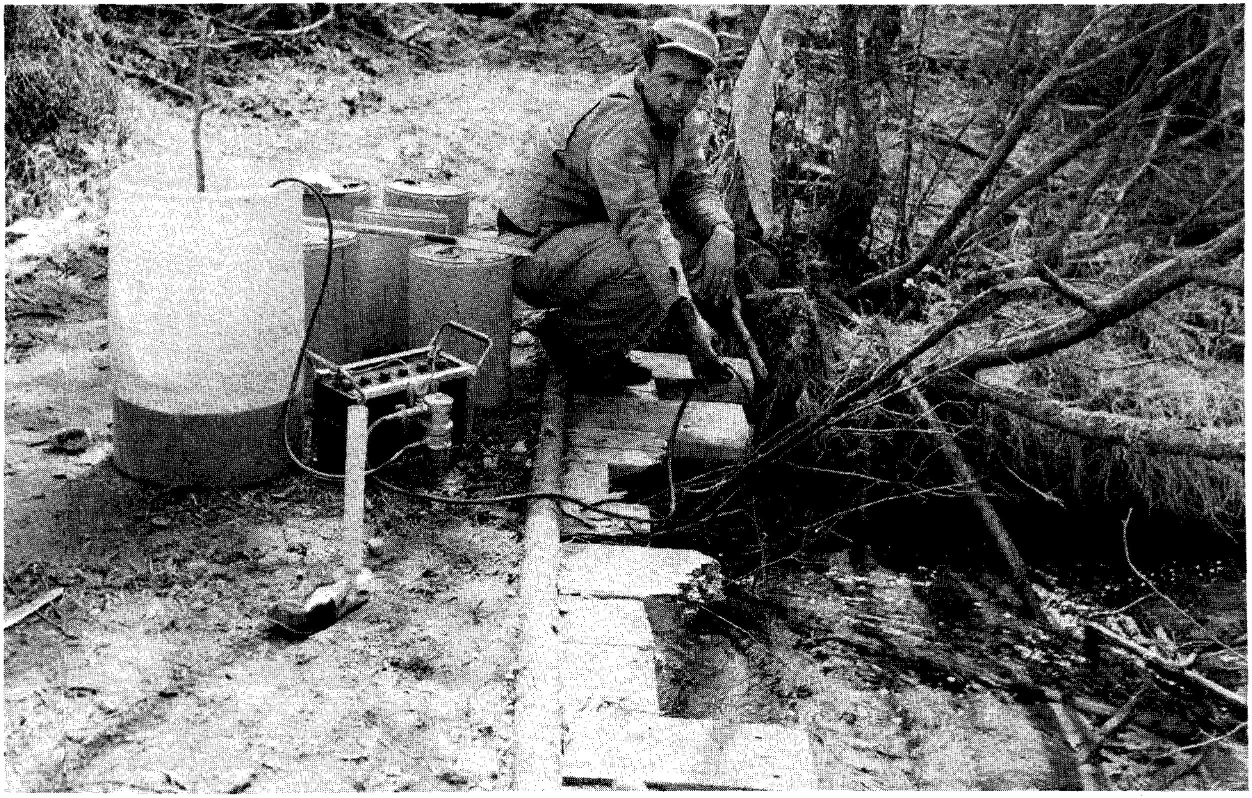

Fig. 14. Application of lampricide into a stream with a battery-operated fuel pump feeder equipped with calibrated orifice that controls rate of flow.

smaller streams an electric fuel pump feeder (Fig. 14) with interchangeable orifices calibrated to deliver known volumes of flow at constant pressure is often used (Anderson 1962); this pump, which is powered by a 12-volt storage battery and has a total weight of only 27.2 kg (60 pounds), is portable and capable of many hours of trouble-free operation.

Canadian treatment crews have obtained good results in treating small streams with the commercially manufactured "Pour-Portioner" drum meter, a gravity operated constant-head valve that requires no other source of power. After some simple modifications, the Pour-Portioner proved to be a more efficient and reliable means of applying small volumes of lampricide than the previously used drip feeder, which consisted of a closed container with two holes near the bottom, one above the other. The drip feeder provided a constant flow until the liquid level reached the upper hole, but it lacked precision and was difficult to regulate.

The TFM is applied for the length of time required to ensure the maintenance of minimum lethal concentrations for the full period indicated by the bioassay. The application time varies from 10 to 24 hours in different streams, although normally it is 12 to 18 hours. The rise and fall of concentrations of toxicant are monitored by colorimetric analysis as the block of water containing the chemical flows past. Concentrations plotted on a graph during the treatment give an instant display of the progress of the treatment and indicate whether corrective measures are required (Fig. 15).

During treatment, samples of dead and dying lampreys are collected throughout the stream system for study of species composition, age, growth, and other biological information.

TREATMENTS IN THE LAKE SUPERIOR WATERSHED, 1958-70

First treatments of streams, 1958-60

The application of chemical controls to the lamprey-infested tributaries of Lake Superior began in 1958. Chemical applications to streams on both shores of Lake Superior were expedited by close cooperation between field personnel of the Fisheries Research Board of Canada and the United States Fish and Wildlife Service. Staff and equipment were pooled to work in both countries, to the advantage of both organizations.

In 1958, 12 streams tributary to Lake Superior were treated (Table 3). The first two treatments along the United States shore (Mosquito and Silver Rivers), and two treatments along the Canadian shore pancake River and West Davignon Creek), were considered experimental and were conducted under the supervision of the Hammond Bay Biological Station (Applegate et al. 1961). Of the total of 12 treatments, 10 were successful; very few ammocetes were observed during posttreatment surveys. The treatment of West Davignon Creek was washed out by a severe thunderstorm and the treatment of the Sucker River, Alger County, Michigan, apparently failed because of a drop in water temperature. The bioassay for the Sucker River had indicated a minimum lethal concentration of 2 ppm at 12.8 C (55 F) and this rate was maintained in spite of a rise in flow from 42 cfs to 88 cfs;

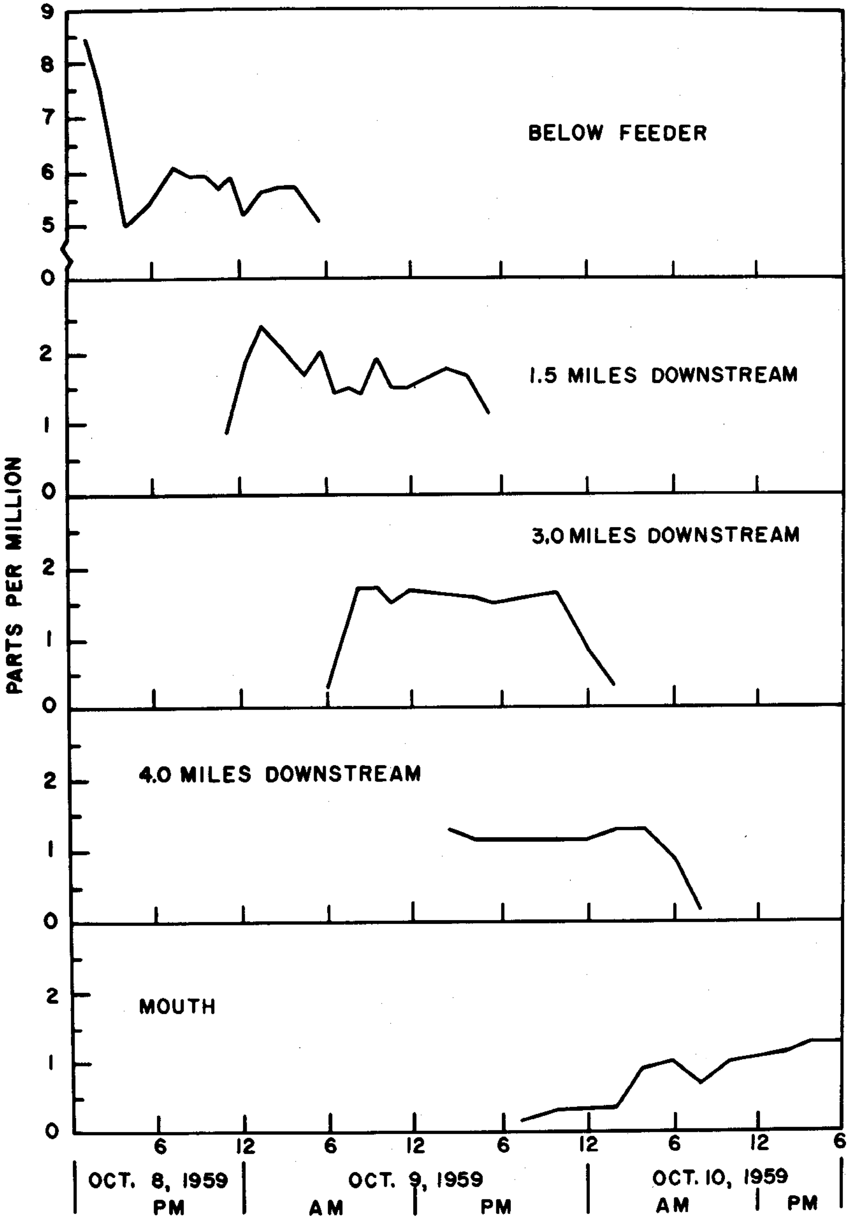

Fig. 15. TFM concentration at five locations in the Traverse River, Houghton County, Michigan, as the lampricide moved downstream during a treatment in October 1959. Minimum lethal concentration was 1.0 ppm and maximum allowable concentration, 4.0 ppm.

however, cold weather dropped the water temperature to 3.9 C (39 F). Because the colder water retarded the activity of the free phenol, ammocetes in the lower sections were not exposed to the lampricide long enough to be killed.

In the following 2 years, 1959-60, 60 streams highly productive of lampreys were treated, bringing the total number of initial treatments to 72. The Sucker River and West Davignon Creek were retreated in 1959 to eliminate lampreys that survived the first treatment, and in 1960 the East Sleeping and Stokeley Rivers, both of which were first treated (unsuccessfully) in 1959, were re-treated. The number of stream treatments conducted in 1958-60 thus totaled 76 (Table 3). The remaining lamprey-producing streams of Lake Superior were, with few exceptions, of lesser importance and were treated in later years.

Problems in stream treatments

Most of the streams were treated with a solution of the sodium salt of TFM in formulations containing 30 to 45% active ingredient by weight, but a few were treated with a liquid formulation of an amine salt of TFM containing 52% active ingredient. Although several formulations, used and stored under a variety of conditions, were generally satisfactory, the ingredients in some of them tended to crystallize at low temperatures, and the crystals were sometimes difficult to redissolve after the temperature rose.

Many other problems encountered in field operations were solved by improving methods and equipment. Equipment used for introduction of lampricides was simplified, reduced in weight, and improved in reliability. The problem of treating inaccessible areas was simplified by development of devices such as the modified fuel pump and the Pour-Portioner. The reliability and speed of analytical methods were increased markedly by the use of mobile laboratories for field analysis, and communication by short-wave radios permitted rapid and accurate adjustment of application rates to compensate for changing stream flows.

Differences in biological activity and selectivity of TFM in different seasons and among streams presented the most difficult and chronic problems in treating tributaries of Lake Superior. Seasonal variations in water quality sometimes reduced the toxicity and occasionally the selectivity of the lampricide to the point where it was necessary to reschedule treatments. In some streams the selectivity was so greatly reduced that the lampricide killed fish at the same concentration required to kill lampreys. Fortunately, it was generally possible to move the treatment crews to an area where conditions were more favorable. Small spring-fed streams were least affected and could be treated at any time during the field season.

Ammocetes near the mouths of untreated tributaries, in beaver ponds, in backwater areas, and in stream-bed springs sometimes survived because of dilution or poor circulation of the lampricide. Escapement into the mouths of untreated tributaries was prevented by the application of lampricide to the mouths of the tributaries (in which no larvae were found during pretreatment surveys) to prevent movement of lampreys into them from the main stem during treatment. Spot-treatment of some backwaters was attempted, but

Table 3. Summary of streams treated and amounts of lampricides used in sea lamprey control in Lake Superior, 1958-70

Year	United States						Canada					
	Number of streams treated	Discharge at mouth (cfs)	Stream miles treated	Active TFM (pounds)	Active Bayer 73 Powder (pounds)	Active Bayer 73 Granular (pounds)	Number of streams treated	Discharge at mouth (cfs)	Stream miles treated	Active TFM (pounds)	Active Bayer 73 Powder (pounds)	Active Bayer 73 Granular (pounds)
1958	10	619	178	6,265	-	-	2	58	24	232	-	-
1959	29	1,616	286	19,147	-	-	9	605	53	5,876	-	-
1960	15	3,651	397	51,400	-	-	11	5,731	240	54,550	-	-
1961	7	453	139	9,653	-	-	5	742	60	8,276	-	-
1962	19	1,567	366	22,471	-	-	13	4,842	317	42,272	-	-
1963	26	3,043	399	38,604	0	-	15	4,006	180	32,925	491	-
1964	25	1,637	259	18,255	113	-	15	7,499	257	59,090	781	-
1965	16	888	214	12,042	0	-	6	3,675	150	24,416	491	-
1966	5	462	100	6,408	0	-	14	3,183	176	26,191	496	-
1967	17	2,628	304	27,672	106	33	10	117	25	737	5	386
1968	2	331	97	7,594	0	6	7	823	124	6,251	115	197
1969	19	1,743	212	17,351	10	235	5	1,184	48	7,609	126	106
1970	10	1,113	248	10,633	24	29	11	4,276	77	35,089	777	23
Total	200	19,751	3,199	247,495	253	303	123	36,741	1,731	303,514	3,282	712

inability to control concentrations and exposure time made this practice hazardous to some species of fish.

Mortality of fish other than sea lampreys during stream treatments was occasionally a problem. Highly susceptible fish species that were sometimes greatly reduced by the lampricide included trout-perch (Percopsis *omiscomaycus),* logperch *(Percina caprodes),* stonecat (Noturus flavus), bullhead *(Ictalurus* spp.), and mudminnow *(Umbra limi).* Mortality of game fish was negligible, however-with a few notable exceptions. In the Middle Branch of the Ontonagon River, Ontonagon County, Michigan, significant numbers of large spawning brown trout *(Salmo trutta)* were killed (109 dead fish were found) on October 19, 1960; and in the lower Bad River, Ashland County, Wisconsin, about *200* walleyes *(Stizostedion vitreum vitreum)* and a total of 50 northern pike (Esox lucius) and muskellunge (E. *masquinongy)* were killed on May 27, 1963.

Heavy losses of game fish have likewise been rare on the Canadian side of Lake Superior. In West Davignon Creek in July 1959 a significant kill of rainbow trout was caused by an accidentally high concentration of lampricide; and in East Davignon Creek in May 1967 a deliberately high concentration, applied to compensate for downstream dilution, caused a heavy kill of brook trout-a totally unexpected occurrence in this small and frequently polluted stream. A heavy mortality of smelt in the Cranberry River in April 1960 was the result of the high susceptibility of this species during the spawning season. White suckers and longnose suckers *(Catostomus Catostomus)* are likewise especially susceptible during their spawning runs, as shown by heavy kills in the Batchawana River in July 1965 and July 1966 and in Harmony River in May 1967.

Bad weather frequently disrupted the application and scheduling of treatments. Continuously rising water volumes during application caused problems, but speedy analysis and communication by radio permitted rapid adjustment of application rates and minimized loss of lethal concentration. Sudden and violent rainstorms are so frequent during the summer that the danger always exists that rising water will dilute and “wash out” a block of lampricide moving downstream.

Survey and treatment of bays, estuaries, and lakes

A small electrified beam trawl, developed to search for and evaluate lentic populations of sea lamprey larvae (McLain and Dahl 1968), was used in 59 locations at the mouths of rivers, in bays, and in inland lakes of the Lake Superior basin. Sea lamprey larvae were capture4 in 12 of the areas. Sampling at five stations in 1961-66 demonstrated that the ammocetes inhabiting the deep-water environments had virtually disappeared (Table 4), apparently because of lack of recruitment from the streams tributary to the areas.

An electric trawl, similar in design to that developed by the United States Fish and Wildlife Service (McLain and Dahl 1968), was operated in several Canadian inshore areas during 1963-65. The equipment was mounted on a pontoon boat powered by an outboard motor. Sampling was conducted in Batchawana Bay, Michipicoten Bay, Helen Lake, and the estuaries of the Jackfish, Jackpine, and Cypress Rivers in Nipigon Bay. Sea lamprey

Table 4. Number of lake-dwelling sea lamprey ammocetes caught per hour in an electric trawl at five localities in Lake Superior, 1961-66

[Number of hours of trawling are shown in parentheses.]

Location	Year					
	1961	1962	1963	1964	1965	1966
East Bay	72.6 (0.7)	0.0 (1.9)	0.0 (0.2)	2.7 (0.4)	0.0 (1.6)	0.0 (0.5)
West Bay	8.3 (2.5)	3.8 (1.3)	0.0 (1.3)	0.0 (0.9)	0.0 (2.4)	0.0 (0.6)
Off Furnace Creek	-	9.2 (1.1)	10.3 (1.1)	7.8 (1.2)	1.3 (5.2)	0.0 (1.1)
Off Little Garlic River	-	-	0.0 (1.1)	-	2.3 (3.5)	0.0 (0.8)
Huron Bay near Ravine River	2.1 (0.5)	0.0 (0.6)	-	0.0 (2.1)	0.0 (1.6)	0.0 (2.1)

ammocetes were collected in Batchawana Bay, Helen Lake, and the estuary of the Jackfish River. In Batchawana Bay in 1964-65, the electric trawl caught an average of 0.2 sea lamprey ammocete per 836 m^2 (1,000 square yards). Although the electric trawl did not provide data closely comparable with those produced by the methods used in 1959-60 (see section on distribution in bays, estuaries, and lakes), there is a suggestion that the sea lamprey population of Batchawana Bay declined in 1961-64.

In 1967, granular Bayer 73 was used in treating the estuarine areas of four Canadian rivers and their adjoining lacustrine areas: the Chippewa, Batchawana, and Sable Rivers (tributaries of Batchawana Bay) and Stillwater Creek (a tributary of Nipigon Bay). A combined total of about 28 ha (70 acres) were treated at an average application rate of 124.7 kg/ha (110 pounds per acre). A power blower mounted on a pontoon boat was used to spread the chemical over the surface of the area to be treated.

The lampricide treatments of the Chippewa, Batchawana, and Sable Rivers in 1967-70 were combined with applications of granular Bayer 73 to areas of Batchawana Bay adjacent to their mouths that equaled 2.75, 7.48 and 3.39 ha (6.8, 18.5, and 8.4 acres), respectively, in 1967 and were similar in the other years. The scarcity of ammocetes off the mouths of the Batchawana and Sable Rivers in 1969 and 1970 indicated that the treatments with granular Bayer 73 were highly effective in reducing the lacustrine population and that recruitment to it from the rivers was limited. This compound was also applied to the mouths of two other rivers, Pancake and Jackfish, in conjunction with conventional TFM treatments.

Results of the surveys of Batchawana Bay, conducted each year from 1959 to 1970, in which combinations of electroshocking, dredging, spot-poisoning, electrotrawling, and finally applications of Bayer 73 granules were employed, have demonstrated the effectiveness of the repeated lampricide treatments of the tributary streams. Although the lake-dwelling populations of sea lamprey larvae off the mouths of the Chippewa, Batchawana, and Sable Rivers persisted almost untouched until the first treatments with granular

Bayer 73 in 1967. the third such treatment (in 1969) revealed that recruitment to the Bay from the Sable River had been eliminated and recruitment from the Batchawana greatly reduced.

Evaluation and classification of streams for re-treatment

Originally, 119 tributaries of Lake Superior contained sea lampreys and 116 were treated with lampricide. Posttreatment studies demonstrated that a stream's capacity to produce ammocetes, and eventually metamorphosed sea lampreys, varied greatly. The streams were therefore classified into three groups (Table 2) on the basis of the current production indicated by three criteria: the number of spawning-run adults captured at the electric barriers, the number of larvae recovered during chemical treatments, and the relative abundance of ammocetes of various year classes in reestablished populations. The classification was flexible; streams were reclassified as additional data became available. Generally fewer and fewer treatments should prove necessary as the lamprey population decreases, although some rivers may stay on the active treatment list indefinitely.

The streams in group 1, the largest and most consistent producers of sea lampreys, have required regular re-treatments. Common features of these streams are a large volume of water (generally more than 100 cfs), a combination of extensive spawning grounds and larval habitat, optimum conditions for survival and growth, a large and consistent run of spawning adults, and good representation of year classes.

Group 2 streams, medium producers of sea lampreys, may have had catches of more than 1,000 spawning-run adults at electric barriers, but factors appear to be present that limit larval production. In some, the electric barriers may have reduced spawning, and in others, it may be insufficient larval habitat. Elimination of barriers and any major increase in size of the spawning runs could place some of these streams in group 1. The history of reestablished populations indicates that, with the number of adult sea lampreys present in 1962-70, the relative numbers of larvae produced in these streams ranged from low to medium.

Streams in group 3 are considered to be marginal producers of sea lampreys. Even during peak years of lamprey abundance they attracted few spawning adults. Most have serious limiting factors such as cold water, steep gradient, limited spawning grounds, little larval habitat, or physical barriers to upstream migration. In the period 1962-70 no larvae became established in 15 of them and only one or two small year classes in 20 others.

Re-treatments 1961-70

Routine re-treatment of several Lake Superior tributaries first became necessary in 1961, when significant numbers of ammocetes that had survived treatment were discovered in surveys. Sixty-five percent of the known lamprey-producing tributaries of Lake Superior had been treated by the end of 1961. Those remaining, when treated, were found to be only lightly infested. In 1962-70 it was necessary to treat streams periodically to destroy reestablished larvae before they transformed and migrated to the lake. In addition, resurveys of potential lamprey-producing streams in this period resulted in the discovery of several additional streams with small populations of lampreys. Lampreys did not become reestablished in seven treated rivers; the others were retreated at various intervals, depending on rate of growth of the larvae. It was necessary to treat four streams frequently to control the establishment of larvae in bays where their destruction is difficult.

One estuary, East Bay, near the mouth of the Sucker River, Alger County, Michigan, was treated in October 1961 with toxaphene (Gaylord and Smith 1966). It contained a sea lamprey ammocete population estimated at 96,300 ± 20,500 (Wagner and Stauffer 1962). It also contained about 13 other species of fish but most were yellow perch *(Perca flavescens),* white suckers, and rainbow trout. The bay was treated with toxaphene at approximately 100 parts per billion for 14 days. Although sea lamprey larvae were more resistant to toxaphene than were the fish, a complete kill was indicated. One year after treatment, no sea lampreys could be found but the population of other species had recovered.

Streams re-treated

In the 13-year period 1958-70, 323 treatments (123 in Canada and 200 in the United States) were conducted on 115 Lake Superior lamprey streams (Table 5). Of the 115 streams, 23 required only one treatment and 92 were treated two or more times to control reestablished sea lamprey populations. One of the 23 was the Trap Rock River, Houghton County, Michigan, which was treated in 1963 even though no sea lamprey ammocetes had been found in it. For a number of years this river had been suspected of harboring sea lampreys but it could not be adequately surveyed because the effectiveness of the electric shockers was greatly reduced by the high conductivity of the water. The treatment established that no sea lampreys were being produced in this river.

In 1963, experimental applications of TFM were made in isolated ponds and oxbows of three river systems in which sea lamprey larvae might have been stranded during floods. Ammocetes were killed in 4 of 13 oxbows of the Ontonagon River and in 3 of 16 ponds along the Sturgeon River, but none were recovered from 2 oxbows of the Bad River.

The effectiveness of treatments made at reduced flows was checked in the Wolf River, a tributary to Black Bay, which was treated twice in 1961 - once on October 5 at a flow of 75 cfs (maintained by manipulating a dam) and the second time on October 13, at a full flow of 200 cfs. The collection of hundreds of sea lampreys during the first treatment and the absence of sea lampreys during the second indicated the feasibility of reducing flow where possible, to conserve lampricide.

Improvements in lampricides

Several improvements were made in 1963-70 in materials and methods used to control lampreys. Tests at the Hammond Bay Biological Station in 1963 revealed that small amounts of the molluscicide Bayer 73 increased the toxicity of TFM without significantly affecting its selectivity toward sea lampreys (Howell et al. 1964). The addition of Bayer 73 at the rate of 0.5 to 4.0% (primarily 1 to 2%) of the TFM has in general reduced the amount of

Table 5. Date (month and year) and number of chemical treatments of tributaries of Lake Superior, 1958-70
[Numbers in parentheses show location of streams in Fig. 10.]

Stream	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Number of treatments
							United States							
Waiska River (1)			Oct	-	-	-	Oct				-	Aug		3
Pendills Creek (2)	-	Aug		-	-	July	-	-	-	-	-	Aug		3
Grants Creek (3)	-	Aug	-		-	July	-	-	-	-	-	-		2
Naomikong Creek (4)				-	-	July	-							1
Ankodosh Creek (5)	-	Aug	-	-	-	July	-	-	-	-	-	-	-	2
Galloway Creek (6)	-	Aug	-	-	-	July	-	-			-	-	-	2
Tahquamenon River (7)			Oct	-	-	-	July	-	-	Oct			-	3
Betsy River (8)	—	–	June	-	June	-	-	*Aug*	-	-	-	-	July	4
Three Mile Creek (9)			-	-	June	-	-	-	-	-	-	-	-	1
Little Two Hearted River (10)	-	June		-	June	-	-	**Aug**					July	4
Two Hearted River (11)	-	June	-	-	June	-	-	July	-	-	-	-	July	4
Dead Sucker River (12)	-	-	-	-	-	Sept	-	-	-	-	-	-		1
Sucker River (13)	Oct	Aug		Oct	-	Sept	-	**Aug**	-	July	-	Sept	-	7
Sullivans Creek (16)	-	Aug	-	-	-	-	-	-	Aug	-	-	-		2
Seven Mile Creek (17)	-	May	-	-	-	July	-	-	-	July				3
Beaver Lake Outlet (18)	-	May		-	-	July	-	Sept	-	July	-	Aug	-	5
Mosquito River (19)	May	-	-	-	-	July	-	-	-	-	-	Aug		3
Miners River (20)	-	May	-	-	May	-	-	-						2
Munising Falls Creek (21)	-	-		-	-	-	Sept	-	—	—	-	-		1
Anna River (22)	-	Sept	-	-				*May*	—	—	-	-		2
Furnace Creek (23)			*May*			-	Apr	Sept			-	July		4
Five Mile Creek (24)			Sept	-May		-	-	-	-	-	-	-	—	2
Au Train River (25)	-	May	-	-	May	-	May	Oct			-	Aug		5
Rock River (26)	Oct	-	-	Sept	-	-	-		-	Aug			—	3
Deer Lake Outlet (27)				-	-	Apr	-	-	-	-	-	-	**Aug**	2
Laughing Whitefish River (28)			-	Sept	-	-	-		-	May	-	-	**Aug**	3
Sand River (29)	-	-	Sept	-	-	-	Aug		-	-	-	Oct	—	3
Chocolay River (30)	Oct	-	-	Oct	-	-	-	-	Aug	-	-	-	**Aug**	4

Table 5. - Cont'd

Stream	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Number of treatments
Carp River (31)				-	-	July	-	-	-	-	-	-	-	1
Harlow Creek (32)	-	Aug	-	-	July	-	-	Aug	-	-	-	July	Oct	5
Little Garlic River (33)	-	Sept	-	-			-	Aug	-	May	-	-	June	4
Big Garlic River (34)	-	May	-	Sept	-	-	July	Sept	Sept	July	-	July	-	7
Iron River (35)	sept	-	-	-	July	-	-	-	-	July	-	-	-	3
Salmon Trout River (36)	-	Sept	-	-	-	Aug	-	-	-	-	-	-	-	2
Pine River (37)	-	Aug	-	-	-	Aug	-	-						2
Huron River (38)	Sept	-	-	Oct	-	-	-	Oct	-	-	-	Aug	-	4
Ravine River (39)	-	-	Oct	-			Sept	-	-	-				2
Slate River (40)	-	-	Oct				Sept	--						2
Silver River (41)	June	-	-	Oct	-	-	-		Aug	-	-	Aug	-	4
Falls River (42)	-	-	Oct			-	Sept	1	-			-	Aug	3
Six Mile Creek (43)	-	-	-	-	-	June	-	-	-				-	1
Sturgeon River (44)	-	-	June	-	-	Sept	–	–	Aug	Sept	-	Aug	Aug	6
Pilgrim River (45)	-	-	-	-	Aug	-	–	–	-	-			-	1
Boston-Lily Creek (53)				-	Aug	-	–	–					-	1
McCallum Creek (46)				-	-	Aug	-	-	-	-			-	1
Trap Rock River				-	-	Aug	-	-	-					1
Mud Lake Outlet (47)	-	-	-				May	May	-				=	2
Traverse River (48)	-	Oct	-	-	-	Aug	May	-	-	-	Sept	-	-	4
Little Gratiot River (49)	-	Oct	-	-	-	-	-	May	-	-				2
Eliza Creek (50)	-	-	July	-	-	Aug	-	-	-	-	-	-	-	2
Gratiot River (51)							-	Oct	-	-	-	-	-	1
Smiths Creek (52)							May	-	-	-	-	-	-	1
Salmon Trout River (54)	-	Oct	-	-	-	Aug	-	-	-	Aug	-	-	-	3
Graveraet River (55)	-	-	-	-	-	Aug	-	-	-	-	-	-	-	1
Elm River (56)	-	Sept	-	-			Sept	-	-	-	-	-	-	2
Misery River (57)	-	Oct	-	-	Sept	-			-	-	-	Sept	-	3
East Sleeping River (58)	-	Oct	Oct	-	Sept	-			-	Oct	-	-	-	4
Firesteel River (59)	-	Oct	-				Sept	-	-				-	2
Ontonagon River (60)	-	-	July	-	-	July			-	Aug	-	Sept	-	4

Table 5. - Cont'd

Stream	1958	1959	1960	196	1962	1963	1964	1965	1966	1967	1968	1969	1970	Number of treatments
Potato River (61)	-	Nov	-				May	-			-	Sept	-	3
Cranberry River (62)	-	Oct	-				May	-	-	Oct	-	-	-	3
Little Iron River (63)							May	-	-				-	1
Union River (64)	-			-	-	-	May	-					-	1
Bad River (65)	-	-	July	-	-	May	Oct	-	-	-	Aug	Oct	-	5
Fish Creek (66)	-	Apr	-	-	-	June	-	-	-	Apr	-	-	-	3
Raspberry River (67)				-	-	June	-				-	-	-	1
Sand River (68)	-	-	-	-	-	-	Oct	-	-	-			-	1
Reefer Creek (69)							Oct	-					-	1
Fish Creek (70)			-	-	-	-	Oct	-	-	-	-	-	-	1
Brule River (71 j	-	Apr	-	-	May	-	-	July	-	-	-	July	-	4
Poplar River (72)	Sept	-	-	-	July	-	-	-	-	-			-	2
Middle River (73)	Sept	-	-	-	July	-			-				-	2
Amnicon River (74)	Sept	-	-	-	July	-			-	May	-	-	-	3
Nemadji River (75)	-	-	-	-	July	-			-	May	-	-	-	2
Splitrock River (76)	-	-	Oct	-	-	-	Oct	-	-	-	-	-	-	2
Arrowhead River (77)				-	July	-	Oct	-	-	-	-	July	-	3
Total in United States	10	29	15	7	19	26	25	16	5	17	2	19	10	200
Canada														
East Davignon Creek (1)	-			-	-	May	-	-	-	May	-	-	-	2
West Davignon Creek (2)	Nov	July	-	-	-	May	-	-	-	June	-	-	-	4
Little Carp River (3)	-	-	May	-	-	-	May	-	-	-	May	-	-	3
Big Carp River (4)	-	June	-	-	Oct	-	-	-	Oct	-	-	-	-	3
Cranberry Creek (5)	-	-	Apr	-	-	-	May	-			-	-	Aug	3
Goulais River (6)	-	-	June	-	Sept	-	May	-	-	-	Aug	-	-	4
Stokeley River (7)	-	July	May	-	-	-	Oct	-	-	-	-	-	Aug	4
Harmony River (8)	-	July	-	-	-	May			-May		-			3
Sawmill Creek (9)	-	-	Oct				July	-	-	-	June	-	-	3
Chippewa River (10)			-	July	Aug	July	July	July	June	Aug	July	-	Aug	9
Batchawana River (11)	-	July	-	Sept	Aug	July	July	July	July	July	Aug	-	-	9

Table 5. - Cont'd

Stream	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Number of treatments
Sable River (12)	-	July	-	Sept	Sept	July	July	July	June	July	July	-	June	10
Pancake River (13)	Aug	-	-	July	-	-	-	July	-	-	-	June	-	4
Agawa River (14)	-			-	May	-	-	-	June	-	-	-	-	2
Sand River (15)				-	June	-	-	-	June	-	-	July	-	3
Michipicoten River (16)	-	-	July	-	-	Sept	-	Sept	-	-	-	-	Aug	4
Dog River (17)				-	-	Aug	-	-	-	-	-	-	-	1
White River (18)	-				-	Sept	-	-	Sept	-	-	-	-	2
Big Pit River (19)	-	-	-	-	-	Sept	-	Aug	-	-	-	-	-	2
Little Pit River (20)	-			-	June	-	-	-	Sept	-	-	-	-	2
Prairie River (21)	-			-	June	-	-	-	Sept	-	-	-	-	2
Steel River (22)				-	June	-	-	-	Sept	-	-	-	-	2
Pays Plat River (23)	-	Aug	-	-	-	June	-	-	-	-	-	-	-	2
Big Gravel River (24)	-	Oct	-	-	July	-	-	-	July	-	-	-	July	4
Little Gravel River (25)	-					-	Aug	-	-	-	Sept	-	-	2
Cypress River (26)	-			-	-	Oct	-	-	-	Aug	-	-	-	2
Jackfish River (27)	-	-	Sept	-	-	-	Sept	-	-	-	-	Sept	-	3
Cashe Creek (28)	-	-						-	Aug	-	-	-	-	1
Nipigon River (29)						-	Oct	-	-	-	-	-	Sept	2
Otter Cove Creek (30)	-			-	-	Oct	-	-	-	Aug	-	-	-	2
Stillwater Creek (3 1)	-				-	Oct	-	-	-	Aug	-	-	-	2
Black Sturgeon River (32)	-	-	Oct	-	-	-	-	-	July	-	-	-	Aug	3
Wolf River (33)			-	Oct	July	-	-	-	July	-	-	-	July	4
Pearl River (34)	-	Sept	-	-	-	June	-	-	-	-	-	-	July	3
Blende Creek (35)	-	-			-	-	Aug	-	-	-	-	-	-	1
McIntyre River (36)	-	-	June	-	-	-	June	-	-	—				2
Kaministikwia River (37)	-	-	June	-	July	-	Aug	-	-	Sept[1]	-	Aug	-	5
Cloud River (38)	-			-	-						-	Sept	-	1
Pigeon River (39)	-	-	Oct	-	-	-	June	-	-	-	-	-	Sept	3
Total in Canada	2	9	11	5	13	15	15	6	14	10	7	5	11	123
Total	12	38	26	12	32	41	40	22	19	27	9	24	21	323

1 Only Corbett Creek, a small tributary was treated.

TFM required by 50%. Reduction of the amount of TFM in turn reduced the cost of treatment considerably. For instance, in treatments of the Sucker River, Alger County, Michigan, the cost of the lampricide in 1959, when only TFM was used and stream flow was 75 cfs, was more than $4,500; the cost in 1969, when a mixture of TFM and Bayer 73 was used and stream flow was 70 cfs, was only $2,500.

The Hammond Bay Biological Station in 1966 cooperated with the Michigan Water Resources Commission in a project to evaluate the effectiveness of Bayer 73 on sand granules for control of snails and lamprey larvae. The material showed considerable promise as a survey tool and possibilities as an agent for killing lampreys in lakes and estuaries. The first field tests were conducted during treatment of the Silver River with TFM. The heavy granules killed about 87% of the lamprey larvae in a screened area in the river.

A test of the effectiveness of Bayer 73 for control was made in 1966 on the delta of the Big Garlic River in Saux Head Lake, where a population of ammocetes had been unaffected by TFM treatments. The granular material was spread over an area of 5,574 m^2 (60,000 square feet) at a rate of 123.6 kg/ha (109 pounds per acre). Estimates based on the kill of lampreys in wire test cages indicated that the treatment was about 89% effective (Manion 1969). Similar tests were conducted in Canada in 1966 on the White River, Lake Superior, as well as on several Lake Huron tributaries. In general, granular Bayer 73 was effective in bringing ammocetes to the surface where (once activated) most died. The reaction was delayed in cold water (4.4 C [40 F] or less) for as long as 1 hour, and heavier applications were required than at higher temperatures (J. H. Howell, personal communication).

DECLINE OF THE SEA LAMPREY AND OTHER EFFECTS OF LAMPRICIDE TREATMENTS, 1962-70

The effect of lampricide treatments in Lake Superior tributaries was soon obvious. The numbers of sea lampreys in the spawning runs dropped sharply, the numbers of ammocetes in streams decreased, fewer newly transformed sea lampreys migrated to the lake, and the number of streams used for spawning was reduced. Other important indications of the effectiveness of the program were the increases in the populations of important species of fish and the decrease in predation as evidenced by a reduction in the incidence of lamprey scars on fish.

Reduction in numbers of sea lampreys in spawning runs

The adult sea lamprey population, as reflected by catches at the electric barriers during the spawning runs, did not change greatly until 1962 (Fig. 16). Although catches declined slightly in 1959 and 1960, it is not clear whether these declines were due to the stream treatments, effects of several years of barrier operation, or natural fluctuations in abundance. The highest catch was recorded in 1961, after 3 years of chemical operations, when 71,081 were taken at 37 barriers. In 1962, however, the numbers of adult sea lampreys fell

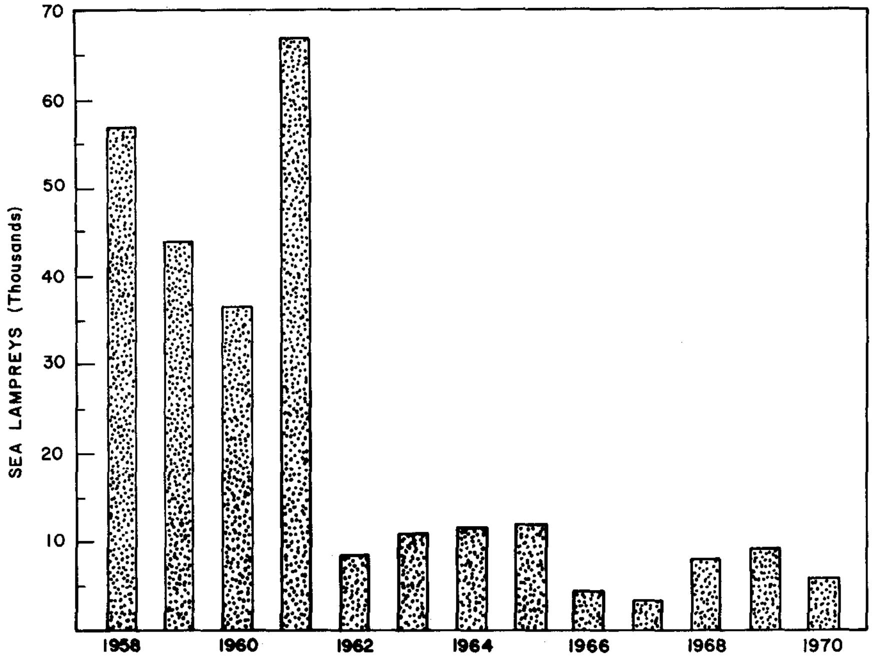

Fig. 16. Sea lamprey catch of spawning migrants at 16 electric barriers on Lake Superior, 1958-70.

suddenly and sharply. The 37 barriers captured only 9,992 individuals, a decline of 86% from the previous year. This major decline in abundance was expected in 1962, and not earlier, because (a) the streams treated in 1959 were relatively small and generally contained fewer lampreys than the large complex watersheds that were deferred until 1960, and (b) the large watersheds could not be treated in 1960 until late spring after the newly transformed lampreys had migrated to the lake. (The delay in treating the larger rivers was necessary to enable the personnel in the newly formed treatment crews to gain experience and develop techniques of stream treatment by working on the smaller, generally simpler watersheds.) The newly transformed lampreys which migrated downstream in the fall of 1959 and spring of 1960 parasitized fish in Lake Superior during 1960 and returned to the barriers in 1961 as a record number of mature adult sea lampreys. This heavy run was followed by the drastic decline of lampreys at the barriers in 1962.

The sharp decrease in the numbers of sea lampreys in 1962 left little doubt as to the effect of the treatments and the ultimate success of control. Catches in the following 3 years, 1963-65, reflected a stabilizing of adult lamprey abundance at about 20% of the 5-year average (1957-61). In 1965 the barriers were reduced to 16 installations in the United States and 8 in Canada, for indexing population abundance. Comparable catches at these installations from 1958 to 1970 are given in Table 6.

Table 6. Number of adult sea lampreys taken at electric barriers operated in 24 Lake Superior streams mainly for assessment of lamprey stocks, 1958-70

[Barriers in United States were operated from about March 26 to July 13, and in Canada from about May 15 to July 31. Numbers in parentheses show location of streams in Fig. 10.]

River	1958[1]	1959[1]	1960[1]	1961[1]	1962	1963	1964	1965	1966	1967	1968	1969	1970
						United States							
Betsy (8)	1,071	1,000	686	1,366	316	444	272	187		57	78	120	87
Two Hearted (11)	3,418	3,990	‘4,222	7,498	1,757	2,447	1,425	1,265	878	796	2,132	1,104	1,132
Sucker (13)	1,727	2,457	4,670	3,209	474	698	386	532	223	166	658	494	337
Miners (20)	94	132	395	220	64	107	74	23	85	75	158	57	90
Furnace Creek (23)	38	493	2,204	1,012	132	142	93	199	118	119	126	178	83
Rock (26)	1,425	1,181	2,589	3,660	399	353	229	237	158	439	498	138	667
Chocolay (30)	6,168	3,490	4,167	4,201	423	358	445	563	260	65	122	142	291
Iron (35)	401	257	310	2,430	1,161	110	178	283	491	643	82	556	713
Huron (38)	3,435	1,433	1,225	4,825	70	201	363	637	8		14	280	4
Silver (41)	2,111	773	1,261	5,052	267	760	593	847	1,010	339	1,032	1,147	321
Sturgeon (44)	28	544	161	427	397	1,445	375	135	259	43	132	46	26
Misery (57)	808	2,465	692	962		24	12	3	10	26	52	90	12
Firesteel (59)	1,528	2,061	243	1,118	70	178	327		15	9	25	14	11
Brule (71)	22,593	19,225	9,523	22,478	2,026	3,418	6,718	6,163	226	364	2,657	3,374	167
Middle (73)	4,819	3,624	2,814	3,502	311	48	45	52	17	19	22	8	16
Amnicon (74)	7,584	980	1,081	4,741	879	131	232	700	938	200	148	1,576	1,733
Total in U.S.	57,248	44,105	36,243	66,701	8,826	10,864	11,767	11,837	4,761	3,362	7,936	9,324	5,690

Table 6. - Cont'd

River	1958[1]	1959[1]	1960[1]	1961[1]	1962	1963	1964	1965	1966	1967	1968	1969	1970
						Canada							
Big Carp (4)	11	15	20	6	5	2	1	15	3	2	-	-	-
Harmony (8)	6	7	19	14	3	0	4	5	0	0	-	-	-
Chippewa (10)	171	290	1,045	453	123	222	274	114	78	92	-	-	-
Batchawana (11)	301	467	626	561	136	336	216	140	119	119	-	-	-
Sable (12)	36	138	241	88	10		5		14	8	-	-	-
Pancake (13)	750	804	1,286	931	187	387	257	94	64	138	-	-	-
Pays Plat (23)	4	30	10	31	9	9	5	0	2	1	-	-	-
Big Gravel (24)	152	537	626	799	315	64	52	188	101	23	-	-	-
Total in Canada	1,431	2,288	3,873	2,883	788	1,056	814	573	381	383	-	-	-
Total	58,679	46,393	40,116	69,584	9,614	11,920	12,581	12,410	5,142	3,745	1,936	9,324	5,690

[1]These figures differ from those in Table 1 which were for the entire operating season.

suddenly and sharply. The 37 barriers captured only 9,992 individuals, a decline of 86% from the previous year. This major decline in abundance was expected in 1962, and not earlier, because (a) the streams treated in 19.59 were relatively small and generally contained fewer lampreys than the large complex watersheds that were deferred until 1960, and (b) the large watersheds could not be treated in 1960 until late spring after the newly transformed lampreys had migrated to the lake. (The delay in treating the larger rivers was necessary to enable the personnel in the newly formed treatment crews to gain experience and develop techniques of stream treatment by working on the smaller, generally simpler watersheds.) The newly transformed lampreys which migrated downstream in the fall of 1959 and spring of 1960 parasitized fish in Lake Superior during 1960 and returned to the barriers in 1961 as a record number of mature adult sea lampreys. This heavy run was followed by the drastic decline of lampreys at the barriers in 1962.

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The adult sea lamprey population again was reduced in 1966. The 5,142 spawning-run adults taken at the 24 index barriers was 60% less than the number in 1965 and 96% below the record high in 1961. The count at the

Although some lake trout spawning had resumed by 1970, wounding rates on large trout were still high, and the numbers surviving to age IX and older were accordingly small. The small population of sea lampreys remaining may still have been too large to permit the establishment of completely self-sustaining lake trout populations. The remnant sea lamprey population was expected to be further reduced by more efficient control measures and by more effective control in the other Great Lakes.

The decline in sea lamprey abundance was clearly illustrated by scarring of large rainbow trout observed at the electric barriers (Fig. 18). The scarring rate rose from 1.5% in 1956 to 13.6% in 1960 (this predation in 1960 was inflicted by the lampreys that spawned in the spring of 1961) 6.2% in 1961, and 3.1% in 1962. The percentage declined to a low of 1.4 by 1967 and then increased slightly to an average of 2.8 in 1968-70.

Reduction in numbers of ammocetes in streams

The reduction in the adult sea lamprey population was readily apparent from barrier counts and wounding of fish, but no similar indices have been available for ammocete abundance. Stream surveys have been primarily concerned with determining occurrence and distribution of sea lampreys, and little emphasis was placed on standardizing these operations to permit estimates of relative abundance or density. Therefore most of the early survey data cannot be safely compared with later information.

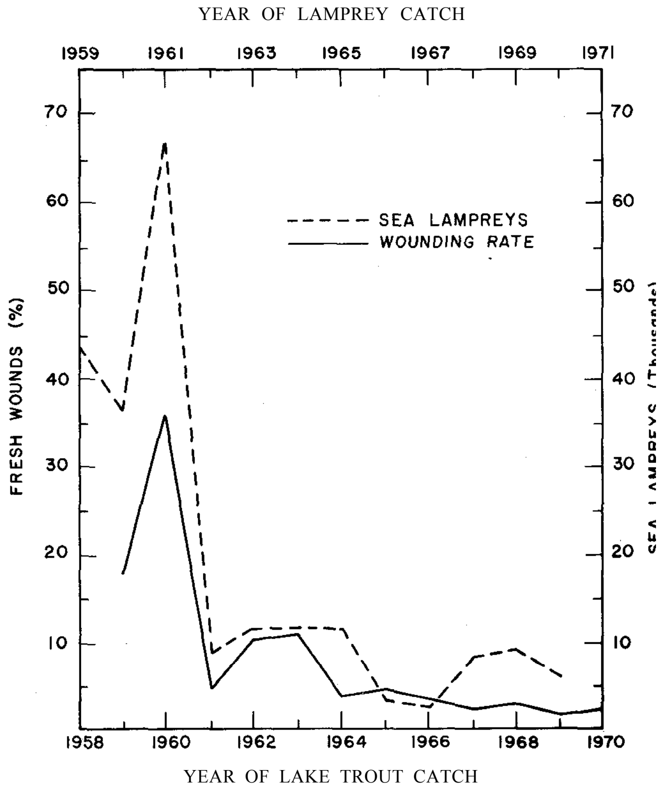

Fig. 17. Catch of spawning-run sea lampreys at 16 United States barriers, 1959-71 (scale at top), and the corresponding wounding rates for lake trout 610 to 632 mm (24-to 24.9-inches long), 1958-70 (scale at bottom). Wounding rates, from the fall of the year, are set forward 1 year to correspond with the catch of lampreys that caused the wounding.

The relative success of individual year classes in nine streams has been determined, as part of the reestablishment studies, by sampling with electric shockers at the same locations each year (Table 7). Some bias was introduced in 1968 when the more efficient transistorized ammocete shocker was substituted for the electric converters used previously. This change may have been responsible for part of the increase noted in 1968-70. The first five year classes (1960-64) were strong, the next three (1965-67) were much weaker, and then a strong 1968 year class was followed by two weaker ones.

The collections of dead and dying lampreys obtained during chemical treatments were intended primarily to provide biological information, including weights, lengths, and proportion of sea lampreys to other species. The possibility of making comparative collections was examined but the time and effort required were beyond the capability of the staff available. It has been noted, however, that the numbers of ammocetes observed dead or dying during re-treatments have been only a small fraction of the numbers observed during initial treatments.

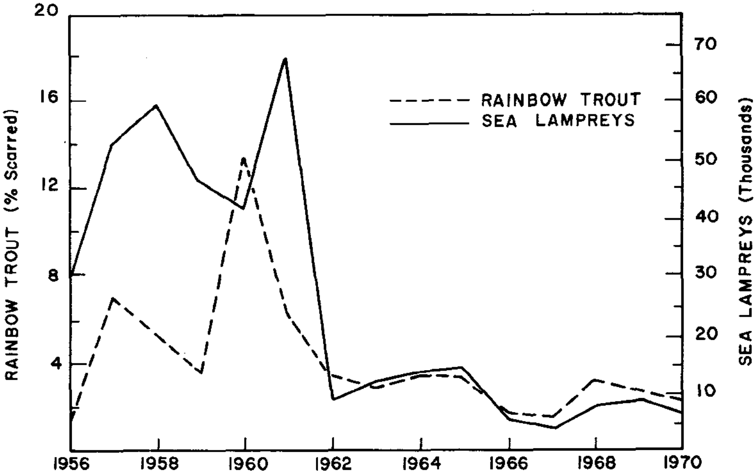

Fig. 18. Percentage of rainbow trout with sea lamprey scars at nine index barriers and number of sea lampreys caught in index streams in Lake Superior, 1956-70 (index barriers were operated in 21 streams in 1956, 24 in 195767, and 16 in 1968-70).

Reduction in numbers of newly transformed lampreys migrating to Lake Superior

An early indication of the effects of chemical control on the lamprey population was the reduction in the numbers of recently metamorphosed sea lampreys migrating to the lake. Fyke nets were fished in eight Lake Superior tributaries from 1961 to 1966 (Table 8).

Table 7. Relative abundance of sea lampreys of different year classes, determined by the number of ammocetes collected per hour with electric shockers in nine tributaries of Lake Superior

[Numbers in parentheses show location of streams in Fig. IO]

Stream	Year class										
	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
Sullivans Creek (16)	73	60	34	15		9	8	18	2	12	7
Seven Mile Creek (17)	10	29	20	6	4	0	0	3	3	0	0
Mosquito River (19)	7	5	-	101	0	0	6	20	28	11	0
Sand River (29)		89	13	20	-	7	0	2	50	0	58
Eliza Creek (50)	44	38	4	2	1	0	0	0	113	5	5
Gratiot River (51)	63	69	29	35	4	3	0	0	51	0	65
Salmon Trout River (54)	79	89	34	-	86	13	55	-	54	0	0
Ontonagon River (60)	–	49	9	2	27	3	-		7	49	11
Cranberry River (62)	2	56	1	0	35	12	3	-7	28	36	9
Total	278	484	144	181	158	47	72	50	336	113	155
Mean	40	54	18	23	20	5	9	7	37	13	17

Table 8. Number of recently metamorphosed sea lampreys captured by fyke nets during the fall in streams of Lake Superior, 1961-66

[Numbers in parentheses show location of streams in Fig. 10.]

Stream	Year treated	1961	1962	1963	1964	1965	1966
Furnace Creek (23)	1960,1964,1965	0	0	0	1	3	0
Au Train River (25)	1959,1962	10	0	1	0	0	0
Rock River (26)	1958,1961	12	6	3	1	0	0
Chocolay River (30)	1958,1961,1966	14[1]	12	4	2	1	0
Fish Creek (66)	1959,1963	0			0	0	0
Brule River (71)	1959,1961,1965	19	4	10	0	0	0
Middle River (73)	1958,1962	1	0	0		0	0
Amnicon River (74)	1958,1962	16	1	0	0	0	14
Total	-	72	30	18	9	4	14

1 The 1961 catch of downstream migrants in the Chocolay River was interrupted by the chemical treatment on October 23.

The nets used were standard "riffle" fyke nets with a 66- by 127-cm (26- by 52-inch) opening and hoop nets with an opening 1.5 m (5 feet) in diameter. The bag was constructed of 6.3-mm (l/4-inch) bar netting with a screen liner (18 by 14 openings to the square inch). Nets were lifted several times a week. Rapid accumulation of debris, algae, and leaves at some locations limited the efficiency of the nets. The nets were fished only in the fall because personnel were not available in the spring.

The total number of young parasitic lampreys captured declined rapidly from 72 in 1961 to 4 in 1965 and 14 in 1966. All 14 captured in 1966 were netted in the Amnicon River, Douglas County, Wisconsin, and were the first taken there since 1962, when one was captured. These ammocetes apparently were produced from a year class established after the stream was treated in 1962.

Reduction in numbers of streams used for spawning

Some obvious changes in ammocete abundance can be deduced from surveys and the collections of dead ammocetes after treatments. An intensive study of lamprey reestablishment in United States streams demonstrated that 15 of the original 80 lamprey-producing streams remained free of ammocetes for the 8-year period, 1962-69 (H. A. Purvis, personal communication). Most are small, cold, spring-fed streams with limited lamprey habitat that originally contained only small numbers of larvae. During the same period, 16 other streams were either reinfested with only one year class or the ammocetes failed to survive to age II. These 31 streams have little potential for producing transformed sea lampreys.

In Canada, only about one-half of the 39 original sea lamprey spawning streams were regularly used by sea lampreys and required routine application of lampricide at 4-year intervals. The remaining streams include those which for one reason or another, such as small size or unfavorable conditions, were seldom used or were unproductive; and six that were used at irregular intervals but, owing to their large size and complexity, were treated only when surveys showed that the ammocetes in them were near the size at which they transform.

Increase in the population of lake trout, rainbow trout, and lake whitefish

R. L. Pycha and G. King (personal communication) analyzed the changes in the lake trout population of Lake Superior after 1950. Briefly, abundance continued downward at an accelerating rate from 1950 to a low in 1961, when lamprey abundance was at its peak. After the sharp drop in sea lamprey numbers in the spring of 1962, commercial lake trout fishing was closed in Michigan and Wisconsin waters in mid-1962 except for fishing by permit to obtain the number of fish needed for biological and statistical data. Lake trout abundance in Michigan waters of Lake Superior rose to about 23% of prelamprey (1929-43) levels in 1962, remained about the same in 1963, and climbed steadily to 98% in 1968 and more than 100% in 1970. The trend was similar in Wisconsin waters; abundance reached 102% of the prelamprey level by 1967.

The changes in populations of important fish species other than lake trout are not easily documented, but reports from fishermen indicate that increases in other species have been significant.

The Michigan Department of Natural Resources estimated that in 1970 anglers took about 68,000 rainbow trout and 44,000 recently introduced coho salmon, ***Oncorhynchus kisutch,*** and chinook salmon, ***0. tshawytscha*** (Great Lakes Fishery Commission 1971). In addition, catches of lake-run brook trout and brown trout were good in some areas.

Another commercially important fish, the lake whitefish, did not recover as rapidly as the lake trout, but whitefish stocks showed some improvement throughout the lake. The 1969 catch of 241,310 kg (532,000 pounds) was the highest in Michigan waters of Lake Superior since 1954. Ontario landings declined slightly from 1968 to 1969, but still were significantly higher than the average catch in 1960-69. Improvements in the whitefish population in Wisconsin were apparent from changes in age and size distribution; furthermore, the average catch per lift in the pound net fishery increased from 12.6 kg (27.7 pounds) in 1958 to 49.1 kg (108.2 pounds) in 1970 (Great Lakes Fishery Commission 1971).

Effects of lampricides on aquatic invertebrates

The possible detrimental effects of lampricides on invertebrates in streams have been of some concern. Dead organisms are often seen during stream treatments. Two investigations have been made, one in the laboratory and one in the field. Studies by Smith (1967) at the Hammond Bay Biological Laboratory on the effects of TFM on representatives of 5 phyla and 15 orders of invertebrates indicated that the chemical is potentially toxic to some of the fauna, but apparently does not harm most invertebrates at the concentrations used for lampricide treatments.

Torblaa (1968) determined the effects of TFM on the organisms in five tributaries of Lake Superior and four tributaries of Lake Michigan. Collections before and after treatment revealed that most groups of aquatic invertebrates were not affected by exposure to the lampricide. Aquatic insects were affected less than other organisms. All groups had returned to pretreatment levels of abundance in samples taken 1 year after treatment.

PROBLEMS

Although sea lamprey control in Lake Superior has met with considerable success, several problems still must be solved before lamprey control can be completely successful and Lake Superior can provide maximum production of high-value food and sport fishes.

Sea lamprey control at the present level is permitting the redevelopment and reestablishment of productive fisheries, but the development of self-sustaining lake trout stocks has been discouragingly slow. Survival of lake trout to full maturity apparently has been inadequate, and large-scale hatchery plantings are still necessary. In United States waters, intensive plantings of lake trout in key areas have created sport fisheries in which fishing success approached that of prelamprey years. Comparable angling success has not been achieved in Canadian waters because plantings made there were smaller and because many of the planted trout were released in remote areas. Owing to the difficulty of exploiting these stocks, they have not contributed significantly to the sport fishery.

Lamprey abundance reached its lowest point in 1967, but gradually increased in 1968-70. The increase can be directly attributed to the extension of the control program to the other Great Lakes without a substantial increase in staff and funds to carry out the additional work. Further suppression of sea lamprey abundance to permit the establishment of a self-sustaining population of lake trout will require more frequent treatment of major lamprey-producing streams.

It has been difficult to evaluate the contribution to parasitic populations of sea lamprey from larvae present in areas which are not affected by routine treatments: estuaries and bays off stream mouths and ponds, lakes, and oxbows within river systems. Additional work is necessary.

Certain aspects of the life history of the sea lamprey during its parasitic phase, such as survival, migration, and feeding habits, have not been investigated thoroughly. In recent years, efforts have been made to fill this gap in knowledge: Tagging studies are being completed; adults collected from commercial fishermen are providing important biological data; and detailed work is beginning on feeding habits.

The size and sex ratio of sea lampreys from Lake Superior changed as the control program progressed. The length and weight of adult lampreys decreased slowly from 1954 to 1961 (Fig. 19). In 1954, the average length was 455 mm (17.9 inches) and the mean weight was 217 g (7.7 ounces). By 1961 (the year of maximum lamprey population), mean length had decreased to 406 mm (16 inches) and weight to 132 g (4.7 ounces). Length fluctuated in 1962-70 between 408 mm (16.1 inches) and 429 mm (16.8 inches) and weight between 141 g (4.9 ounces) and 169 g (5.9 ounces). Although the trend in size has been downward, there is no correlation between abundance and size. Size

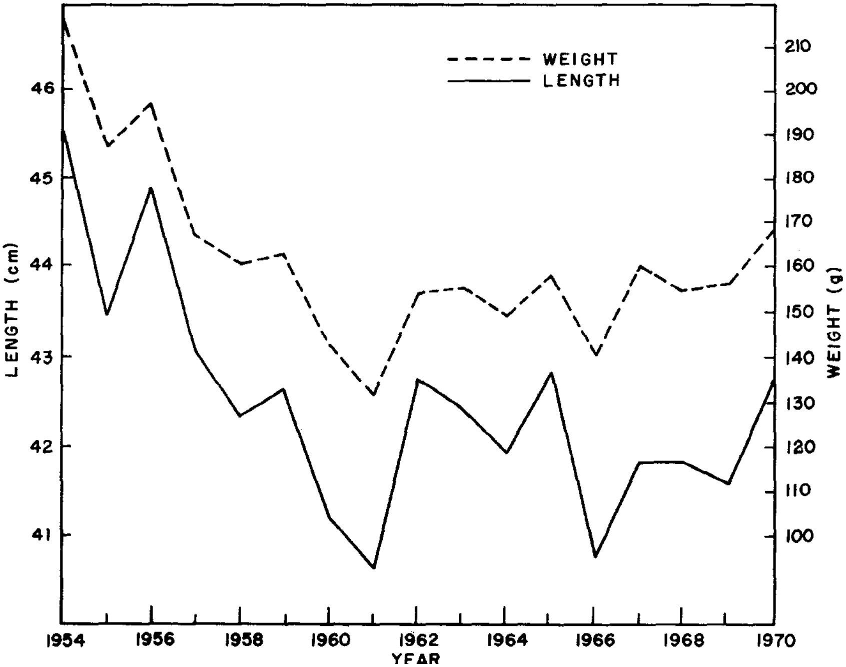

Fig. 19. Length in centimeters and weight in grams of spawning-run sea lampreys from Lake Superior, 1954-70.

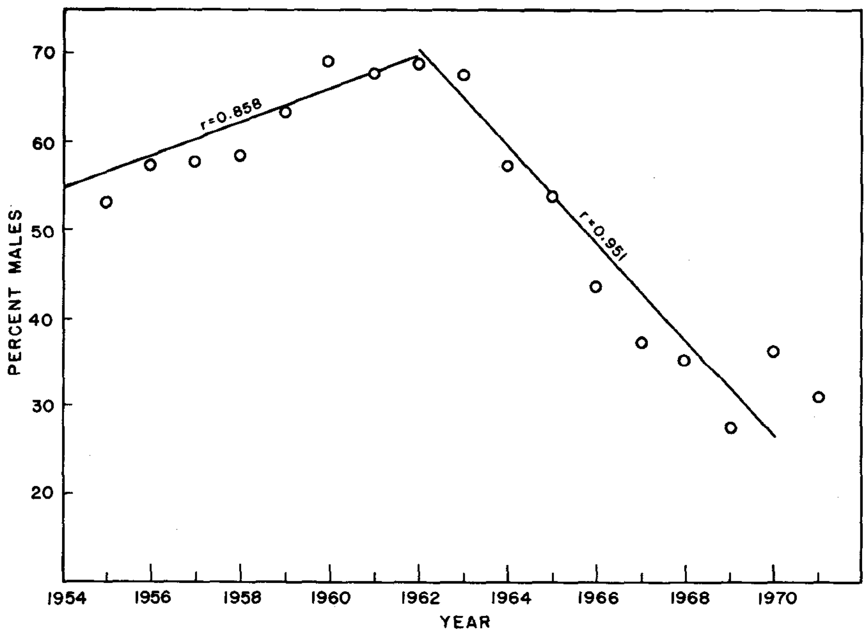

Fig. 20. Percentage males in the spawning run of sea lampreys from streams of Lake Superior, 1954-70.

decreased as abundance increased, but did not increase progressively as the population decreased.

Males and females were about equally represented in the collections from Lake Superior in 1950 (53% males), 1951 (52%) and 1953 (49.7%). The dominance of males increased with the increase in the lamprey population (Fig. 20) to a high of 68.2-69.6% in 1960-62. The percentage began a decline in 1963 (after the drastic decrease in lamprey abundance in 1962) that continued until 1969, when it was only 26.7%. The percentage then increased slightly, to 35% in 1970. These biological responses of sea lampreys to control must be closely monitored for changes, which, if not detected and compensated, could lead to an increase in the sea lamprey population.

ACKNOWLEDGMENTS

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