Experimental Control of Sea Lampreys with Electricity on the South Shore of Lake Superior, 1953-60

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EXPERIMENTAL CONTROL OF SEA LAMPREYS WITH ELECTRICITY ON THE SOUTH SHORE OF LAKE SUPERIOR, 1953-60

by

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CONTENTS

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ABSTRACT

Experimental control of the sea lamprey, *Petromyzon marinus,* with electric barriers was begun in Lake Superior in 1953. Electrical devices were the most practical and promising method of control then available. Installed below spawning grounds in streams and rivers tributary to Lake Superior, these barriers were designed to prevent the sexually mature sea lampreys from reproducing.

The catch of sea lampreys at the electric barriers increased rapidly from 1,668 in 1953 to 66,931 in 1958, The total catches dropped substantially in 1959 and 1960 to 52,173 and 39,783, respectively.

Electric fields of sufficient intensity to block sea lampreys were potentially lethal to other fish and caused undesirable mortality. Improvements in design and installation, and the development of a direct-current diversion device reduced the mortality and increased the efficiency of operation.

The development of control by selective chemicals in 1958 superseded the barrier control system which was terminated at the end of the 1960 season.

The electric barrier operation provided considerable information on mature sea lampreys, including data on time of migration, length, weight, and sex composition.

Electric devices of the type and design used are capable *of* blocking entire runs of adult sea lampreys. An accurate appraisal of the effectiveness of the barrier system is impossible, however. Most of the barriers were not operated long enough to reduce the contribution of parasites from the streams. Furthermore, a complete system of efficient electric barriers was never realized. The greatest weakness of this method of control lies in maintenance of the units in continuous, uninterrupted operation through consecutive migratory seasons.

Introduction

The search for means to control the sea lamprey, *Petromyzon marinus,* in the Great Lakes led to the development of electric barriers and traps (Applegate, Smith, and Nielsen, 1952). These devices, first built and tested in streams tributary to northern Lakes Huron and Michigan, were designed to prevent reproduction by blocking the upstream migration of sexually mature sea lampreys.

Sea lamprey depredations in Lakes Huron and Michigan had all but eliminated lake trout, *Salvelinus namaycush,* from these waters (Hile, 1949; Hile, Eschmeyer, and Lunger, 1951) by 1950. Lake Superior contained the only remaining stocks of this valuable commercial and game species. The rapidity with which lake trout populations had been destroyed in the two lower lakes warranted the immediate use of any promising method of suppressing numbers of sea lampreys in Lake Superior. A program was initiated, therefore, during the spring of 1953 in streams tributary to Lake Superior to test the practicability of electric barriers as a means of control. The 1953-54 operations have been reported by Erkkila, Smith and McLain (1956). A review of this early work and the operation of the barriers from 1955 through 1960 is presented here. At the end of the 1960 season the use of barriers for experimental control ended. They now serve as monitoring devices to assess the effectiveness of chemical control.

History of the Program

Surveys were made of the physical characteristics of streams tributary to the U.S. waters of Lake Superior in 1950-52 (Loeb and Hall, 1952; Loeb, 1953). This work provided information on streams having habitat suitable for sea lamprey reproduction. The surveys also indicated that sea lamprey runs at that time were confined chiefly to streams entering the eastern part of Lake Superior. The first electric barriers, therefore, were built in this area.

Plans for the 1953 program called for the installation and operation of devices on 23 streams which were selected to provide diversity of stream characteristics, to cover an area sufficient to acquaint the staff with problems of servicing, and to include streams actually used by sea lampreys. Acquisition of land easements and leases caused so much delay that only

10 of the proposed units were ready for operation at the start of the 1953 spawning season. Construction of the other barriers continued, and although 9 more were completed by June 1, they were not operated that year.

The number of electric barriers was expanded in 1954 to 44, extending from the Waiska River at the eastern end of the lake, to the Union River a few miles west of Ontonagon, Michigan. This stretch of some 500 miles of Lake Superior's south shore has approximately 300 tributaries, including man-made ditches and wet-season drainages, about 145 of which were considered as possibly usable by spawning sea lampreys. The 44 streams selected for barriers were known to have, or were believed most likely to have sea lamprey runs.

During the 1954 season, no sea lampreys were caught at 18 of the 44 control devices. Rather than continue the installation of barriers on all potential spawning streams, it appeared more practical to operate them only on those streams in which sea lamprey runs existed. Ten of the 18 "unproductive" barriers were placed on standby. Control structures were installed on 2 new streams in which spawning was discovered. A total of 36 barriers was operated in 1955.

Toward the end of 1955, a study of the effects of temperature on embryological development showed that under constant temperatures no live larvae were produced below 60° F. or above 70° F. (Piavis, 1961). This knowledge contributed to a decision to place additional barriers on standby.

The 1956 barriers numbered 34. Sea lampreys were found in 3 new streams and 4 more "unproductive" units were placed on standby. Two of the new structures extended the operation west to Ashland County, Wisconsin.

The 1957 barrier system comprised 39 structures including an experimental direct-current device which was tested in the Brule River, Wisconsin. The number of barriers was increased to 45 for the 1958 season. Five of these units were temporary installations to check streams where results from previous attempts to determine the status of sea lamprey runs were considered unreliable.

The first field applications of selective larvicides were made during the 1958 season (Applegate, Howell, Moffett, Johnson, and Smith, 1961). The promise of a more immediate and effective method of control ended further construction of electric barriers. Installation of new structures was halted and repairs and modifications to existing structures were curtailed. Forty electric barriers were operated in 1959 and 37 in 1960. The 3 devices that were discontinued formed a group serviced by one crew. Their elimination reduced personnel costs and made more money available for chemical control. The experiment to control sea lampreys with electric barriers ended in 1960.

Electric Barriers and Traps

Development of the electric barriers

The original electric devices were of the 3 basic types described by Erkkila, Smith, and McLain (1956). Basically, they consisted of an electrode array across a stream to establish an electric field from one bank to the other. A trap with leads or wings was installed at each barrier. The 3 types differed as to the electrode arrangement. The first, which consisted of 2 parallel rows of hanging electrodes suspended across the stream by catenary cables, was designed for the deeper streams. The second had a single row of suspended electrodes and a submerged electrode on the bottom parallel to the suspended electrodes. These barriers were installed in streams of medium depth. The third, consisting of 2 submerged electrodes lying parallel across a streambed, was restriced to shallow waters.

Traps were installed with the wings or leads terminating at the downstream fringe of the electric field. It was believed that many fish migrating upstream would be diverted by the fringe of the electric field and, in their search for a passage, would enter the trap. Thus, the traps interrupted the electric fields and served as part of the barrier in the early structures. The ability of the sea lamprey to withstand a relatively severe electric shock without apparent physical harm and their persistence frequently enabled them to find any passage which existed or developed under or around the traps. By 1956, most barriers were modified to establish an uninterrupted field from one bank to the other. The traps were installed downstream from the electric field, usually adjacent to a stream bank.

Experience led to further modifications. Only 3 barriers were installed with the double row of suspended electrodes. These structures lacked the flexibility required for alteration of electrode spacing and surface area to provide the field intensity required by the low electrical Conductivities of water in Lake Superior tributaries.

New installations or modifications to existing barriers were based on the design with a single row of suspended electrodes or on the shallow-water type. Each device was built to meet the electrical and physical characteristics of the particular stream.

The electrode arrays were energized with 115-volt alternating current. Some of the largest and most complex barriers used multiple 115-volt fields. The scope of the program made the use of alternating current mandatory. Cost was important as was simplicity which increased reliability, reduced maintenance, and eased the burden of training a comparatively large staff.

Generators supplied the alternating current where commercial power was not available. Auxiliary power plants were maintained at all sites to provide power automatically should the main source fail. A small building housed the generators, control panels, switch boxes, and spare parts.

Many modifications or innovations were incorporated to increase the efficiency of the structures but they did not materially influence the electric fields. Changes and additions included: the installation of wood or concrete abutments which served to channel the stream flow and increase water velocity; enlarged traps; and bottom stabilization. The improvements reduced mortality of fish and increased the ability of the barriers to capture desirable migrants to be moved upstream.

The abutments also provided a secure mounting for traps and facilitated installation and servicing of larger traps under adverse stream conditions. The traps were successively enlarged and improved. Several installations had compartmented traps with multiple-funnel arrangements to increase trapping and holding efficiency.

Each control device was completely enclosed by a fence and posted to warn the public. A red light also was installed as a warning signal. Safety switches were placed at each installation and were manned during servicing. In addition, fishing was prohibited in the immediate vicinity of the electric barriers.

Electric fields

The effectiveness of each structure depended upon the ability of its electric field to immobilize all adult sea lampreys. The intensity of the field had to be great enough to induce paralysis regardless of the orientation of the animal's body to the lines of current flow. The effective field also had to be sufficiently deep to prohibit the momentum of a rapidly swimming sea lamprey from carrying the stunned animal completely through the barrier. These conditions had to be maintained throughout the operational period during which physical and electrical characteristics of the stream varied widely.

The most difficult period through which to maintain an effective field was early spring when the water was high, temperatures were low, and water Conductivities were at the minimum. The problem was made more troublesome by the lack of reliable criteria or standards upon which to base the strength of the electric fields. Originally we believed that we could use an earlier comprehensive series of voltage-gradient measurements from electric fields established in streams tributary to northern Lakes Huron and Michigan (Applegate, Smith, and Nielsen, 1952). This series indicated that a minimum gradient of 0.75 volt per inch must exist to block the sea lamprey run completely. A voltage gradient of at least 1.00 volt per inch was recommended to provide a margin of safety. This standard was adopted during the early years of operation on Lake Superior. Unfortunately, the escapement that occurred during 1953 and 1954 was the result of mechanical failures. Not until later was it discovered that a field with a voltage gradient of 1.00 volt per inch was not sufficiently intense to block all sea lampreys during the periods of low water conductivities on some Lake Superior streams. The problem was brought out even more sharply by work on the Canadian side of Lake Superior (Lawrie, 1959). Electric barriers based on the specifications of those used in U.S. waters were partially ineffective due to low water Conductivities (Lenson and Lawrie, 1959).

The combined effect of water conductivity and voltage gradient on the reaction of a fish has long been recognized. McMillan (1928) demonstrated that a much higher voltage gradient was required to paralyze a fish in water of low conductivity than in conductive water. Other investigators have discussed the relation of the resistivity of the body of a fish to that of the water. Among them are: Haskell, 1954; Whitney and Pierce, 1957; Meyer-Waarden, 1957; and Rollefson, 1958. Despite these studies, no reliable standards existed on which the intensity of the electric field could be based to assure a complete block of all sea lampreys at minimum water conductivities. It was undesirable to increase field intensity indiscriminately at all barriers since it was necessary to keep mortality of other fish low.

An extensive series of conductivity measures[1] obtained after 1954 to provide a background for establishing the intensity of the electric fields, led to maintenance of more intense fields in streams with relatively low water conductivity. McCauley (1960) published data on the relationship between water conductivity and the voltage gradient required to paralyze a sea lamprey. McCauley demonstrated that the relation is not linear and that below 100 micromhos the critical gradient becomes markedly dependent on water conductivity. This finding provided a more reliable criterion on which to base field intensity.

Direct-current diversion devices

Mortality of fishes was considerable at some of the early electric barriers (Erkkila, Smith, and McLain, 1956). During 1956, 2 direct-current diversion devices were tested in conjunction with the alternating-current barriers in an attempt to reduce fish mortality and increase trapping efficiency. The diversion devices, described in detail by McLain (1957), were successful. The experimental models used interrupted direct current at a duty cycle of 0.66 and a repetition rate of 3 pulses per second. The wave shape of the pulses was essentially square.

The experimental equipment to provide the interrupted direct current proved unsatisfactory for prolonged, uninterrupted use. This equipment was replaced by one of two types of direct-current relaxing pulse generators[2] One type produced unfiltered, half-wave, rectified alternating current and the other had an output of unfiltered, full-wave, rectified alternating current.

Half-wave, rectified alternating current was tested during 1952 (McLain and Nielsen, 1953) and both full- and half-wave, rectified alternating currents were tried during 1954. The galvanotactic response to either type of current is not as satisfactory as that elicited by square-wave pulses of direct current. The scope of the program, economic considerations, and other factors made it desirable, nevertheless, to use the output of the relaxing pulse generators.

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[1] Conductivity measurements were taken with a conductivity bridge, Industrial Instruments, Inc., Model RC - 16B - 1.

[2] Designed and constructed by Mr. George Belprez, Walled Lake, Michigan.

Seven diversion devices, including the 2 experimental models, were operated during 1957 in conjunction with alternating-current barriers. Eventually 12 of these devices were in operation in tributaries to Lake Superior where the destruction of fish by the alternating-current fields had become a problem?

Experience in the operation of the diversion devices led to no major change from the basic principles. Several improvements in the installation and in design were developed, however. The single structure that deviated from the basic design was installed with its electrode array in the form of a "V" with the apex downstream. Located in the Brule River, Wisconsin, it was one of the most efficient of the diversion barriers.

Operation of the Control Barriers

The experimental electric barriers finally extended along the south shore of Lake Superior from Sault Ste. Marie, Michigan, to Superior, Wisconsin. This distance was divided into 11 control zones designated as S-l to S-11 from east to west (Fig. 1). Each zone, with the exception of S-8, contained from 3 to 8 control devices which could be serviced daily by 1 crew (Table 1). No runs of sea lampreys developed in streams of control zone S-8.

No barriers were installed in streams along the Minnesota shore. The Pigeon River which forms the border between the State of Minnesota and the Province of Ontario had the only known sea lamprey run. Sea lampreys spawned occasionally in several Minnesota streams but no ammocetes were established in these streams.

A 3-man crew was assigned to each control zone. The men worked a 5-day week on a staggered basis so that 2 men were on duty each day. They were responsible for servicing each electric barrier once daily.

Fish and sea lampreys were removed from the traps and the fish were released, those killed by the electric field were

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[3] Some of the later structures were energized with the output of direct-current relaxing pulse generators, Model 30-B, manufactured according to our specifications by the Electric Fish Screen Company, Hollywood, California.

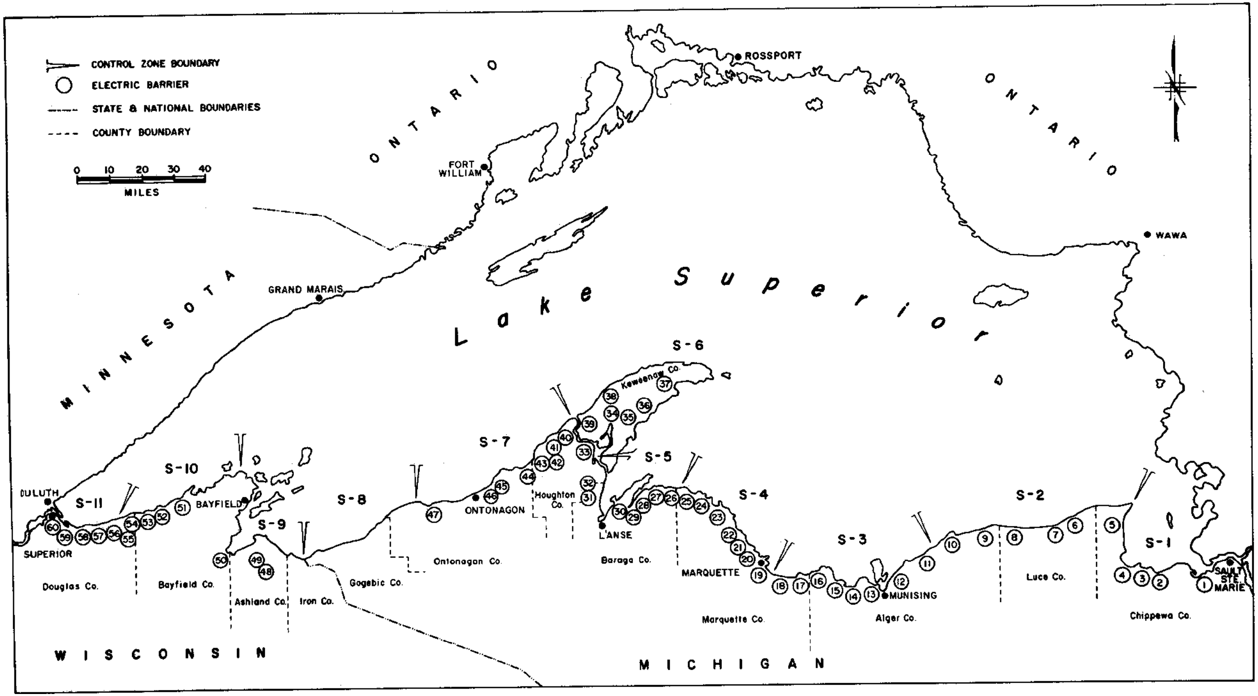

Figure 1. - Map of Lake Superior showing boundaries of control zones and the location of all electric barriers. The numbers on the map correspond to the numbers assigned to individual streams listed in Table 1.

Table 1. - Control zones and streams tributary to Lake Superior in which electric barriers were installed and the years of operation

[The number assigned to each stream is the barrier number in Figure 1.1

Control zone and stream	Years of barrier operation
Zone S-l	
1. Waiska River	1954-60
2. Pendills Creek	1953-60
3. Halfaday Creek	1954-58
4. Ankodosh Creek	1954
5. Betsy River	1953-60
Zone S-2	
6. Little Two Hearted River	1957-60
7. Two Hearted River	1953-60
8. Dead Sucker River	1953-54
9. Sucker River	1953-60
10. Hurricane River	1954-60
Zone S-3	
11. Beaver Lake Cutlet	1953-58
12. Miners River	1953-60
13. Furnace Creek	1953-60
14. Au Tram River	1953-60
15. Rock River	1955-60
16. Laughing Whitefish River	1953-60
17. Sand River	1954
18. Chocolay River	1954-60
Zone S-4	
19. Carp River	1954-60
20. Harlow Creek	1954-60
21. Little Garlic River	1954-55
22. Big Garlic River	1954-60
23. Iron River	1954-60
24. Salmon Trout River	1954-56; 1959-60
25. Pine River	1954-60
Zone S-5	
26. Little Huron River	1954
27. Huron River	1954-60
28. Ravine River	1954-60
29. Slate River	1954
30. Silver River	1954-60
31. Sturgeon River	1954-60
32. Otter River	1954-58

Table 1. - Continued

Control zone and stream	Years of barrier operation
Zone S-6	
33. Pilgrim River	1954
34. Traprock River	1954-55
35. Traverse River	1954-59
36. Tobacco River	1954
37. Little Gratiot River	1954-59
38. Gratiot River	1954-59
39. Boston and Lily Creek	1954
40. Schlotz Creek	1954
Zone S-7	
41. Graveraet River	1954
42. Elm River	1954-60
43. South Branch Elm River	1954-55
44. Misery River	1955-60
45. Firesteel River	1954-60
46. Flintsteel River	1954-60
47. Union River	1954-55
Zone S-8	
Zone s-9	
48. Bad River	1956-59
49. White River	1956-60
50. Fish Creek (Eileen Township)	1957-60
Zone s-10	
51. Cranberry River	1958-60
52. Iron River	1958
53. Reefer Creek	1958
54. Fish Creek (Orienta Township)	1958
55. Brule River	1957-60
Zone s-11	
56. Poplar River	1957-60
57. Middle River	1957-60
58. Amnicon River	1957-60
59. Black River	1958-60
60. Nemadjii River	1958-60

collected, and the numbers and species recorded. Water temperature, water level, weather, power consumption, and other data were recorded. The crews maintained and repaired all barrier components.

At least 1 river in each control zone was designated as an "index" stream in which sex, weight, and length were determined for individuals in samples from the daily catch of sea lampreys.

The work load diminished as fish runs declined. It then became the duty of the service crews to check for sea lamprey escapement and for any indication of sea lamprey spawning in uncontrolled streams in their zones.

Sea Lamprey Catch

1953 season

The 10 electromechanical weirs operated in 1953 captured or killed 1,668 adult sea lampreys. Only 1 device, on the Dead Sucker River, failed to take lampreys.

1954 season

The 44 units produced 4,922 sea lampreys, including 1,227 from a mechanical weir which had been installed in the Chocolay River, near Marquette, Michigan. The catch for the 10 original devices increased to 3,048 individuals, nearly double that of the previous year. The 33 new electric barriers captured only 647, or 13.1 percent, of the total.

The capture of 4,327 of the 4,922 adults at the 17 barriers east of Marquette confirmed earlier indications that sea lampreys were concentrated in the eastern portion of Lake Superior. The 27 barriers west of Marquette captured 595 sea lampreys and 529 of these were taken east of the Keweenaw Pennisula. Eighteen of the 44 devices took no sea lampreys (14 of the 18 were west of Marquette).

1955 season

The number of barriers was reduced to 36 in 1955. Ten barriers, unproductive in 1954, were placed on standby and new barriers were installed on the Misery and Rock Rivers. The mechanical weir on the Chocolay River, which had allowed considerable escapement and had placed excessive demands on the staff for operation, was replaced by an electrical device.

The 36 barriers captured or killed 10,639 adult sea lampreys, more than double the number taken in 1954. The most significant increase was at structures west of Marquette. The increase was threefold-from 595 in 1954 to 1,917 (including 183 adults from the new device on the Misery River) in 1955. The catch east of Marquette was 8,722 sea lampreys as compared to 4,327 in 1954, but 1,633 individuals from the new device on the Rock River made a significant contribution to the increase.

1956 season

Thirty-four electric barriers were operated in 1956. Four additional units were placed on standby and structures were installed on the Bad and White Rivers in Ashland County, Wisconsin.

The upward trend in numbers of adult sea lampreys continued in 1956. The barriers captured 24,084 individuals, again more than doubling the catch of the previous year. The new structures on the Bad and White Rivers took 685 and 219 lampreys, respectively.

1957 season

During the 1956 spawning season, sea lampreys were found in 5 more Wisconsin streams. Electrical devices were installed and readied for the 1957 season on 4 of them (Fish Creek, Bayfield County, and the Poplar, Middle, and Amnicon Rivers in Douglas County). A barrier was not completed on the fifth stream, Brule River, but an experimental direct-current diversion device was installed and operated from May 19 to July 18.

The barrier on the Salmon Trout River which had captured only 1 sea lamprey in 3 years was placed on standby. A new device constructed on the Little Two Hearted River increased the number of barriers to 39 including the experimental device on the Brule River.

The barriers took 57,820 adult sea lampreys in 1957 including 3,988 from the special unit on the Brule River. Again, the catch more than doubled that of the preceding year, but only because of the contribution of the new structures in Wisconsin streams. The 4 new units captured 15,990 adults. The combined production from Wisconsin streams totaled 23,042 sea lampreys, or nearly 40 percent of the entire catch.

Barriers along the eastern half of Lake Superior's shoreline, the area covered since 1954, produced 34,778 sea lampreys as compared with 23,200 in 1956. The numbers for the first time failed to double; the increase was only about 50 percent over the preceding year.

Several major modifications were made to some of the barriers. Direct-current diversion equipment was installed and operated on the Two Hearted River, Sucker River, Beaver Lake Outlet, Chocolay River, Huron River, Silver River, Bad River, and Fish Creek. Major improvements were made to 6 barriers on other streams. The extent of increase in catch attributable to the improvements is not known.

1958 season

The control barriers were increased to 45 units for the 1958 season. A new device was installed on the Cranberry River, the Brule River structure was completed, and 5 structures were installed as checking devices to determine the status of streams in which the establishment of runs was questionable. Fifteen devices remained on standby.

The 45 electric barriers took 66,931 adult sea lampreys in 1958. Only 5 barriers failed to capture adults. The 32 barriers in Michigan waters accounted for 24,293 adults (36.3 percent) and those in Wisconsin took 42,638 (63.7 percent). Over 94 percent (62,890) of the lampreys were produced in 12 rivers. The Brule River alone accounted for 22,842 individuals, or 34.2 percent, of the total catch.

For the first time, the numbers of sea lampreys in streams tributary to the eastern half of Lake Superior were lower than in the preceding year. Previously, the catch from 19 eastern streams had nearly doubled each year since 1954 until 1957 when the increase was only 52.9 percent. In 1958, the number dropped to 19,509, a reduction of 31.9 percent as compared to the high of 28,642 adults in 1957 (Table 2).

The increase of 1958 (66,931) over the 1957 catch (57,820) may not reflect an actual increase in the population of adult sea lampreys. The catch on the Brule River in 1957 was made by the diversion device which was not designed to capture all sea lampreys and was not operated throughout the migratory period. Experienced observers estimated that numbers of sea lampreys in the Brule River greatly exceeded the 3,988 captured. Any number from the Brule in excess of 10,000 would have made the 1957 catch larger than that of 1958.

Table 2. - Total catches of sea lampreys from 19 streams of eastern Lake Superior that had control devices for 7 years, 1954-60

Stream	1954	1955	1956	1957	1958	1959	1960
Waiska River	32	47	71	55	70	43	127
Pendills Creek	40	45	42	47	17	40	33
Betsy River	567	569	1,577	786	1,092	1,006	705
Two Hearted River	638	600	1,766	7,899	3,577	4,141	4,508
Sucker River	1,309	1,713	4,400	3,597	1,842	2,522	4,980
Hurricane River	8	25	99	188	29	65	80
Miners River	53	148	96	427	97	159	411
Furnace Creek	47	66	209	274	41	396	2,293
Au Train River	350	486	613	739	348	168	80
Laughing Whitefish River	25	16	19	37	11	28	42
Chocolay River	1,227	3,350	6,888	8,096	6,221	3,500	4,216
Carp River	0	2	1	4	0	5	5
Harlow Creek	1	1	0	3	3	31	14
Iron River	67	206	335	737	428	266	342
Pine River	10	12	18	34	22	43	28
Huron River	147	472	1,628	2,868	3,526	1,492	1,377
Ravine River	1	4	2	10	5	23	8
Silver River	247	786	963	2,810	2,152	878	1,386
Sturgeon River	1	1	4	31	28	544	161
Total	4,770	8,549	18,731	28,642	19,509	15,350	20,796
Percentage change	...	79.2	119.1	52.9	-31.9	-21.5	35.5

1959 season

The successful field trials during 1958 with selective larvicides for the control of the sea lampreys ended further expansion of the electric barrier program. Plans for the construction of new devices were abandoned. The number of barriers was reduced from 45 to 40 for the 1959 season. Detection of sea lampreys in the Salmon Trout River led to re-activation of its barrier, which had been on standby since 1956.

The 40 barriers captured 52,173 sea lampreys during the 1959 season, a reduction of 22.0 percent from the 1958 catch.

able 3. - Total catches of sea lampreys from 11 streams of western Lake Superior that had control devices for 3 years, 1958-60

Stream	1958	1959	1960
Elm River	2	8	12
Misery River	896	2,581	‘761
Firesteel River	1,546	2,084	276
Flintsteel River	2	0	0
White River	231	552	233
Fish Creek	251	428	354
Cranberry River	0	14	50
Brule River	22,842	19,389	9,755
Poplar River	580	8	58
Middle River	4,853	3,645	2,839
Amnicon River	7,670	986	1,165
Total	38,873	29,695	15,503
Percentage change	. . .	-23.6	-47.8

For the second consecutive year, the numbers of sea lampreys decreased in streams tributary to the eastern part of Lake Superior. The reduction of 31.9 percent in 1958 was followed by a 21.5-percent drop in 1959 (Table 2). The total catch of adults decreased also in streams tributary to the western half of Lake Superior. Streams west of the Keweenaw Peninsula produced 29,695 individuals as compared to 38,873 in 1958 (Table 3).[4]

Again, over 90 percent of the adults were taken from 12 streams. The Brule River accounted for 19,389, or 37.2 percent, of the season’s catch. The 30 barriers operated in Michigan waters produced 22,669 (43.4 percent) and those in Wisconsin captured 29,504 (56.6 percent) of the sea lampreys.

1960 season

A total of 37 electric barriers was placed in operation for the 1960 season. Their effectiveness was greatly lessened in

[4] Comparisons of seasonal catches are based on only those streams in which the operation of barriers was not interrupted.

early season by unprecedented floods. Several traps were inundated for periods up to 30 days. The Bad River barrier, one of the largest and most complex structures, suffered such serious damage that it was abandoned.

A second barrier, Big Garlic River, was removed because of the need for a complete re-installation. Thus, only 35 electric barriers actually operated through the 1960 season.

The catch of sea lampreys was 39,783 during the 1960 season.[5] After two consecutive years of decline, the catch from 19 streams in the eastern half of Lake Superior increased. These streams produced 20,796 adults as compared to 19,509 and 15,350 in 1958 and 1959, respectively (Table 2). This increase was more than compensated by a drop in the numbers of adults in the western streams. The total catch from 11 western streams dropped from 29,695 in 1959 to 15,503 in 1960, a reduction of 47.8 percent (Table 3).

Over 90 percent of the sea lampreys caught in 1960 were taken from 11 streams; the Brule River alone accounted for 24.5 percent of the catch. The Flintsteel River was the only stream that did not produce a sea lamprey. Most unusual among the runs during 1960 was at Furnace Creek, a small stream in Alger County, Michigan. It produced 2,293 adults as compared to its highest previous record of 396 in 1959.

Summary for 1953-60

Beyond the initial increase in the numbers of sea lampreys during the first few years, the runs showed few trends (Table 4). The most easterly of the streams, those in control zone S-1, appeared to have reached their peak production in 1956. Streams in control zones S-2 to S-5 yielded their greatest catches in 1957, and by 1958, the peak was reached in the western rivers. Subsequent fluctuations in numbers are unexplained but may reflect a normal variation in the size of the population as it became established. Since no definite conclusion has been reached relative to the duration of the larval stage, it is difficult to speculate as to whether the barriers had been operated on enough streams and for a long enough time to have contributed to the indicated drop in population levels in 1959 and 1960.

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[5] Including 87 sea lampreys taken by the Big Garlic weir prior to its removal on May 29.

Table 4. - Catches of sea lampreys by control zone and stream for all electric barriers operated in U.S. tributaries to Lake Superior, 1953-60

Control zone and stream	1953	1954	1955	1956	1957	1958	1959	1960
Zone S-1								
Waiska River	...	32	47	71	55	70	43	127
Pendills Creek	23	40	45	42	47	17	40	33
Halfaday Creek	...	12	3	14	4	2	...	...
Ankodosh Creek	...	0	...	...		...	...	...
Betsy River	221	567	569	1,577	786	1,092	1,006	705
Zone total	244	651	664	1,704	892	1,181	1,089	865
Zone S-2								
Little Two Hearted River	...		...	...	739	460	461	715
Two Hearted River	371	638	600	1,766	7,899	3,577	4,141	4,508
Dead Sucker River	0	0	...	...	...	...	...	...
Sucker River	750	1,309	1,713	4,400	3,597	1,842	2,522	4,980
Hurricane River	...	8	25	99	188	29	65	80
Zone total	1,121	1,955	2,338	6,265	12,423	5,908	7,189	10,283
Zone S-3								
Beaver Lake Outlet	8	19	19	20	49	18	...	...
Miners River	64	53	148	96	427	97	159	411
Furnace Creek	18	47	66	209	274	41	396	2,293
Au Train River	204	350	486	613	739	348	168	80
Rock River	...	..	1,633	3,407	3,102	1,488	1,250	2,646
Laughing Whitefish River	9	25	16	19	37	11	28	42
Sand River	...	0	...	...	...	...	...	...
Chocolay River	...	1,227	3,350	6,888	8,096	6,221	3,500	4,216
Zone total	303	1,721	5,718	11,252	12,724	8,224	5,501	9.688

Table 4. - Continued

Control zone and stream	1953	1954	1955	1956	1957	1958	1959	1960
Zone S-4								
Carp River	...	0	2	1	4	0	5	5
Harlow Creek	...	1	1	0	3	3	31	14
					...	...	...	...
Little Garlic River	...	54	89	154	270	262	247	87[1]
Iron River	...	67	206	335	737	428	266	342
Salmon Trout River	...	1	0	0	...	-	68	5
Pine River		10	12	18	34	22	43	28
Zone total	...	133	310	508	1,048	715	660	481
Zone S-5	...							
Little Huron River	...	0		...	...	...		...
Huron River	...	147	472	1,628	2,868	3,526	1,492	1,377
Ravine River	...	1	4	2	10	5	23	8
			...		...	...	...	...
Slate River	...	247	786	963	2,810	2,152	878	1,386
Sturgeon River	...	1	1	4	31	28	544	161
Otter River		0	0	1	0	0	...	...
Zone total	...	396	1,263	2,598	5,719	5,711	2,937	2,932
Zone S-6	...							
Pilgrim River	...	0	...	...	...	...	...	...
Traprock River	...	0	0	...	...	...	598	...
			4	37	45	76		...
Tobacco River	...	0	...	...	...	...	...	...
Little Gratiot River	...	0	1	4	9	1	11	...
Gratiot River	...	1	0	4	2	31	11	...

Table 4. - Continued

Control zone and stream	1953	1954	1955	1956	1957	1958	1959	1960
Zone S-6 Continued								
Boston and Lily Creek	...	0	...	...	...	...	...	...
Scholtz Creek	...	0	...	...	...	...	...	...
Zone total	...	4	5	45	56	108	620	...
Zone S-7								
Graveraet River	...	0	...	...	...	...	...	...
Elm River	...	0	7	7	7	2	8	12
South Branch Elm River	...	0	0	...			...	...
Misery River	...	...	183	571	868	896	2,581	761
Firesteel River	...	- 60	150	229	1,039	1,546	2,084	276
Flintsteel River	...	2	1	1	2	2	0	0
Union River	...	0	0	...	...	...	...	...
Zone total	...	62	341	808	1,916	2,446	4,673	1,049
Zone S-9								
Bad River	...	...	...	685	2,652	6,203	4,468	...
White River	...	...	...	219	412	231	552	233
Fish Creek	...	...	...	...	520	251	428	354
Zone total	...	...	...	904	3,584	6,685	5,448	587
Zone S-10								
Cranberry River	...	...	...	...	...	0	14	50
Iron River	...	...	...	...	...	0	...	...
Fish Creek	...	...	...	...	...	0	...	...
Reefer Creek	...	...	...	...	...	1		...
Brule River	...	...	...	...	3,988[2]	22,842	19,389	9,755
Zone total	...	...	...	...	3,988	22,843	19,403	9,805

Table 4. - Continued

Control zone and stream	1953	1954	1955	1956	1957	1958	1959	1960
Zone S-11								
Poplar River	. . .	. . .	. . .	. . .	126	580	8	58
Middle River	. . .	. . .	. . .	. . .	4,289	4,853	3,645	2,839
Amnicon River	. . .	. . .	. . .	. . .	11,055	7,670	986	1,165
Black River	. . .	. . .	. . .	. . .	. . .	4	13	21
Nemadji River	. . .	. . .	. . .	. . .	. . .	3	1	10
Zone total	. . .	. . .	. . .	. . .	15,470	13,110	4,653	4,093
Total	1,668	4,922	10,639	24,084	57,820	66,931	52,173	39,783

‘Operation terminated May 29.

‘Catch from experimental device operated from May 19 to July 18, not indicative of total run.

Table 5. - Sea lamprey catch by I-day periods expressed as percentage of total run, 1953-60

Period	1953	1954	1955	1956	1957	1958	1959	1960
March 22-26		0.00	0.02	0.05	0.00	0.001	0.00	0.00
March 27-31	...	0.02	0.04	0.03	0.00	0.02	0.02	0.00
April 1-5	0.00	0.00	0.09	0.10	0.01	0.11	0.44	0.01
April 6-10	0.06	0.06	0.05	0.02	0.14	1.09	0.42	0.11
April 11-15	0.06	0.21	0.08	0.34	0.15	0.99	0.90	0.22
April 16-20	0.06	0.10	0.25	0.31	0.19	2.06	0.15	0.25
April 21-25	0.84	0.76	0.97	0.54	0.74	3.02	0.63	0.64
April 26-30	0.30	0.84	9.33	0.54	3.38	1.62	0.98	0.69
May 1-5	2.70	4.42	13.13	0.76	5.83	4.30	8.66	1.14
May 6-10	14.69	1.25	2.24	3.84	12.86	6.09	8.94	1.19
May 11-15	11.15	11.89	6.02	6.87	5.63	18.98	8.58	3.02
May 16-20	10.13	6.63	5.76	3.34	3.23	9.01	6.81	9.84
May 21-25	7.61	11.26	10.42	8.82	11.55	8.16	5.40	10.39
May 26-30	5.58	3.74	3.48	11.07	10.05	7.22	12.88	9.57
May 31-June 4	8.57	3.06	7.02	7.40	12.84	4.04	10.53	9.38
June 5-9	12.59	17.99	8.53	15.05	5.75	11.06	15.20	9.91
June 10-14	11.45	9.28	3.01	16.46	8.85	5.31	6.21	8.70
June 15-19	10.07	9.20	10.95	4.08	6.16	5.83	3.59	7.13
June 20-24	1.08	5.32	6.45	5.23	3.98	3.03	1.84	6.57
June 25-29	0.24	6.22	5.08	1.83	2.19	2.76	1.88	9.08
June 30-July 4	0.48	2.55	2.97	2.92	2.17	1.39	1.76	3.15
July 5-S	0.42	1.79	1.53	1.83	1.19	0.96	1.26	2.80
July 10-14	1.26	1.32	0.89	2.84	0.45	1.13	0.90	2.12
July 15-19	0.42	0.72	0.70	1.57	1.37	0.63	0.84	1.11
July 20-24	0.12	0.64	0.41	0.89	0.32	0.50	0.34	0.99
July 25-29	0.12	0.37	0.30	1.02	0.34	0.27	0.25	0.78
July JO-Aug. 3	0.00	0.14	0.08	0.69	0.18	0.14	0.20	0.50
Aug. 4-8	...	0.08	0.09	0.62	0.15	0.11	0.11	0.27
Aug. 9-13	...	0.12	0.05	0.60	0.10	0.06	0.10	0.17
Aug. 14-18	...	0.02	0.06	0.23	0.07	0.04	0.06	0.15
Aug. 19-23	...	...	0.00	0.07	0.07	0.04	0.06	0.08
Aug. 24-28	...	...	...	0.04	0.02	0.02	0.03	0.03
Aug. 29-Sept. 2	...	...	...	0.00	0.01	0.01	0.02	0.01
Sept. 3-7	...	...	...	0.001	0.01	0.001	0.001	...
Sept. 8-12	...	...	...	0.00	0.02	0.00	0.01	...
Sept. 13-17	...	...	...	...	0.001	...	0.00	...

[1] Less than 0.005.

Biology of Sea Lamprey Spawning Runs in Lake Superior

Time of migration

The catches at experimental barriers along the south shore of Lake Superior provided considerable information on the sea lamprey spawning migration. Conclusions presented by Applegate (1950) on timing of runs in tributaries to northern Lake Huron are in general agreement with those reached for Lake Superior except for differences attributable to the colder climate in the Superior area. Applegate stated, ". . . water temperature is the best guide as to when migratory activity will begin as well as to fluctuations in its intensity once it has started."

A few sea lampreys, although sporadic in their appearance at the barriers, can be expected as the mean daily water temperatures in streams reach and exceed 40° F. Upstream movement increases considerably after 50° F. is reached, generally during the first or second week of May (Smith, 1962). The intensity of the runs frequently fluctuates during this early period when water temperature and weather generally are variable. Once the waters exceed, and remain above, 50° F., the spawning runs become well established. They usually reach their peak by the end of May or during the first half of June (Table 5).

The runs slowly diminish through the last half of June, and by the end of the first week in July, over 90 percent of the migrants have entered the streams. The termination of the run is not abrupt. Although the numbers are small, almost daily catches can be expected from the larger streams through mid-August. By the end of August, only an occasional straggler appears at the barriers.

The operation of the barriers was generally terminated by the end of August, with the exception of those few streams in which late stragglers were most common. On occasion, individual barriers have been operated until September 19. The latest capture of a sea lamprey at a control device was on September 15.

The use of electric barriers as a method of control calls for awareness of the possible significance of those few individuals within a population that deviate from the rather well defined migratory behavior of the majority. Throughout the period of study, adult sea lampreys have been taken by experimental devices, nets, larvicide, or have been observed in some Lake Superior stream nearly every month of the year.

It was believed originally that sea lampreys entered the mouths of rivers with deep estuaries well in advance of any warming of the river waters, but that their upstream penetration was limited. The number and geographic distribution of the barriers demanded that the devices be activated at the earliest possible time because the period between ice break-up and a temperature rise in stream waters can be exceedingly

Table 6. - Average lengths (inches) and weights (ounces) of sea lampreys (sexes combined) from index streams of Lake Superior, 1953-60

Stream	1953	1954	1955	1956	1957	1958	1959	1960
Betsy River								
Length	...	18.3	17.7	18.0	17.0	16.6	17.0	16.6
Weight	...	...	7.4	7.3	5.7	5.6	6.3	5.5
Sucker River								
Length	...	18.0	17.0	17.7	16.8	16.6	16.8	16.4
Weight	. .	8.0	6.9	7.3	5.6	5.5	5.8	4.9
Au Train River								
Length	17.8	17.7	17.0	17.9	17.1	16.6	17.1	16.5
Weight	...	7.5	6.5	8.0	6.5	5.8	5.9	5.5
Chocolay River								
Length	..	18.1	17.2	18.0	17.0	16.5	16.9	16.2
Weight	.8.0	8.0	6.7	7.1	5.9	5.6	6.0	5.0
Iron River								
Length	. .	17.8	16.5	17.6	16.7	15.9	16.4	16.1
Weight	...	8.0	6.0	6.8	6.0	5.5	6.2	5.3
Silver River								
Length	...	17.9	17.4	17.5	16.7	16.7	16.3	16.1
Weight	...	8.1	7.2	6.6	6.1	5.5	5.7	5.1
Misery River								
Length	...	...	...	...	...	...	...	17.4
Weight	...	...	...	...	...	...	...	5.3
Firesteel River								
Length	...	17.9	17.5	17.5	17.1	16.6	17.6	16.8
Weight	. .	7.9	6.8	6.8	6.1	5.3	6.0	5.1
White River								
Length	...	...	...	18.1	17.0	16.6	16.9	16.1
Weight	...	...	...	7.1	5.7	5.5	5.9	5.0
Brule River								
Length	...	...	...	...	...	16.9	16.9	16.3
Weight	...	...	...	...	...	6.1	5.9	5.4
Middle River								
Length	...	...	...	...	..,	...	...	16.6
Weight	...	...	...	...	...	...	...	5.4
Amnicon River								
Length	...	...	...	...	17.4	17.2	16.7	16.6
Weight	...	...	...	...	6.6	6.1	5.8	5.3
Length all streams								
Inches	17.8	18.1	17.2	17.8	17.0	16.8	16.9	16.4
Millimeters	452	460	437	452	432	427	429	417
Weight all streams								
Ounces	8.0	8.0	6.9	7.2	6.2	5.8	5.9	5.2
Grams	227	227	196	204	175	165	167	148

short. It became routine to install electrodes where practical by cutting openings in the ice. This procedure revealed that sea lampreys, although not numerous, did move considerable distances up some rivers at low water temperatures.

The Huron River device, located approximately 3 stream miles above the mouth, captured 3 adult sea lampreys in 1957 while the river was still ice-covered and the maximum recorded temperature was 33° F. In 1958, 8 adults were taken before the mean daily temperature had exceeded 35° F., and in 1960, 10 were trapped before a mean daily temperature of 34° F. was surpassed. The Chocolay River structure, some 15 stream miles above the river's mouth, took 3 adults in 1957, 9 in 1958, and 2 in 1959 before the mean daily temperature exceeded 37° F.

Length and weight of spawning migrants

One tributary (or more) in each control zone was designated as an index stream. Individuals in the daily catch of sea lampreys, or a representative sample, from each index stream were weighed and measured, and the sex was determined.

Length, weight, and sex data for sea lampreys comprising spawning runs have been reported from populations in Lakes Huron, Michigan and Superior, and in Cayuga Lake (Applegate, 1950; Applegate and Smith, 1950; Applegate *et al.,* 1952; Erkkila et al., 1956; and Wigley, 1959). It could be expected that the average size of lampreys in the relatively new population in Lake Superior would exceed that in the established populations of Lakes Huron and Michigan. It was expected further that as numbers increased, the decline of host fishes or increased competition would bring a decline in the size of sea lampreys. Erkkila et *al.* (1956) stated that as the population increases in Lake Superior, a reduction in their size should become apparent.

Sea lampreys weighed and measured from the catch at the barriers in 1954 had an average length of 18.1 inches (sexes combined) and a mean weight of 8.0 ounces (Table 6). Since 1954, the trend in size, as predicted, has been downward. The average length and weight of animals appearing at the barriers during 1955 were 17.2 inches and 6.9 ounces. Size increased in 1956 to 17.8 inches and 7.2 ounces, but it dropped again in 1957 to 17.0 inches and 6.2 ounces. The decrease of size was small in 1958--0.2 inch in average length and 0.4 ounce in weight (16.8 inches and 5.8 ounces). The change from 1958 to 1959 again was small, 0.1 inch in length and 0.1 ounce in average weight, but the downward trend reappeared in 1960 when as a group, the spawning run had the smallest individuals encountered during the operation of the experimental barriers. The average length and weight of sea lampreys from the 1960 pawning run were 16.4 inches and 5.2 ounces, 1.7 inches shorter and 2.8 ounces lighter than in 1954.

Sex was recorded for all sea lampreys that were weighed or measured. Differences in average length of males and females were not significant (Table 7). The average weight of females consistently exceeded that of males, but by only 0.1 to 0.2 ounce.

Sex ratio

The sex composition of upstream migrants captured at the electric barriers on index streams has been determined each season (Table 8). Erkkila et al. (1956) reported that the spawning run in 1953 included 49.7 percent males and that 58.3 percent were males in 1954.[6] During 5 of the 8 seasons (1954 and 1956-59), the sex composition remained almost constant;

[6] As actually reported the sex ratios were 99 males to 100 females in 1953 and 140 males to 100 females in 1954.

Table 7. - Average lengths and weights by sex of sea lampreys from index streams of Lake Superior, 1954-60

Year	Male			Female		
	Number	Inches and ounces	Millimeters and grams	Number	and ounces	Millimeters and grams
1954						
Length	1,966	18.1	460	1,370	18.0	457
Weight	1,657	7.9	223	1,090	8.1	229
1955						
Length	3,282	17.2	437	2,892	17.3	439
Weight	3,282	6.9	196	2,892	7.0	198
1956						
Length	5,506	17.8	452	4,087	17.8	452
Weight	5,506	7.2	204	4,087	7.2	204
1957						
Length	6,345	17.0	432	4,670	17.1	434
Weight	6,345	6.1	172	4,670	6.3	178
1958						
Length	7,576	16.7	424	5,409	16.8	427
Weight	7,576	5.8	165	5,409	5.9	167
1959						
Length	8,826	16.9	429	6,216	16.9	429
Weight	8,826	5.9	167	6,216	6.0	169
1960						
Length	10,260	16.4	417	4,562	16.4	417
Weight	10,258	5.2	148	4,555	5.3	150

between 57.4 and 58.7 percent of the upstream migrants were males. The percentage of males dropped to 53.1 percent in 1955. The sex composition changed significantly in 1960 when the percentage of males increased to 69.2 percent.

Investigators have indicated that the trend toward an increasing proportion of males among mature sea lampreys may reflect a rising trend in the total population. Applegate (1950) stated that he did not believe a preponderance of males represents a natural sex ratio for the species and supported his contention by reporting a ratio of 79 males to 100 females (44.1 percent males) in a sample from the Sheepscot River in Maine. During 1950 and 1951, a mechanical weir with trap was operated in Pendills Creek, a tributary to Lake Superior (Applegate *et al*. 1952). The small sea lamprey runs (38 in 1950 and 20 in 1951) in this creek were comprised of 52.6 and 52.4 percent males for the 2 years. It was assumed this sex composition was indicative of a rather recently established population.

Sea lampreys in Cayuga Lake, New York, represent a long established fresh-water population. Wigley (1959) determined the sex composition of sea lampreys in the spawning migration in Cayuga Inlet, reviewed the findings of Meek (1889) and Surface (1899), and concluded the annual differences in the sex ratio do reflect changes in the abundance of sea lampreys.

Catches at the electric barriers give no indication of a close relation between sex ratio and abundance of sea lampreys in Lake Superior. The sex composition remained almost constant as the population increased sharply to 1958 and began to decline in 1959. Then in 1960, a further drop in the abundance of sea lampreys was accompanied by a significant increase in the preponderance of males.

Electric barriers also have been operated in streams entering Lake Michigan along its north and west shores. Males were consistently more plentiful than females in spawning runs of this established population. The percentage of males fluctuated from a low of 60.2 percent (1956) to a high of 69.1 percent (1957) from 1954 through 1960. The years with the highest and lowest percentage of males in the spawning runs were at the time when the catch at barriers indicated sea lampreys to be most abundant in Lake Michigan. The percentage of males increased from 1958 through 1960 while numbers of sea lampreys declined.

The causes of changes in the sex composition of the Lake Superior lamprey population are unknown. A preponderance of males conceivably may be characteristic of the species in a fresh-water environment.

Table 8. - Percentage of males from index streams on Lake Superior, 1953-60

[Number of sea lampreys in parentheses.1

Stream	1953	1954	1955	1956	1957	1958	1959	1960
Betsy River	50.3 (221)	52.2 (567)	55.6 (569)	58.8 (1,577)	58.5 (786)	59.0 (1,092)	56.7 (1,006)	65.9 (705)
Sucker River	49.5 (750)	57.8 (1,309)	50.5 (1,713)	50.5 (4,400)	61.5 (3,597)	57.8 (1,842)	55.9 (2,522)	68.5 (4,980)
Au Train River	56.1 (204)	56.3 (350)	53.3 (486)	64.8 (613)	58.2 (739)	51.7 (348)	64.4 (168)	68.4 (80)
Chocolay River	. . . . . .	66.8 (1,227)	54.8 (3,350)	59.5 (6,888)	57.4 (8,096)	55.2 (6,221)	56.1 (3,500)	72.2 (4,216)
Iron River	. . . . . .	57.8 (67)	56.7 (206)	57.3 (335)	55.8 (737)	52.4 (428)	58.3 (266)	72.5 (342)
Silver River	. . . . . .	51.0 (247)	51.9 (786)	52.8 (963)	52.6 (2,810)	53.1 (2,152)	54.1 (878)	64.9 (1,386)
Misery River	. . . . . .	. . . . . .	. . . (183)	. . . (571)	. . . (868)	(896)	. . . (2,581)	70.1 (761)
Firesteel River	. . . . . .	54.3 (60)	49.2 (150)	48.5 (229)	52.6 (1,039)	53.9 (1,546)	62.3 (2,084)	60.8 (276)

Table 8. - Continued

Stream	1953	1954	1955	1956	1957	1958	1959	1960
White River	...	...	...	54.5	55.2	63.5	65.8	69.1
	...	...	...	(219)	(412)	(231)	(552)	(233)
Brule River	...	...	...	...	...	60.5	61.1	70.8
	...	...	...	...	...	(22,842)	(19,389)	(9,755)
Middle River	...	...	...	...	...		..	68.8
	...	...	...	...	(4,289)	(4,853)	(3,645)	(2,839)
Amnicon River	...	...	...	...	59.8	61.4	55.9	65.8
	...	...	...	...	(11,055)	(7,670)	(986)	(1,165)
All streams	49.7	58.3	53.1	57.4	57.6	58.3	58.7	69.2

Fish at the Electric Barriers

Species taken and their abundance

Large numbers of fish appeared at the barriers. Each individual entering the traps was identified and released. Those dead in the electric fields or below the weirs also were identified and removed. Before a list of names of the 62 species and a broad classification as to abundance is offered, certain factors affecting the catches should be reviewed briefly.

Principal factors in the numbers of each species taken at weirs were the actual abundance in the lake, the habitat preferences, and the migratory habits. Restricted geographic distribution along the lake shore influenced the catches of a few species and some fish that attain a small maximum size escaped the traps in large numbers. Examples of these influences illustrate the situation.

Such fish as bowfin and American eel are extremely scarce in Lake Superior and some species as lake sturgeon, muskellunge, carp, and largemouth bass, though taken more frequently, never appeared in large numbers. From these species that clearly are rare or uncommon, the gradation passes through such classifications as uncommon, common . . . to highly abundant.

Habitat preferences of different species limit the interpretation of catches at weirs in terms of true abundance. The most plentiful commercial species of Lake Superior, the lake herring, was rare in the catches and the widely distributed round whitefish was caught only sporadically. Other common to abundant fish were not taken and would not be expected at the barriers. Among them may be listed: lake whitefish (Coregonus clupeaformis), deepwater ciscoes (Coregonus spp.), pygmy whitefish *(Prosopium coulteri),* and fourhorn sculpin *(Myoxocephalus quadricornis).* Catches of many, if not most, species at barriers were influenced in some measure by habitat preference but we are not in position to judge the effects accurately.

Species that moved upstream to spawn during the period of barrier operation were taken in substantial to enormous numbers. Among them may be mentioned smelt, longnose sucker, white sucker, trout-perch, rainbow trout, and, of course, the sea lamprey. If only part of the spawning period coincides with barrier operations (as with rainbow trout), the catch is reduced accordingly.

Among the fish that should have been caught in larger numbers except for restricted geographical distribution are American brook lamprey taken only in eastern Lake Superior and stonecat and tadpole madtom captured only in Wisconsin streams.

Species that would have been captured in greater numbers except for their small size include many of the minnows, Iowa darter, Johnny darter, logperch, brook stickleback, and the two nonparasitic native lampreys.

Even though numbers taken at barriers cannot be interpreted closely in terms of the actual abundance of species some classification of fishes in terms of catch still seems desirable. The following listing of species is divided into broad categories ranging from "highly abundant" to "rare." The accompanying comments should aid in the understanding of the records.

<u>Highly abundant</u> - catch exceeded 10,000 for 1 or more seasons

American smelt *(Osmerus mordax)*	Caught in vast numbers, but rare or lacking in some streams.
Longnose sucker *(Catostomus Catostomus)*	Widespread and extremely abundant; catches seriously limited by capacity of traps; immature fish absent except in the Brule River.
White sucker *(Catostomus commersoni)*	Widespreadbut less abundant than longnose suckers; catch also limited by capacity of traps; immature individuals common with spawning migrants.
Trout-perch *(Percopsis omiscomaycus)*	Widespread but numbers fluctuated widely; most abundant in streams of zones S-5, 6, and 7.
Sea lamprey *(Petromyzon marinus)*	The barrier operation covered a period during which the take of sea lampreys rose from less than 2,000 in 1953 to nearly 67,000 in 1958.

<u>Abundant</u> - catch exceeded 5,000 for 1 or more seasons

Common shiner *(Notropis cornutus)*	Widespread, but most abundant inwestern streams; common in the larger eastern streams.
Longnose dace *(Rhinichthys cataractae)*	Taken at all barriers; since they could not be retained easily by the traps, they probably were more abundant than catches indicated.

Logperch *(Percina caprodes)*	Widespread; this species also could not be retained efficiently by the traps.
Rainbow trout *(Salmo gairdneri)*	Widespread; classified as abundant when migratory adults are combined with young or immature fish; barrier operation did not cover entire migratory period; annual catch of spawning migrants varied from 1,500 to 2,200.
Lake chub *(Hybopsis plumbea)*	Uncommon in tributaries to eastern Lake Superior, but abundant in Wisconsin streams.
Brown bullhead *(Ictalurus nebulosus)*	Widespread; the catch fluctuated widely but the year-to-year trend was toward increased numbers and an increasednumber of streams.

Plentiful - catch exceeded 2,000 for 1 or more seasons

Mottled sculpin *(Cottus bairdi)*	Commonthroughout the area.
Silver lamprey *(Ichthyomyzon unicuspis)*	Widely distributed; not taken in large numbers at any 1 barrier.
Creek chub *(Semotilus atromaculatus)*	Present at most barriers, but greatest catches were from the larger streams.
Rock bass *(Ambloplites rupestris)*	Common to many streams throughout the area.
Brook trout *(Salvelinus fontinalis)*	Taken at nearly all barriers; most common in the catches from the Keweenaw Peninsula eastward.
Brown trout *(Salmo trutta)*	Recorded from many streams; most common in Wisconsin waters; strong spawning migration in the Brule River; seasonal termination of barrier operations coincident with beginning of run, possibly is the reason spawning runs were not detected in other streams.
Stonecat *(Noturus flavus)*	Catches restricted to barriers in Wisconsin streams.

Northern redhorse *(Moxostoma macrolepidotum)*	Limited to the larger rivers; generally deep and sluggish; majority of catch from the Bad and Sturgeon Rivers.

Common - catch exceeded 500 for 1 or more seasons

Northern brook lamprey *(Ichthyomyzon fossor)*	Not retained well by the traps; most abundant west of Marquette.
Black bullhead *(Ictalurus melas)*	Widespread; most common in streams of western Lake Superior.
Yellow perch *(Perca flavescens)*	Represented at many of the barriers; most numerous in streams with lakes in their systems.
Golden shiner *(Notemigonus crysoleucas)*	Scatteredthroughout the area covered by the barriers; largest catches at the Brule and Nemadji Rivers.
Burbot *(Lota lota)*	Widespread; catch consisted principally of small or immature fish.
Johnny darter *(Etheostoma nigrum)*	Common and undoubtedly abundant in most streams with barriers, but too small to be retained effectively by the traps.

Uncommon - catch less than 500 individuals per season

Brook stickleback *(Eucalia inconstans)*	Too small to be retained efficiently by the traps; taken in small numbers throughout the area.
American brook lamprey *(Lampetra lamottei)*	Too small to be retained effectively by the traps; recorded only at barriers of eastern Lake Superior.
Northern pike *(Esox lucius)*	Taken at most barriers, but not in large numbers.
Walleye *(Stizostedion vitreum vitreum)*	Caught in numbers comparable to northern pike, but at fewer barriers; generally from larger rivers.
Slimy sculpin *(Cottus cognatus)*	Widespread; most common in the colder streams.

Central mudminnow *(Umbra* limi)	Widespread; recorded at many of the barriers.
Hornyhead chub *(Hybopsis biguttata)*	Most common at barriers west of the Keweenaw Peninsula.
Smallmouth bass *(Micropterus dolomieui)*	Widely distributed; not taken in large numbers at any 1 barrier.

Sporadic - most of the catch at 1 or 2 barriers

Pumpkinseed *(Lepomis gibbosus)*	Taken in small numbers at several barriers, except for Chocolay River where catch has exceeded 5,000 in 1 season.
Round whitefish *(Prosopium cylindraceum)*	Up to 560 individuals from Two Hearted River in 1 season.
Black crappie *(Pomoxis nigromaculatus)*	Common in Sturgeon River up to 643 in 1 year; occasionally taken from 4 Wisconsin streams.
Spottail shiner *(Notropis hudsonius)*	Large catches from Beaver Lake Outlet.
Ninespine stickleback *(Pungitius pungitius)*	Taken in large numbers from 1 or 2 streams, but not every year.

Rare - annual catch varied from none to less than 60 per season

Bluegill *(Lepomis macrochirus)*	Five to 57 per season; widely distributed.
Northern redbelly dace *(Chrosomus eos)*	Maximum catch for 1 season was 55; recorded only from barriers on Michigan streams; too small to be retained well by the traps.
Silver redhorse *(Moxostoma anisurum)*	Recorded at the barriers in the larger deep, and sluggish rivers.
Blacknose dace *(Rhinichthys atratulus)*	Up to 54 recorded in 1 season; many undoubtedly escaped the traps.
Pearl dace *(Semotilus margarita)*	Too small to be retained efficiently by the traps; maximum number recorded for 1 season, 39.

Muskellunge *(Esox masquinongy)*	Maximum catch for 1 season, 35; confined principally to Wisconsin streams.
Alewife *(Alosa pseudoharengus)*	Rarely taken at the barriers although numbers appear to be increasing in Lake Superior; largest catch, 29 individuals from the Silver River in 1960.
Largemouth bass *(Micropterus salmoides)*	From 2 to 16 per season from scattered barriers.
Brassy minnow *(Hybognathus hankinsoni)*	Although reported throughout the area, taken only at barriers in Michigan waters.
Fathead minnow *(Pimephales promelas)*	Catch from none to 11 per season.
Finescale dace *(Chrosomus neogaeus)*	Although reported as present in Wisconsin streams, taken only from Michigan waters; maximum catch for 1 season, 10.
Tadpole madtom *(Noturus gyrinus)*	A maximum of 8 individuals for 1 season from barriers on 2 Wisconsin streams.
Emerald shiner *(Notropis atherinoides)*	Common along the shores of Lake Superior, but rarely taken; captured at only 3 barriers.
Carp (Cyprinus *carpio)*	Catch, none to 6 individuals per year; recorded from several streams throughout the area.
Lake herring *(Coregonus artedi)*	From 1 to 5 per year; generally from the larger rivers.
Iowa darter *(Etheostoma exile)*	From none to 5 per season from eastern barriers; too small to be retained effectively by the traps.
Blacknose shiner *(Notropis heterolepis)*	Maximum of 4 individuals in 1 season, but reportedly widespread; taken only from eastern streams.
Sand shiner *(Notropis stramineus)*	Maximum of 4 in 1 season.
Bluntnose minnow *(Pimephales notatus)*	Only an occasional specimen takenfrom the larger rivers.

Lake sturgeon *(Acipenser fulvescens)*	Relatively scarce in Lake Superior; taken in 2 streams; individuals also observed that were too large to enter the traps.
Lake trout *(Salvelinus namaycush)*	Small or immature fish taken from 2 streams, both of which have fish cultural stations.
Mimic shiner *(Notropis volucellus)*	Maximum of 2 in 1 season; too small to be retained well by the traps.
Bowfin *(Amia calva)*	Rare in Lake Superior; 1 specimen from the Middle River, June 1, 1960.
American eel *(Anguilla rostrata)*	One specimen from Beaver Lake Outlet, 1957.

Susceptibility of species to electric fields

The alternating-current electric fields were capable of inflicting heavy mortality upon all species of fish. Size and habits influenced the extent of mortality of a given species of fish at a barrier. It also became apparent that certain species were less susceptible than others to the electric current. outstandingly resistant were bullheads. Yellow perch, rock bass, and pumpkinseeds also had a very light kill.

The large size of the spawning white suckers, longnose suckers, and rainbow trout made them more susceptible to injury or death from the electric fields. The suckers occurred in such large numbers that even a small percentage mortality of the total could give several hundred dead individuals. Rainbow trout, like the suckers, also were killed easily by the alternating current. Even though mature rainbow trout appeared at the barriers in comparatively small numbers, they are so highly esteemed by sport fishermen that their mortality created a public-relations problem.

Few of the other species offered difficulties except in isolated situations or at particular devices. Smelt, which appeared in extremely large numbers some seasons, caused little trouble. The high water of the period of the smelt run produces water velocities favorable for the survival of smelt.

Some data were obtained on the mortality of fish returning downstream through the barriers after spawning. At a number of the control devices all rainbow trout, longnose suckers, and white suckers were marked by clipping a portion of a fin before they were released upstream. This mark permitted easy identification of fish killed while moving back downstream. Mortality of fish on their return toward the lake varied from stream to stream but generally was low. In only 1 river did the kill reach 10 percent of the total number released above the barrier.

The number of marked fish killed during downstream movement did make a significant contribution to the total mortality at some of the barriers - as much as 33.0 to 62.5 percent. High water velocity lessened mortality of fish moving down through the barriers.

Measures to decrease mortality of fish

Considerable effort was put forth continually to reduce mortality. The installation of direct-current diversion devices on “problem” streams, improvements of traps, installation of abutments, and other modifications to barriers contributed to a steady reduction in the number of fish killed. Mortality of white suckers in 1955 was 55.7 percent of the total number handled. The percentage of kill was gradually reduced to 17.1 percent by 1960 (Fig. 2). Mortality among longnose suckers dropped from 32.5 percent in 1955 to 13.6 percent in 1960, and for mature rainbow trout the kill dropped from 51.8 to 18.8 percent. The actual mortality was smaller as many live fish remained below the barriers and hence were not “handled.”

The operation of the electric barrier on the Brule River in 1960 offers an outstanding example of low mortality with a device having a lethal potential. Some 98,800 fish, including sea lampreys, were trapped but only 392 were killed (Table 9).

Frequently the traps became full of suckers so that large numbers were held in the stream below the barriers. The possible effect of this delay has not been determined. Usually, suitable spawning habitat existed downstream from the barrier. Blockage at the barriers at times did cause heavy spawning in a limited length of stream. No indication of any change in species composition or relative abundance of different species has been detected, however, as a result of the barriers. Annual fluctuations in numbers of rainbow trout, longnose suckers, and white suckers have been without trend over a 7-year period (Table 10).

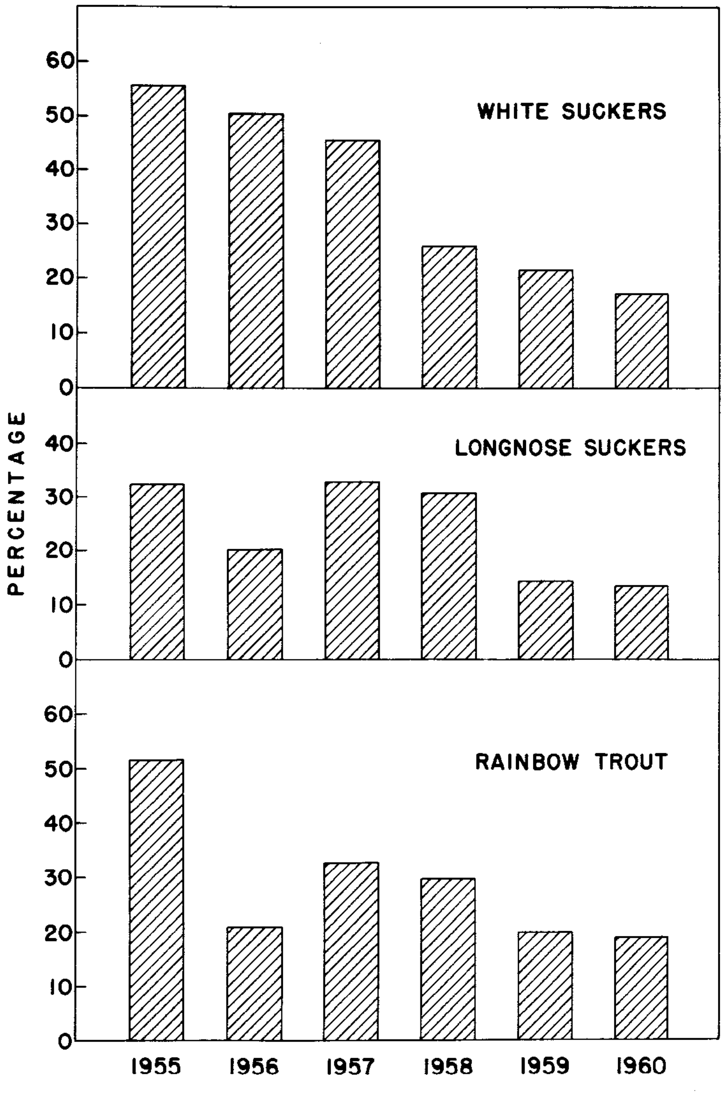

Figure 2. - Percentage mortality of white suckers, longnose suckers, and rainbow trout expressed in terms of numbers handled at the electric barriers, 1955-60.

Table S.-Total number of sea lampreys and fish trapped and electrocuted in the Brule River, 1960

	Number trapped	Number electrocuted
Sea lamprey	9,712	43
Silver lamprey	149	0
Rainbow trout (large) [1]	75	17
Rainbow trout (small)	278	1
Brown trout (large)[1].	232	45
Brown trout (small)	322	2
Brook trout	2	0
American smelt	72,000’	150
White sucker (large) [3].	1,054	10
White sucker (small)	1,057	3
Longnose sucker	11,073	113
Northern redhorse	10	3
Golden shiner	177	0
Creek chub	315	2
Common shiner	239	0
Spottail shiner	6	0
Lake chub	1,076	0
Hornyhead chub	1	0
Longnose dace	11	0
Black bullhead	84	0
Stonecat	273	1
Northern pike	19	0
Burbot	7	0
Trout-perch	270	1
Yellow perch	307	0
Walleye	13	0
Logperch	3	0
Johnny darter	2	0
Smallmouth bass	1	1
Pumpkinseed	1	0
Rock bass	6	0
Mottled sculpin	34	0
Unidentified	5	0
Total	98,814	392

[1]Over 12 inches, total length.

2 Estimated catch.

[3]Over 9 inches, total length.

Table 10. - Total number of rainbow trout,[1] white suckers, and longnose suckers handled at control barriers in 9 Lake Superior streams over a 7-year period, 1954-60

Stream	1954	1955	1956	1957	1958	1959	1960
Two Hearted River							
Rainbow trout	80	77	152	274	205	380	208
White suckers	1,375	831	3,705	2,245	2,336	2,341	718
Longnose suckers	1,860	527	2,128	2,076	2,641	2,366	934
Sucker River							
Rainbow trout	22	59	36	31	64	64	175
White suckers	468	1,247	1,258	291	1,474	2,302	2,776
Longnose suckers	36	86	179	217	276	222	548
Hurricane River							
Rainbow trout	24	235	387	311	131	199	269
White suckers	0	3	0	0	0	0	0
Longnose suckers	17	174	11	24	0	0	0
Miners River							
Rainbow trout	10	56	144	94	40	105	83
White suckers	176	156	135	343	79	942	592
Longnose suckers	265	795	419	581	7	486	517
Laughing Whitefish River							
Rainbow trout	12	39	71	68	43	23	19
White suckers	265	152	489	146	591	452	262
Longnose suckers	1,333	446	4,695	3,517	3,456	834	1,710
Chocolay River[2]							
Rainbow trout	46	86	126	62	40	24	13
White suckers	3,126	694	2,050	1,934	3,076	3,165	1,845
Longnose suckers	26,023	4,034	5,389	4,943	3,812	5,611	2,712
Huron River							
Rainbow trout	20	36	146	219	413	623	245
White suckers	285	546	697	1,185	3,272	3,915	1,803
Longnose suckers	3,098	2,275	5,669	8,269	10,164	9,276	5,992
Silver River							
Rainbow trout	10	30	55	64	87	40	21
White suckers	6,420	3,349	4,981	3,172	5,770	4,778	3,748
Longnose suckers	143	136	77	135	150	43	71
Firesteel River							
Rainbow trout	5	17	21	28	25	43	45
White suckers	642	1,273	1,439	2,028	3,737	4,776	3,567
Longnose suckers	1,525	1,944	3,624	3,873	2,826	6,733	3,432

1 Over 12 inches, total length.

2 A mechanical device was operated on the Chocolay River in 1954. The trap was emptied more frequently than is done at any of the electric devices. It is believed that the frequent cleaning of the trap accounted for the large number of fish handled that year.

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Electrode array for the D.C. diversion device in the Two Hearted River, Luce County, Michigan. The array joins the lead to a trap located at the abutment on the far side of the river. The suspended electrodes of the A.C. barrier can be seen to the left (upstream) of the D.C. array.

Effectiveness of the Experimental Barriers

The potential effectiveness of the experimental electric barriers for the control of the sea lamprey cannot be evaluated accurately. Some streams used by the sea lampreys for spawning on both the Canadian and U.S. sides of Lake Superior lacked barriers. Most of the barriers were not operated through enough seasons to be expected to reduce the numbers of adults. Improvement of the efficiency of some of the control devices was slow because of limited experience during the early years of operation.

The exact number of years barriers must be operated and the necessary level of efficiency required to effect a suppression in numbers of sea lampreys are unknown. Investigators have estimated the duration of larval life from 41 months to 7 years or more (Gage, 1928; Applegate, 1950; Wigley, 1959; and Stauffer, 1962). Data from growth studies of populations reestablished after chemical treatments and observations of an isolated known-age group have provided a reliable means of separating the first 2 age groups. In some rivers, the third age group is distinguishable but larger ammocetes cannot be grouped by age. Early data from the known-age ammocetes definitely indicate the larval stage will exceed 4 years from the date of hatching.

It is clear, nevertheless, that under the proper conditions electric barriers of the type and design used are capable of blocking entire runs of adult sea lampreys. The data from 2 streams can serve as examples of evidence on this point. The Brule River had the largest known sea lamprey run on the U.S. side of Lake Superior. Its barrier was first operated during the 1958 migratory season. The river was chemically treated in April, 1959. Members of the 1958 year class were lacking in the larval collections. The Fish Creek device was first operated in 1957. This stream also was treated in the spring of 1959. Both the 1957 and 1958 year classes were missing. Similar observations on other streams gave further evidence of effectiveness. In still others the presence of ammocetes of all sizes after years of barrier operation proved the need for additional improvements of function.

Continued experience with the barriers assuredly would have carried the efficiency to a much higher level than was achieved through 1960, but the rare mechanical breakdown, the occasional excessive flood, and upstream movement of a few spawners before barriers could be activated still would have kept the method short of perfection.

Summary and Conclusions

The threat of total destruction to the last remaining natural stocks of lake trout in the upper Great Lakes demanded an effort to control the sea lamprey in Lake Superior with the least possible delay. The electric barriers as developed in streams tributary to Lakes Huron and Michigan offered the only known, economically feasible tool available when the program started. The method's most serious weakness lay in the number of years the barriers needed to be operated before benefit could be expected. Each generation already present in the streams as ammocetes had to reach the age of transformation and go through the parasitic stage before it became susceptible to control.

The failure of sea lampreys to use all streams that apparently offer suitable spawning conditions[7] made the control attempt practical. An undesirable situation was created by the fact that shortages of funds stretched the period of installation over several years and forced delay in the installation of a barrier in a particular stream until the use of that stream by lampreys was definitely established.

A further difficulty lay in the unavoidable slowness in recognizing the inefficiencies of the original devices, and the time required to gain the knowledge and experience to redesign, modify, and improve the barriers to make them function properly in a wide variety of conditions.

The need to protect fish at the barriers contributed to some inefficiency. Nearly all fish species were more susceptible to injury or death than were sea lampreys. Far too often, the intensities of the electric fields were maintained at an undesirably low level to reduce the mortality of fish.

The great length of the Lake Superior south shore, the poor condition of many roads, problems of access, and a shortage of trained personnel also contributed to the time required to overcome some deficiencies of barriers and barrier operation.

The catch of sea lampreys increased rapidly from 1953 to 1958. The numbers of adults dropped substantially in 1959 and again in 1960. Although the barriers may have contributed to the 1959-60 decreases, they can not be given major credit for the reduction in numbers of sea lampreys. Not all streams were blocked and many of the barriers had not been operated

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[7] As late as the end of 1962, sea lampreys were known to inhabit only 71 streams tributary to the U.S. waters of Lake Superior.

for a sufficient number of years to end production of parasites by the streams. Many which had been in operation for several seasons were ineffective during the earlier years. It is doubtful, therefore, that a sufficient level of efficiency had been reached in time to have contributed greatly to the decrease in numbers in 1959 and 1960.

The experimental attempt to suppress numbers of sea lampreys in Lake Superior with electricity was terminated at the end of the 1960 season. An exact answer to its possible ultimate effectiveness will remain unknown. The operation did make significant contributions to knowledge and provide some important conclusions. The most obvious are:

1. It is possible to block the upstream migration of sea lampreys or fish with electric barriers of the design and type developed and used.

2. The electric barriers are subject to mechanical failures or breakdowns. Although the frequency of interruptions of operation can be reduced greatly, some escapement is to be anticipated each season at 1 or more barriers in a system.

3. Because the method of control requires continuous operation over a number of years, the opportunity for inefficiency as the result of abnormal conditions is increased accordingly.

4. Some reproduction, although possible minor, could occur from the few migrants that move upstream before it is possible to activate the barriers in the spring.

5. The electric barriers provided considerable information on sea lamprey runs and populations of lampreys and other fishes in the waters of Lake Superior. Valuable data also were collected on temperature, stream discharge, and other biological, ecological, and physical characteristics of streams tributary to Lake Superior. Information accumulated during the operation was most useful in the application of the selective larvicide.

6. The electric barriers prevented the establishment of ammocete populations in some streams and limited the size of ammocete populations in others. The chance for success in the initial chemical treatments was increased correspondingly.

7. Development and use of electricity for sea lamprey control contributed to knowledge of methods and techniques in the use of electro-fishing gear in fishery management and research.

8. The electric barriers assumed a new importance when their use for experimental control was terminated. The devices became the principal means for the evaluation of the results of the chemical control.

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