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Scope and Method of Study: This report has been undertaken as a brief survey of the sea lamprey situation that has existed in the upper Great Lakes for the last four decades. A brief history of the invasion into the upper lakes is presented, along with the economic problems created by this invasion. The identification and life history of sea lampreys are discussed in detail because control methods are band upon certain characteristics of the life cycle. Control methods are traced from the basic underlying concepts, through the various stages of experimentation and application, to and including the results of each. The literature surveyed in this study included: scientific reports of governmental agencies, articles from scientific and conservation journals, and biological textbooks.

Findings and Conclusions: Sea Lampreys gained access to the upper Great Lakes via the Welland Canal after its completion in 1829, although they were not actually observed in these lakes for nearly 100 years. During the time they have been in the upper lakes, these parasites have virtually eliminated the lake trout populations, which resulted in over five million dollars lost annually to the fishing industry. Control methods, which have met with varying degrees of success, are based upon certain characteristics of their rather complicated life history. Of the three major controls attempted, that which is aimed at destruction of the larval phase has been most successful.

Low concentrations of a selective chemical, the sodium salt of 3-trifluormethyl-4-nitrophenol, kill the lamprey larvae in the streams which they inhabit, but do not harm the other forms of life. A large scale treatment program of the Lake Superior drainage was completed in 1960. About one-half of Lake Michigan's tributaries have been treated with completion of the program expected by 1966. Preliminary, pre-treatment surveys have been completed for Lake Huron. Preliminary results indicate that the Lake Superior program has been at least partially successful. At present trends the trout population is expected to regain its previous proportions in a few years. Periodic application of the larvicide is expected to keep the lamprey population under control.

ADVISER'S APPROVAL L. Herbert Bruneau

A SURVEY OF SEA LAMPREY STATUS AND CONTROL IN THE GREAT LAKES

By

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A SURVEY OF SEA LAMPREY STATUS AND

CONTROL IN THE GREAT LAKES

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PREFACE

Sea lampreys, present in the upper Great Lakes for approximately forty years, have practically eliminated the lake trout populations once so prevalent there. This has resulted in the virtual destruction of the multimillion dollar fishing industry of the region. The purpose of this paper is to investigate the economic problem posed by this situation; the methods of controlling sea lampreys, which is the only feasible solution to the problem; and the biological characteristics of lampreys upon which the control methods were based.

In presenting the life history of lampreys, I include not only the various stages of the life cycle, but also the activities and environmental requirements of each stage. This is done in an effort to illustrate the close relationship that exists between lampreys and the other forms of life in a habitat. This proximity proved to be a major factor when trying to develop control methods which would isolate and eliminate lampreys without seriously affecting other forms.

In the discussion of control methods, an effort is made to point out the basic concept upon which the control was based. Also, the success or failure of each control is discussed as well as the method involved.

I wish to acknowledge Dr. L. H. Bruneau for his assistance in the preparation of this paper.

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CHAPTER I

INTRODUCTION

Much concern has been aroused regarding the future of commercial and sport fishing in the upper Great Lakes due to the recent appearance and rapid population rise of the parasitic sea lamprey, *Petromyzon marinus*.

Although a newcomer to the upper Great Lakes, the sea lamprey is no stranger to Lake Ontario or the waters of the North Atlantic. Since it is primarily a marine species that enters fresh water to spawn, it probably occurred in the St. Lawrence Sea (now Lake Ontario) at the close of the last ice age some 9000 years ago. As the ice cap retreated and the weight of ice decreased, the earth's crust bulged upward cutting off the Lake Ontario basin from the Atlantic Ocean. As the water in the basin slowly became fresh, it is likely that the sea lampreys adapted to a completely fresh water life cycle (Baldwin, 1963). Here they became well established and flourished for centuries, their migration to the upper Great Lakes being blocked by Niagara Falls.

With the completion of the Welland Canal in 1829, the route for sea lamprey migration into Lake Erie and the other Great Lakes was unwittingly opened. Conditions, however, were evidently not satisfactory for passage until the canal was deepened (1913 - 1918), as the first lamprey was not taken from Lake Erie until 1921.

Sea lampreys, although present in Lake Erie longer than in the upper lakes, have not become well established there. This would appear strange at first, since the western end of that lake produces more pounds of fish annually than any other area of equal size in the Great Lakes, thus insuring an adequate food supply for the parasites (Trautman, 1949). However, the lake is warm, comparatively shallow, and the feeder streams are silt - laden or have impassable barriers near their mouths. These are conditions which are not conducive to lamprey establishment.

Although Lake Erie did not support a thriving lamprey population, it did provide a link to the upper Great Lakes for lamprey invasion. By the 1930's they had become firmly established in Lakes Huron and Michigan where the food supply and water conditions were ideal for growth and survival. They then moved toward Lake Superior. The dam and navigation locks at the head of St. Mary's River slowed the rate of invasion, but enough lampreys arrived in the lake to establish a rapidly growing population. In 1946 the first specimens were taken from the lake off Isle Royale and Whitefish Point (Dees, 1960).

CHAPTER II

ECONOMIC FACTORS

With the establishment of sea lamprey populations in the Great Lakes, the trout fishing industry began a rapid decline and eventual collapse in Lakes Michigan and Huron.

Lampreys prefer a diet of the large, tasty lake trout. Thus the trout industry was the first to feel the effects of the invasion. However, in the absence of an adequate trout supply they will attack other larger species such as the chubs and whitefish. For this reason the entire Great Lakes fishing industry has suffered a drastic decline.

Since lake trout supplied the bulk of commercial fishing, most estimates of losses are concerned only with this species. Lennon (1954) stated that the trout catch from Lakes Michigan and Huron dropped from 8,600,000 pounds to 26,000 pounds per year in ten years. Lake Superior yielded 4,500,000 pounds in 1948, but only a few hundred thousand pounds in 1961 (Burrows, 1963). Baldwin (1963) claimed that the three upper lakes produced 14,800,000 pounds per year during the 1930's, but only 500,000 pounds in 1961. According to Moffett (1956) the entire industry suffered an 11,000,000 pound per year loss totaling 5.5 million dollars annually. Dees (1960) stated that Lakes Michigan and Huron produced 5,000,000 pounds per year from 1930 to 1939, but only 500,000 pounds in 1950. Probably the most accurate summary of year by year and overall losses in each lake is presented in Figure 1, page 4.

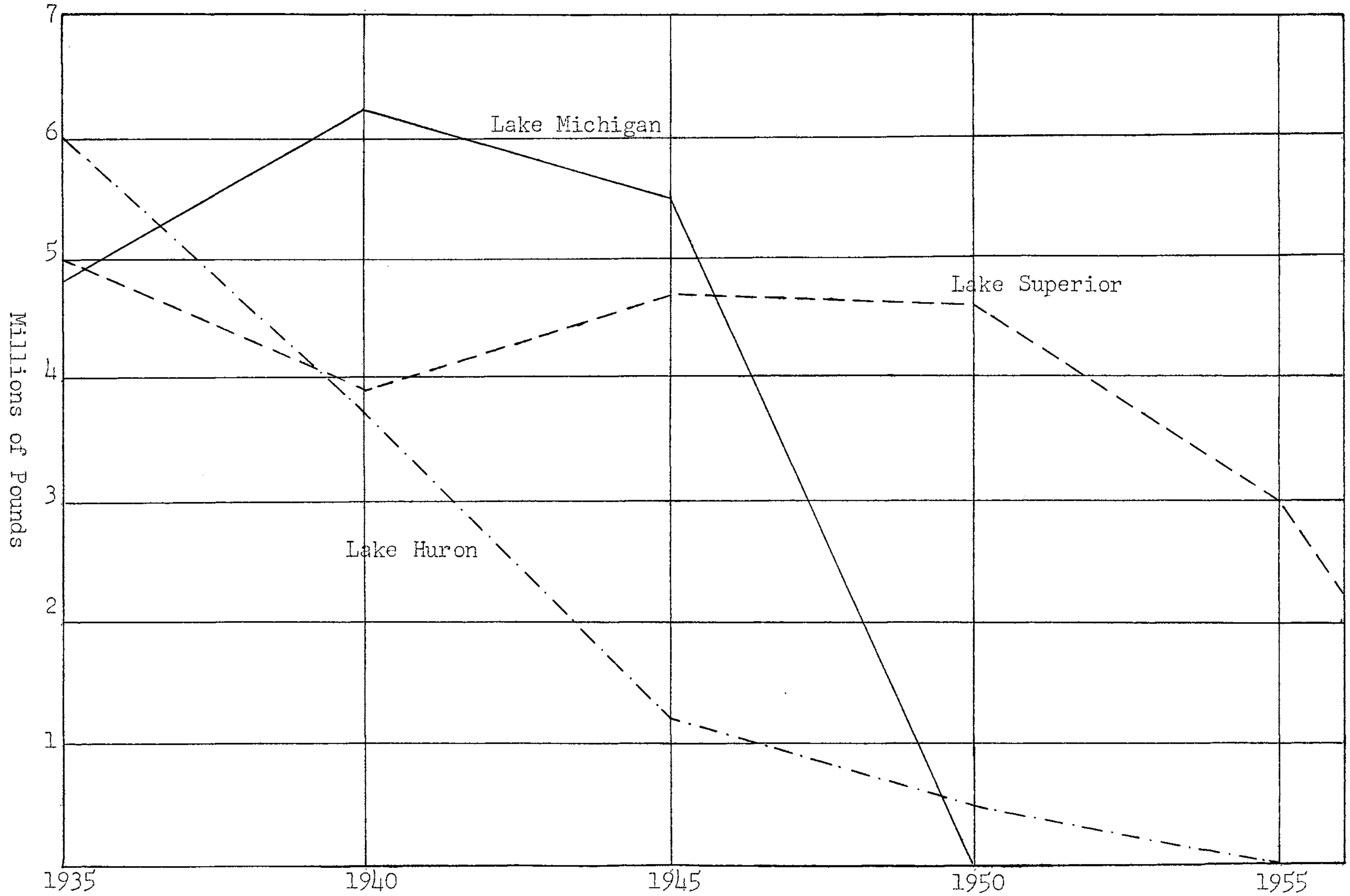

Fig. 1. Great Lakes production of lake trout (Mc Veigh, 1958).

The losses to sport fisheries and related trades, though also very great, cannot be estimated (Dees, 1960).

The above figures indicate that the lamprey has virtually eliminated a multimillion dollar industry. The solution to this economic dilemma seemed to lie in either an elimination of the sea lamprey, or replacing the fishing industry with a lamprey industry by finding some utility for the parasite.

The latter alternative has been investigated, but to no avail. Though lampreys are considered table delicacies in some European countries (Trautman, 1949) they are not palatable to the American public. Applegate (1950) stated that lamprey flesh, either smoked or freshly cooked, has unappetizing black streaks through it, is soft or mushy in texture, and gives off an acrid, unpleasant odor not unlike that of a decaying lamprey.

Reduction of lamprey flesh to meal and oil has been investigated, but is not economically feasible. According to Applegate (1950), whole lamprey would have to sell at $1.40 per pound to offset the cost of capture. Additional expenses of processing, handling, and transporting would make the retail cost of such meal or oil very prohibitive.

Other possible uses of lampreys are for sale as fish bait and for sale to biological supply houses. Both of these avenues are extremely limited, and could hardly compensate for the collapse of a multi-million dollar fishing industry.

From the above facts, one could conclude that the only recourse available was the elimination or control of the sea lampreys and the eventual reestablishment of the trout population. To accomplish this a thorough knowledge of the identification and life history of the adversary was required.

CHAPTER III

IDENTIFICATION OF THE SEA LAMPREY

General Characteristics

Both marine and fresh water lampreys belong, according to Romer (1962), to the vertebrate class Agnatha. Representatives of this class lack true jaws and paired appendages; possess a single, median nostril; and all living species possess a round mouth (Weichert, 1959).

The only living species of this class are found in order Cyclostomata, which encompasses only the lampreys and hagfishes (Romer 1962). The cyclostomes have round, eellike bodies with laterally compressed tails; completely cartilagenous skeletons; median fins; and soft, scaleless skins (Weichert, 1959).

Lampreys, not to be confused with eels which are true fishes, can be distinguished from hagfishes by several characteristics. The hagfish mouth is located in a near-terminal position, whereas the lamprey mouth is ventrally located. The hagfish mouth has paired tentacles about its margin, but the lamprey mouth has no tentacles. The hagfishes, in some species, have only a single pair of external gill openings. In other species, the gill openings vary from six to fourteen pairs. In all hagfishes the gills are removed some distance back from the head region. All lampreys possess seven pairs of external gill openings located close to the head (Weichert 1959).

The lamprey gill openings "are not slits, as in typical fishes, but spherical pouches connected by narrower tubes with gut and body surface" (Romer, 1962). The gill openings are designed so that water enters and exits via these. Thus, the mouth does not function in respiration, but can be attached indefinitely to the animal's prey.

Species Identification

Characteristically, all lampreys pass through a metamorphasis in their life cycle. Therefore, all of the five species found in the Great Lakes and their tributaries exhibit a larval form and an adult form. Species identification of the larvae is very difficult, thus positive identification requires examination of the adult.

Of the five species mentioned above, four are native to the waters. The sea lamprey is the only exotic species. Two of these five species (the American brook lamprey and the Michigan brook lamprey) are non - parasitic. They attain a length of six to eight inches, and may be distinguished by their small, degenerate mouths and mouth parts. The two native parasitic lampreys (the chestnut lamprey and the silver lamprey) attain a length of six to fourteen inches, and may be distinguished from their non - parasitic relatives by their large, functional mouths and mouth parts.

The sea lamprey is the largest of the lampreys found in the Great Lakes, and may attain a length of 30 inches. The horny, sucking mouth and mouth parts, and the notched dorsal fin serve to identify this parasite. The American brook lamprey also has a notched dorsal fin, but the adult size difference precludes false identification of either (Brasch, 1950).

The native lampreys have been in these waters probably since glacial periods without causing apparent harm. Therefore, the recent degradation of fish populations can safely be attributed to the activities of the sea lamprey.

CHAPTER IV

LIFE HISTORY

Egg and Larval Stage

The actual spawning activities of the sexually mature sea lampreys will be discussed in the spawning phase of the life cycle. It is sufficient at this point to state that the eggs, which are fertilized externally, are deposited in a previously constructed nest located in a clear, clean, trout stream tributary to the Great Lakes.

Estimates of the number of eggs laid per individual vary from 24,000 to over 100,000 with approximately 60,000 being accepted as the average (Burrows, 1963). The eggs are very small but heavy and sticky, therefore, they are carried by the current only to the downstream rim of the nest where they adhere to the rocks and are eventually overlaid with sand stirred up by the activities of the adults.

In 10 to 20 days the eggs hatch, however, the time of hatching and the number of eggs that do hatch are quite dependent on the temperature. Piavis (1961) stated that no viable larvae are produced at temperatures above 70°F. or below 60°F. The optimum temperature is 65°F. at which there is 78 per cent survival to the burrowing stage of the larvae. Survival sharply decreases above or below this optimum temperature such that at 60°F. only 10 per cent survive and at 70°F. only 12 per cent will survive to the burrowing stage. Thus, the temperature factor may very well explain why many apparently suitable streams do not produce larvae.

The newly-hatched larvae or ammocoetes remain in the nest for about 20 days. By this time they are perfectly developed and leave the nest by wiggling out of the sand and entering the current. Experimental counts of ammocoetes leaving the nest indicate that only 0.4 per cent to 1.1 per cent of the reproductive potential survive (Applegate, 1950). Thus, although temperature, as indicated above, may be a mortality factor, there are many other factors in the natural environment which limit reproductivity.

When in the current, the ammocoetes are swept downstream to quiet pools or eddies where they dive to the bottom and burrow into the mud or sand. Experiments indicate that the diving behavior is a reaction to sluggish current, thus, automatically guiding them to optimum habitats (Applegate, 1950).

Having established itself in a burrow, the ammocoete will remain there for the next several years leading a rather sedentary type of existence. Authorities disagree on the length of the larval life, but it is probably not less than four years (Applegate, 1950) nor more than six (Trautman, 1949).

During this period of non-parasitic existence the ammocoete feeds on aquatic micro-organisms separated from the water by a sieve apparatus similar to that in amphioxus (Romer, 1962). Mucus is secreted in the hypobranchial groove which extends the length of the pharynx. The mucus is moved forward and upward around the gillslits by ciliary action. Water carrying micro-organisms is drawn in through the oral hood and as it passes out through the gillslits, the food material is entrapped in the mucus. The mucus then collects in the epibranchial groove and passes posteriorly to the intestine for digestion. Because of this method of feeding, the stream must not carry great loads of silt.

During this period of the life cycle the ammocoete attains a length of about six inches. However, there is no growth or feeding during the last three and one-half months of larval existence, since this is the period when metamorphasis occurs (Applegate, 1950).

Metamorphasis involves some very profound anatomical changes. The projections of the oral hood fuse and form the circular sucking-disk. The sieve apparatus degenerates and a rasping tongue replaces it in the throat. Both the suctorial disk and the tongue are beset with epidermal teeth (Weichert 1959). The deep - set eyes appear and develop into highly functional organs. The color changes from the brown of the larval stage to the dorsal blue-gray and ventral silvery-white of the adult (Applegate 1950). The gall bladder and bile duct degenerate. The paired ovaries or testes, depending on the sex, fuse into one large organ. The pharynx undergoes a radical change in that it splits into two separate tubes with the upper one connecting the mouth to the esophagus, and the lower one ending blindly. The gill sacs open into the lower tube allowing respiration to occur independently of the mouth (Romer 1962). All of these changes are, or course, indications and adaptations for the predaceous existence that is to follow.

The newly transformed lamprey is now ready for migration into the Great Lakes. The migration is usually greatest during March and April due to the rise and crest of floods resulting from the spring break up (Applegate and Brynildson, 1952). A few scattered individuals migrate prior to this, and the initial surge occurs in late October or early November due to late fall rains. This would indicate that the primary factor influencing migration is rising or fluctuating water levels. This is indicated in Figure 2, page 13. Movement at this time is usually very passive, therefore, the high water provides the impetus for the migration.

Since there may be some time lapse from the completion of metamorphasis to the time of migration, and since the migratory routes to the Great Lakes many times are through inland lakes, authorities were concerned for the fish populations in these areas. Applegate and Brynildson (1957) state that very few lampreys attempt to feed during migration. When the journey is interrupted by a small lake the migrants pass through it without attacking resident fish. When, however, a large lake is encountered the migrants will prey upon the fish, but the number of attacks is very small. Studies indicate (Guard 1952) that some of the larger lakes actually support lamprey populations. The populations are small, however, and statistical observations over a period of years do not indicate any significant increase in number of lampreys or decrease in the fish populations. These observations would indicate that the presence of lampreys in inland waters is not of particular significance.

Parasitic Phase

The parasitic phase of the life cycle begins with the arrival of the lamprey into the Great Lakes. Lennon (1954) feels that feeding during migration does not occur because the teeth are not developed sufficiently, but by the time the Great Lakes are reached the teeth are hard and fully developed.

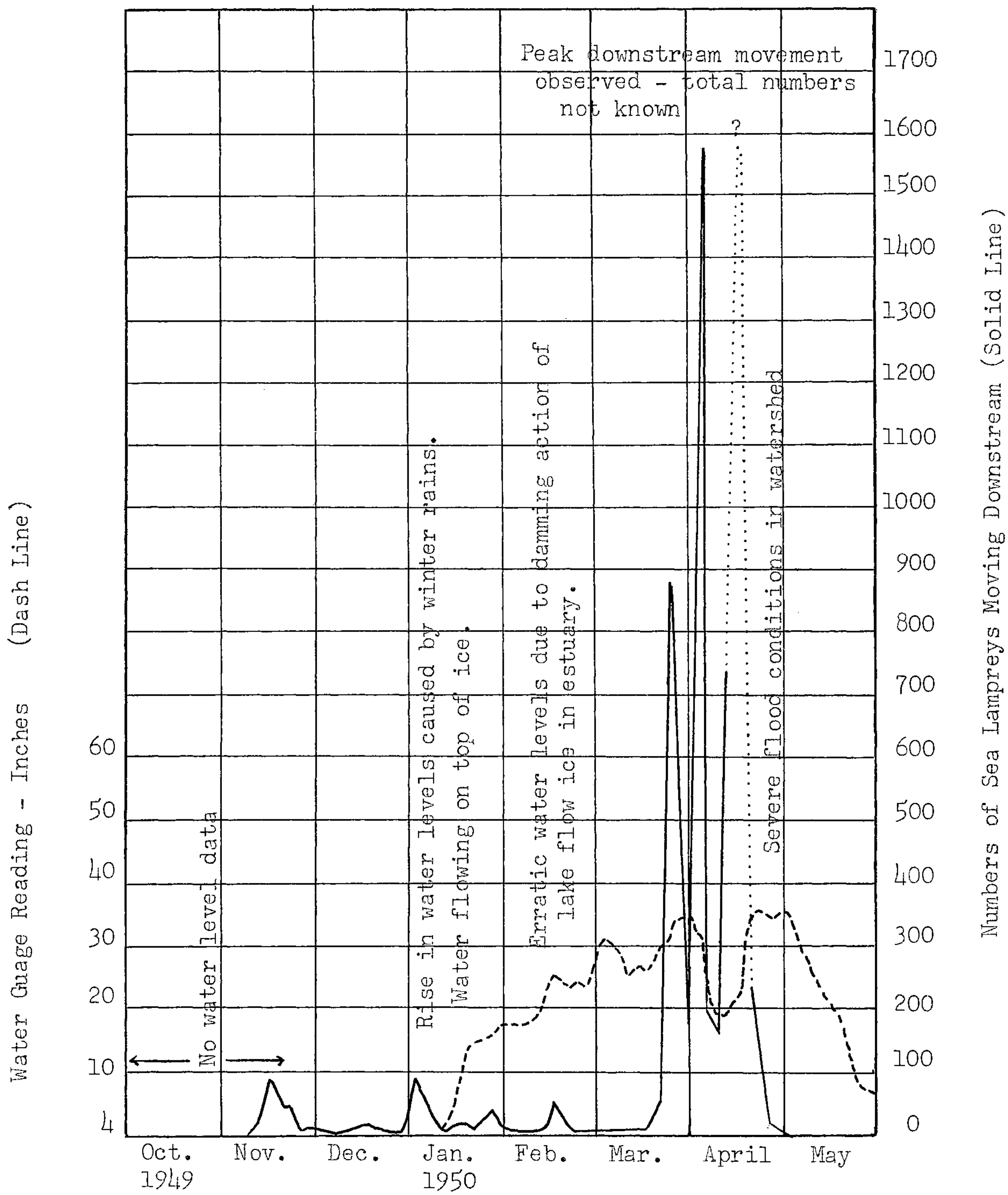

Fig. 2. Numbers of recently transformed sea lampreys migrating downstream in the Carp Lake River and fluctuations of water level, during the 1949 - 1950 season. (Applegate and Brynildson, 1952)

Food during the adult stage is, of course, obtained from the prey fish. It consists primarily of the fish's blood, and to a lesser extent of body juices and flesh reduced to liquid by lampredin, the secretion from the buccal glands. Some authorities feel that insects, worms, and eggs also serve as food, but Lennon (1954) stated that the lamprey's feeding mechanism is adapted for a liquid diet only.

The actual attack of a lamprey is a very swift, direct process. The lamprey has acute vision and is a very strong swimmer for short periods of time. Also, fish are apparently not frightened by the presence of lamprey, therefore, they are easy prey for the parasite. Once contact has been made the fish reacts violently, however, the suction pressure is so great that the lamprey is seldom dislodged. The suction is actually strong enough to cause an indentation on the opposite side of the fish's body across two inches of musculature (Lennon 1954).

Lampreys will sometimes attach to other lampreys, however, the victim can remove the attacker by tying itself in a knot at the point of attachment. There have also been cases where they attached to humans swimming in the Great Lakes. Needless to say, the attacks were of very short duration. During Lennon's (1954) investigations at the Hammond's Bay laboratory a technician was attacked with the lamprey attaching to the back of his hand. The investigators persuaded the victim to allow the lamprey to remain attached. The attack lasted for five minutes until the pain necessitated removal of the predator. At the end of this time the technician's hand showed blood drawn very close to the surface and scratches nearly penetrating the skin from the rasping action of the tongue.

The point of attachment on a fish varies considerably. Most scars indicate that the area directly behind the pectoral fin is preferred (Trautman 1949). Lennon (1954) found in running aquarium tests, however, that the attachments were also very numerous on the head. This could not be determined from examining scars of a natural population because such attacks are almost always fatal. He also found with these experiments that multiple attachments on a fish were very common, and that increased activity of a fish seemed to cause an increase in the number of attacks on it.

Once attachment has been accomplished, the lamprey rasps a hole in its prey by the combined action of the tongue and the lytic activity of lamphredin. Lamphredin is secreted by the buccal glands, which are two bean shaped structures located in the throat region. These develop early in metamorphasis. They are drained by a duct to the mouth, with muscular contractions aiding in the secretory process (Lennon, 1954).

Lamphredin is an anticoagulent, a hemolytic agent, and a cytolytic agent. Injections of this substance under the skin of a fish result in the formation of a large blister followed, usually, by death of the individual. Incisions into the blistered area show it to be filled with a thick, foul smelling, purple fluid resulting from a mixing of blood and liquid products from lysed body cells. The flesh in this area is eroded away forming a crater-like effect and that which remains around the blistered area is discolored. Thus, no tissues of a fish, including bone, can form an effective barrier against the combined efforts of lamphredin and the rasping tongue of the lamprey.

The extent of damage inflicted upon a fish depends on the size of the fish, the size of the lamprey, the site of attack, and the duration of the attack. The attack usually lasts until the fish is dead or the lamprey is glutted. The most direct cause of death is from severe hemorrhaging resulting in blood volume, red cell count, and hemoglobin being drastically reduced. Secondary fungus infections in the wound can result in death in those fishes which are not killed by the attack itself (Lennon, 1954).

This phase of the life cycle lasts from 12 to 20 months during which time the lamprey may attain a length of 12 to 24 inches or larger (Dees, 1960), and destroy 30 to 40 pounds of fish (Baldwin, 1963).

Spawning Phase

The spawning activities of the sea lamprey occur in late May and early June in suitable streams tributary to the Great Lakes. As indicated previously, the streams must be clean and free of silt, also there cannot be barriers to prevent the upstream migration.

Prior to the migration, the lamprey undergoes further changes. The gonads begin to ripen so that by the end of the upstream run almost the entire body cavity is filled with mature eggs or sperm. As the gonads ripen, the eyes and digestive tract undergo a progressive degeneration. For this reason parasitism is discontinued, and the animal lives on stored body fat for the remainder of its life.

The lampreys usually congregate at the mouths of the tributary streams for several nights prior to the run. This probably occurs because the water temperature of the streams is too low. When the temperature gets above 40°F. the migration begins (Dees, 1960) with distances up to 49 miles being covered during the run.

According to Applegate (1950) the spawning activity begins at a temperature of about 50°F. The first evidence of activity is the construction of a nest. This is done in the riffles of a stream by cleaning the gravel and small stones from a circular area and depositing these in a concentric ring on the downstream margin of the clearing. The stones are moved individually by picking them up with the suctorial mouth. Both the male and female usually engage in constructing the nest.

The spawning itself may last from 16 hours to three and one-half days. The female attaches her oral disk to a stone in the upstream portion of the nest and orients her body with the current flow along the bottom of the nest. The male approaches the female along the long axis of her body and firmly attaches his mouth to her body in the branchial region. He then wraps the posterior one-third of his body about the female so their vents are approximated. The bodies of both individuals vibrate very rapidly for two to five seconds while the eggs and milt are extruded. The male then releases the female immediately.

The interval between spawning acts varies up to five minutes during which time both sexes attach to rocks and vibrate their bodies to stir up sand. This sand then covers the eggs which are lodged in the downstream rim of the nest. Approximately 20 to 40 eggs are extruded during each act.

Following spawning the spent female is carried downstream by the current to die in the quiet pools of the stream. The male remains in the nest clinging to a stone for up to three days, after which he too is carried downstream and dies. Decay of the lamprey is very rapid, therefore large numbers of dead are not found near the spawning grounds. Some authorities question if the spent lampreys actually die, but

Applegate (1950) states conclusively that they do. By the end of the spawning act they are completely blind and the digestive track has degenerated to a mere thread. Also, large irregular patches of the epidermis are sloughed off. Thus, it seems hardly possible that these individuals could live to spawn again. Lampreys which are prevented from spawning show a similar degeneration and eventually die.

It was feared that if upstream migration were prevented the lampreys would spawn near the sandy shores of the Great Lakes. Applegate (1950) trapped and observed many lampreys, and found that they would not spawn if prevented from migrating. These trapped individuals became very restless and all eventually died. Applegate (1950) assumed that if spawning did actually occur in the Great Lakes it would be very unsuccessful since the spawning process is adapted to rather swift flowing streams.

With the life cycle completed a discussion of the investigations to determine in what phases the parasites are most vulnerable to control measures and the effectiveness of these measures is in order.

CHAPTER V

CONTROL METHODS

Control of the sea lamprey over such a large area as the Great Lakes required not only the efforts of the states bordering the lakes, but also the efforts of the Federal Governments of the United States and Canada. Since 1946 these two governments have been engaged in a cooperative research program, and in 1954 a joint treaty was signed establishing the Great Lakes Fishery Commission to direct the action of lamprey control (Dees, 1960).

Investigations have shown three phases or weak spots of the life cycle where control measures might be successfully applied. The three possibilities are: prevention of spawning, prevention of downstream migration of newly transformed lampreys, and destruction of the larvae. Control methods could best be applied at these stages because the individuals are concentrated into relatively small areas, whereas in the lakes the area is so vast that controls would be impossible.

Prevention of Downstream Migration of Young Lampreys

Although this method never developed beyond the experimental stage, it merits some discussion. Authorities felt that a trapping device near the mouth of a lamprey infested stream would trap the newly transformed lampreys as they migrated toward the Great Lakes to begin their parasitic activities. Such a device would also aid in gaining information about the actual migration.

The Carp Lake River, which runs for nine miles from Carp Lake, Michigan, to the Straits of Mackinac, was chosen for the experiment. Spawning runs had been observed in this river, and the presence of extensive areas of suitable larval habitat suggested a large potential stock of downstream migrants.

According to Applegate and Brynildson (1952) an inclined screen trapping device was built about 1500 feet from the mouth of Carp Lake River in 1948. The trap required the construction of a dam 60 feet wide and five and one-half feet high, which was built of wood. The trap itself was composed of a sloping screen and a trap box. The lampreys were captured by the screen as the water passed through it. The slope of the screen and the wiggling action of the lampreys directed them into the trap box.

The device operated satisfactorily from October, 1948 to July 1951 during which time 39,307 transformed lampreys, 517 adult lampreys, and 21,663 larval lampreys were taken. During the spring breakup and subsequent flood conditions, however, it was impossible to stop the movement of the migrants. Because of the high water, this was also the period when the migration reached its annual peak as indicated in Figure 2, page 13.

From the results of this investigation it was concluded that this method of control would not be efficient enough to greatly reduce the lamprey population.

The investigation did show that no runs of fishes occurred during the period when the bulk of lampreys were imigrating. Applegate and

Brynildson (1952) proposed from this that lethal devices such as high voltage electric fences could be used during this time to destroy the migrating lampreys with little effect on the fish populations. Dees (1960) stated that "enough electricity to kill lampreys at this stage would cost an exorbitant amount." The proposal, therefore, was not pursued further.

Prevention of Spawning

As mentioned previously, lampreys which are prevented from spawning undergo a degeneration similar to spent lampreys and eventually die. Since many potential spawning streams are not utilized due to natural barriers preventing upstream migration, investigators felt that by blocking spawning streams with man-made devices the life cycle would be interrupted and the parasites eventually brought under control.

This type of control measure was actually one of the earliest to be tried since some streams were blocked by mechanical weirs or fences as early as 1946. The mechanical weirs functioned satisfactorily except during flood conditions, at which time they were frequently damaged and lampreys could then pass through. Because of the difficulty and expense of maintenance, the mechanical weirs were soon replaced by electromechanical barriers (Baldwin 1963).

The electromechanical weir consists primarily of an electrical field produced in a stream to block the migration, and mechanical traps placed at each end of the field to capture the lampreys and migrating fish (Dees, 1960).

The program was operated experimentally in the Ocqueoc River on the west shore of Lake Huron in 1951 (Baldwin, 1963) and in 1953 was adopted as the most practical attack then known for controlling the lamprey (Moffett, 1956). A comprehensive program was begun in Lake Superior in 1954, with 48 structures in operation in 1955. Moffett (1956) estimated that 50 additional structures would be required before the known spawning streams of Lake Superior were under control. Moffett also estimated that about 100 structures would be required to control Lake Michigan and 33 to control the United States side of Lake Huron. These estimates only included those streams in which spawning was known to occur, not all potential spawning streams.

According to Erkkila, Smith, and McLain (1956), the electromechanical weirs used in Lake Superior tributaries were of three types: (1) two parallel rows of hanging electrodes suspended by a cable for use in deep, soft-bottomed streams of low velocity; (2) a single row of suspended electrodes and a parallel submerged electrode for streams of moderate depth, firm bottoms, and relatively fast velocity; (3) two parallel, horizontal, submerged electrodes for shallow, rapid-flowing streams. All devices were equipped with shielded traps and energized by 110 volt, 60 cycle, alternating current. The current was supplied by commercial lines or gas-powered generators.

These devices have proven successful, at least to a point, in lamprey control. In 1954 and 55 weirs in operation on Lake Superior yielded a catch of 4,922 lampreys. The number turned back to either die or find another spawning stream is impossible to estimate. These devices were also effective during flood conditions, and were therefore an improvement over the mechanical weirs.

The electromechanical devices, however, were not a panacea for the lamprey problem. As mentioned previously, many lampreys were observed turning back from the barriers to return to the lakes in search of other spawning streams. This would not have been a significant factor if all streams were blocked, but the cost of erecting and operating that many weirs was an important limiting factor.

Power failure was another problem encountered. With the electricity off, the streams were open to lamprey invasion and although not especially significant, it was still a limiting factor of the control measure.

The rather large number of fish killed by the electrical barriers, as indicated in Table I, was another problem to be considered. Fish mortality is affected by such things as stream velocity, water conductivity, and location of traps. Stream velocity is apparently the most important factor affecting fish electrocution. Usually more fish are killed in a low water velocity stream than in one of similar size but higher water velocity. However, if the fish follow a well-defined route in a low velocity stream they can be trapped before entering the electric field.

The water conductivity of a stream fluctuates considerably from time to time and an increased conductivity is dangerous to fish. Increased conductivity causes an increase in the field intensity which may result in excessive fish mortality. Increased conductivity also increases the size of the electric field to the point where it may encompass the entrance to the traps. Since the fish are not guided into the traps by the fringe of the field, a high mortality rate may result (Erkkila, Smith, and McLain, 1956).

The fish mortality rate has been reduced somewhat by a supplementary direct current device which aids in guiding them into the traps. The lampreys may also be guided into the traps by this device, in which case

TABLE I

TOTAL NUMBER OF SEA LAMPREYS AND FISH TRAPPED AND ELECTROCUTED AT CONTROL DEVICES, 1954 (ERKKILA, SMITH, AND McLAIN, 1956)

FISH	IN LAKE SUPERIOR			IN LAKE MICHIGAN		
	Number Trapped	Number Electrocuted	Total	Number Trapped	Number Electrocuted	Total
Sea lamprey	4,277	645	4,922	6,569	798	7,367
Native lamprey	530	1,831	2,361	526	370	896
Rainbow trout (large)*	364	307	671	8	8	16
Rainbow trout (small)	2,363	2,725	5,088	9	19	28
Brook trout	1,564	645	2,209	98	53	151
Smelt	12,041	1,512	13,553	10,022	4,404	14,426
White sucker	15,090	11,638	26,728	1,540	948	2,488
Longnose sucker	35,945	10,966	46,911	267	91	358
Northern pike	60	84	144	11	219	230
Brown trout	102	36	138	1	0	1
Round whitefish	191	45	236	0	0	0
Yellow perch	1,191	81	1,272	10	13	23
Walleye	93	32	125	4	96	100
Longnose dace	3,977	1,017	4,994	264	147	411
Trout-perch	61,399	7,277	68,676	10,326	1,273	11,599
Sculpin	623	308	931	23	63	86
Spottail shiner	2,473	144	2,617	948	154	1,102
Bullhead	1,795	24	1,819	1,441	22	1,463
Logperch	1,448	3,806	5,254	1,336	46,200	48,536
Miscellaneous**	3,947	1,455	5,402	3,298	1,503	4,801

*Over 12 inches, total length

**Miscellaneous includes: common shiner, smallmouth bass, pumpkinseed, rock bass, burbot, white bass, creek chub, stickleback, mudminnow, silver redhorse, lake chub, bowfin, hog sucker, and carp the fish are moved safely upstream and the lampreys destroyed, or being less suseptible to electricity, the lampreys continue into the A. C. field where they are electrocuted (Dees, 1960).

The most important problem with using electrical control was that four to five generations of lamprey still existed upstream in the larval stage. These would have to migrate to the lakes, pass through the parasitic phase, and prepare to spawn before the use of electrical barriers would show an appreciable decrease in the lamprey population. Since the Lake Superior fishing industry was near the brink of collapse, the search for a method of attacking the larval stage of the lamprey continued long after the development of the electromechanical weirs.

Destruction of Larval Stage

Lamprey larvae can be collected by many ways such as with electrical probes, but to thoroughly cover a stream system with such equipment is an impossible task. The use of poisons was long considered, however, indiscriminate poisoning of streams was very undesirable. The only apparent answer was to find a selective poison for the larval lamprey (Moffett, 1956).

The search for a selective larvicide was conducted at the Hammond Bay station, Michigan, under the directorship of Dr. Vernon C. Applegate. Approximately 6000 chemicals were tested in over two years of research (McVeigh, 1958).

The laboratory tests were conducted in ten liter glass battery jars containing five liters of water each. The test jars were aerated with standard stone air-breakers and temperatures were held constant by immersion of the vessels in a specially constructed water bath.

In the early phases of research the test animals used were larvae of the sea lamprey, and fingerlings of rainbow trout, brown trout or blue gill sunfish. These fish specimens were chosen because they are the most important species found in the streams. Two specimens of each species were added to a vessel containing a known concentration of the compound to be tested. The tests were conducted for 24 hours at a temperature of 55°F.

The principle objective of the tests was to determine the chemicals which are acutely toxic to larval lampreys at low concentrations, but which are not toxic to other fishes at relatively high concentrations. Also the toxic chemicals were required to destroy the larvae in relatively short periods of time.

Of all the chemicals tested only six exhibited sufficient differential toxicity to permit their application to streams. These six chemicals are all halogenated mononitrophenols (Applegate, Howell, and Smith, 1958). These all have from one to three halogens substituted in the benzene ring or in an aliphatic side chain. Only one nitro group is present in the compound. The number and type of halogens attached to the molecule and the position of the nitro and halo groups differ. The chemicals are listed in Table II.

Because of ease of handling in the field, effectiveness at low concentration, and cost, 3-trifluormethyl-4-nitrophenol was selected for development for field use.

The compound, 3-trifluormethyl-4-nitrophenol, abbreviated T F M, is a crystalline solid at room temperature, brown in color in technical grade preparations, and only slightly soluble in water. It is very stable and is not detoxified by natural processes. The sodium salt of

TABLE II

DIFFERENTIAL TOXIC EFFECTS AMONG LARVAL LAMPREYS AND FISHES OF CERTAIN MONONITROPHENOLS CONTAINING HALOGENS. SODIUM SALT IS EXPRESSED IN PARTS PER MILLION OF FREE PHENOL. (APPLEGATE, HOWELL, AND SMITH, 1958)

Name and form of compound	Concentration required to kill all lamprey larvae (ppm)	Concentration required to cause significant mortality* among fishes (ppm)		
		Rainbow Trout	Brown Trout	Bluegill Sunfish
2-Bromo-4-nitrophenol				
Free phenol	5	13	11	
Na salt	7	15		
3-Bromo-4-nitrophenol				
Free phenol	5	11		15
5-Chloro-2-nitrophenol				
Free phenol	3	5	5	
2,5-Dichloro-4-nitrophenol				
Free phenol	3	13	7	
Na salt	5	17		
3,4,6-Trichloro-2-nitrophenol				
Free phenol	5	17	15	
Na Salt	13	23		
3-Trifluormethyl-4-nitrophenol				
Free phenol	2	9	7	
Na salt	2	7		

*Mortality of approximately 10 per cent of all test animals.

T F M has toxic properties similar to the free phenol and is much more soluble, therefore, it was used for the laboratory and field experiments.

After T F M was selected for development as a larvicide, further testing was conducted before streams were actually treated with it. The laboratory experiments were similar to those previously described. Test larvae and rainbow trout were placed in ten liter glass battery jars containing known concentrations of the larvicide. Usually three specimens were placed in each vessel with sixteen simultaneous replications conducted at a given concentration. The temperature was held constant for a particular set of replications, although it was varied considerably from set to set. Water of widly differing characteristics was obtained from tributaries of the Great Lakes. All tests were conducted for 24 hours.

The laboratory experiments indicated that water temperature had very little effect on the toxicity of T F M. Stream characteristics, however, did influence the toxic effects of the chemical. Soft, acid waters reduced the lethal concentrations to as low as 0.5 parts per million for the larvae. As pH, conductivity, and alkalinity increased, the dosage requirements also increased. The range between lethal concentrations for lampreys and maximum allowable concentrations for trout, however, remained quite constant.

The laboratory tests gave some insight into the physiological effects of T F M upon larval lampreys, although these are still not completely explored. The chemical causes rupturing of the respiratory epithelium and dialation of the blood vessels. This results in severe hemorrhaging from the respiratory capillaries which fills the gill pouches with blood.

Thus the lampreys suffer a general circulatory collapse aggravated by suffocation.

Rainbow trout exposed to high concentration of T F M give no evidence of hemorrhaging, but exhibit symptoms of anoxia. The gills become coated with mucus which probably results in suffocation.

Mammals were subjected to low concentrations of T F M in their drinking water, however, no harmful effects were observed.

As an intermediate stage of testing, running-water raceways were constructed at Hammond Bay station to simulate natural stream conditions. The raceways were concrete throughs 65 feet long, six feet wide, and 30 inches deep. A stream bed was constructed of materials from local rivers. Certain stream characteristics such as pools and riffles were built into the bed. Water was pumped from Lake Huron to the head of the trough and after passing through the race, was discharged into a waste flume.

A variety of test specimens were used for the raceway tests, but usually included larval and adult lampreys, three trout species, other miscellaneous fish, turtles, and aquatic invertebrates.

Each treatment was conducted for 24 hours during which time the T F M was metered into the raceway by a fluid proportioning pump. This was checked frequently to assure an accurate concentration was maintained.

The raceway test results are summarized in Table III. They indicated that the differential toxic effects of T F M among lampreys and trout were similar to the laboratory test results. The raceway tests showed that adult lampreys were also killed by T F M at concentrations of three ppm. This was significant because the treatment of streams

TABLE III

TOXICITY OF AN AQUEOUS SOLUTION OF THE SODIUM SALT OF 3-TRIFLUORMETHYL-4-NITROPHENOL TO SEA LAMPREYS (PELROMYZON MARINUS), FISHES, AQUATIC INSECTS, CRAYFISH, AND TURTLES AS DETERMINED BY SIMULATED STREAM TESTS IN A RUNNING-WATER RACEWAY. (APPLEGATE ET AL, 1961) /TESTS AT INDICATED CONCENTRATIONS WERE CONDUCTED FOR A 24-HOUR PERIOD AT VARIOUS WATER TEMPERATURES RANGING FROM 45° TO 55°F. MEAN WATER TEMPERATURES EXTANT DURING TESTING AT EACH CONCENTRATION ARE LISTED BELOW./

Concentration of T F M (ppm)	Mean Water Temperature (F.°)	PERCENTAGE MORTALITY OF TEST SPECIES (Number of specimens of each species utilized indicated parenthetically beneath each mortality datum; total number of test animals utilized - 1,749.)										
		Larval sea lampreys	Adult sea lampreys (mature upstream migrants)	Adult sea lampreys (recently transformed)	Rainbow trout	Brook trout	Brown trout	Rock bass	Sunfishes	Yellow perch	White suckers (adults)	White suckers (immature)
1.5	47.4	91.5 (153)	0.0 (5)	0.0 (9)	0.0 (10)	0.0 (10)	0.0 (10)	0.0 (1)	0.0 (5)	0.0 (6)	0.0 (5)	0.0 (6)
3.0	45.9	100.0 (150)	100.0 (5)	100.0 (5)	0.0 (10)	0.0 (10)	0.0 (10)	...	0.0 (11)	0.0 (6)	0.0 (5)	0.0 (5)
5.0	45.2	100.0 (149)	100.0 (5)	100.0 (10)	0.0 (10)	0.0 (10)	0.0 (10)	...	0.0 (12)	0.0 (8)	0.0 (5)	0.0 (2)
7.0	49.3	100.0 (150)	100.0 (5)	100.0 (10)	0.0 (10)	0.0 (10)	0.0 (10)	0.0 (3)	0.0 (8)	12.5 (8)	0.0 (5)	28.5 (7)
9.0	54.4	100.0 (150)	100.0 (5)	...	0.0 (10)	0.0 (10)	10.0 (10)	0.0 (1)	10.0 (10)	50.8 (12)	80.0 (5)	50.0 (10)
10.0	43.6	100.0 (149)	100.0 (5)	...	0.0 (10)	0.0 (10)	10.0 (10)	0.0 (8)	100.0 (5)	100.0 (10)	80.0 (5)	100.0 (8)
11.0	45.9	...	...	...	0.0 (10)	0.0 (10)	0.0 (10)	0.0 (5)	...	...	...	...
13.0	54.2	...	...	...	80.0	0.0	50.0	...	...	...	...	...

TABLE III (Continued)

Concentration of T F M (ppm)	Mean water Temperature (F.°)	PERCENTAGE MORTALITY OF TEST SPECIES (Number of specimens of each species utilized indicated parenthetically beneath each mortality datum; total number of test animals utilized - 1,749.)										
		Bullheads	Common shiners	Lake chubs	Creek chubs	Longnose dace	Central mudminnows	Logperch	Mottled sculpins	Turtles	Crayfish	Caddisfly larvae
1.5	47.4	0.0 (8)	40.0 (5)	...	0.0 (1)	0.0 (7)	...	0.0 (2)	...	...	...	...
3.0	45.9	0.0 (15)	0.0 (20)	0.0 (9)	0.0 (1)	0.0 (20)	...	...	0.0 (5)	0.0 (1)	0.0 (10)	...
5.0	45.2	66.6 (12)	0.0 (10)	0.0 (5)	...	0.0 (5)	0.0 (5)	100.0 (1)	0.0 (10)	0.0 (2)	0.0 (15)	0.0 (3)
7.0	49.3	100.0 (11)	0.0 (16)	0.0 (3)	0.0 (1)	16.6 (6)	0.0 (5)	...	0.0 (7)	...	0.0 (8)	0.0 (4)
9.0	54.4	100.0 (11)	10.0 (10)	...	0.0 (1)	100.0 (10)	...	100.0 (1)	...	...	0.0 (3)	0.0 (4)
10.0	43.6	93.3 (15)	100.0 (10)	...	...	100.0 (13)	100.0 (5)	100.0 (1)	100.0 (4)	0.0 (1)	0.0 (5)	0.0 (15)
11.0	45.9	...	...	...	...	...	...	...	...	...	0.0 (5)	0.0 (10)
13.0	54.2	...	...	...	...	...	...	...	...	...	...	...

during migratory runs would result in destruction of the migrants and the larvae.

The effects on the other animals tested were quite varied. Most showed no significant mortalities until concentrations well above those lethal to lampreys were reached. Bullheads, logperch, and suckers were susceptible at rather low concentrations, however, these were not considered to be significant because a substantial number usually survived.

The raceway tests proved that T F M could be metered into running water and effectively kill larval lampreys. The next step before wide scale application of the larvicide could be conducted was to test the effects of T F M in a few experimental streams. Three streams varying greatly in physical and chemical characteristics were selected for experimental applications of T F M. The three streams were: Mosquito River, Alger County, Michigan; Silver River, Baraga County, Michigan; and Pancake River watershed, District of Algoma, Ontario.

Before a stream can be treated a few of its characteristics must be established. The concentration and period of application of T F M varies from stream to stream, and thus must be determined experimentally by methods similar to those described previously for the laboratory testing procedure. A mobile laboratory unit greatly facilitates the performances of these tests.

After the concentration of T F M is determined for a given stream, the rate at which it must be pumped into the water is calculated from the volume of stream flow. The rate is then controlled by the fluid - proportioning pump which forces the chemical through a perforated hose placed across the stream.

The Mosquito River was treated on May 14, 1958. The larvicide was pumped into the river at a natural falls one and three-fourths miles above the mouth because no lampreys were found above this barrier. The concentration of T F M varied at first but averaged 5.5 ppm. This concentration was periodically checked with a Klett - Summerson colorimeter which allows a comparison of the color of samples of treated stream water with standard solutions of T F M.

Prior to the treatment, 40 cages containing 1000 larval lampreys were placed in the river. Of these control specimens 91 per cent were dead in three and one-half hours, 97 per cent in four and one-half hours, 99 per cent in five and one-half hours, and all were dead after seven and three-fourths hours of treatment.

Dead and dying resident larvae, were observed in the stream after only two hours of exposure. Post - treatment examination of 1400 linear feet of stream with electric shockers revealed no live sea lamprey larvae.

No effect was observed upon the fish or aquatic invertebrates of the stream.

The Silver River was treated with T F M on June 11, 1958 for 13 and one-half hours at a concentration of 2.8 ppm. The larvicide was pumped into the river four and one-half miles up stream at a water fall which served as a natural barrier against spawning lampreys.

After eight and one-half hours all 1205 caged larvae, which served as control specimens, were dead. Many thousands of dead resident larvae were seen in the river after the treatment was concluded. Post - treatment examination of 50,000 square feet of the river bed with electric schockers revealed only one live larval lamprey.

Of the twenty-five species of fish present in the Silver River only the log perch were significantly affected by the larvicide. These, however, were still present in sufficient numbers to reestablish themselves. No significant effects were observed among the aquatic invertebrates of the stream.

The Pancake River and its tributary, Gimlet Creek, posed a problem not previously encountered in the treatment procedure. In order to maintain a constant concentration of T F M, it was necessary that the two treated water masses reach the confluence of the streams simultaneously. By timing the downstream movements of dye, it was established that the treatment of Gimlet Creek would have to be started 36 hours prior to that of Pancake River.

On August 26, 1958 the treatment of Gimlet Creek was begun about three miles above its confluence with Pancake River. Thirty-six hours later, T F M was introduced into Pancake River about 12 miles above its mouth. Both streams were treated for 12 hours at a concentration of 2.5 to 3.3 ppm.

The caged control larvae in both streams were all dead at the end of eight and one-half hours of treatment except for two cages of specimens located in a semi-isolated estuary of Pancake River. This was probably due to restricted water exchange between it and the main stream.

The total number of dead larvae observed at the conclusion of treatment was estimated to range from one-half to three-fourths million. Post-treatment examination of both streams yield no live sea lamprey larval. This included an extensive examination of the estuary where the caged specimens had survived.

Most of the fish species in the streams showed some susceptibility to the poison with the sculpins suffering the heaviest losses. However, no species suffered such severe mortalities that it could not rapidly restore its numbers by natural means (Applegate et al 1961).

With the differential toxicity of T F M thus vertified under laboratory, simulated stream, and natural stream conditions, a large scale control program was begun in the Lake Superior drainage. This control, as with the electrical barriers, was first used extensively on this lake rather than the others because this was the only lake with a significant trout population. Authorities felt that if this population could be saved the other lakes, once rid of lampreys, could be restocked from it. All known lamprey streams were treated by the end of 1960, with new spawning streams being treated as they were discovered.

With the first series of treatments completed in Lake Superior tributaries, emphasis is now being placed on the completion of an initial program on Lake Michigan. About one-half of the known lamprey producing streams in the Lake Michigan drainage have been treated, and the remainder should be treated by 1966.

Preliminary surveys on Lake Huron have been completed and have paved the way for a control program in its tributaries (Baldwin, 1963).

It is too early to obtain clear evidence upon which to judge the success of the larvicide control program, however, some encouraging signs have been noted in Lake Superior. The number of lampreys that appeared at the electromechanical barriers in the 1962 spawning season was less than ten per cent of the number counted in 1961 (Burrows, 1963). Fresh lamprey wounds on lake trout have been reduced from 30 to 90 percent depending on the area. There has been an increase in the survival of older, larger trout which are normally most vulnerable to lamprey attack (Baldwin, 1963).

The larvicide is not expected to eliminate the sea lamprey from the Great Lakes. However, control of the lamprey, by periodic application of the larvicide, is anticipated.

CHAPTER VI

SUMMARY

Sea lampreys, long established in Lake Ontario, gained access to the upper Great Lakes with the opening of the Welland Canal in 1829. Although the route to the upper lakes has been opened to lampreys for many years, their presence in these lakes was not confirmed until about forty years ago.

During the forty years the lampreys have been in the upper Great Lakes, the lake trout production has dropped from 10 to 15 million pounds per year to a few hundred thousand pounds per year. The result has been the destruction of the multimillion dollar trout fishing industry. Since lampreys have very little commercial value, authorities felt the remedy to this economic disaster was the elimination or control of the lampreys; and the reestablishment of the trout population.

Through the joint efforts of the United States and Canada, much research on the characteristics and life history of lampreys was conducted. Lampreys are identified from hagfishes, both of which are cyclostomes, by characteristics of the mouth and accessory mouth parts, and by the structure and location of the gill pouches. Species identification of the lampreys is accomplished by differences in both length, mouth size, and functional mouth parts. The sea lamprey is the largest species found in the Great Lakes and their tributaries. It has a large mouth with horny mouth parts; and the dorsal fin is notched, a characteristic found only in one other very small species.

Sea lampreys show a complex life cycle exhibiting a larval stage, metamorphasis, and an adult stage. Upon hatching, the non-parasitic larvae burrow into the stream bottom and remain there for several years, living on microorganisms filtered from the water. For this reason the stream must be clear and clean.

During metamorphasis the larvae undergo many profound anatomical changes which result in the adult, parasitic form. During the spring break up following metamorphasis, the newly transformed lampreys migrate downstream to the lakes where the parasitic phase begins.

During the parasitic phase a lamprey destroys about 30 to 40 pounds of fish, preferrably lake trout. The lamprey accomplishes this by attaching to the fish's body, rasping a hole through the flesh, and sucking the victim's blood and body juices.

After twelve to twenty months of parasitism, the lampreys migrate up the numerous trout streams to spawn in the riffles. Upon completion of spawning both sexes die within a few days.

At three points in the life cycle the lampreys are congregated sufficiently for the application of control measures. The possible controls are: blocking downstream migration of newly transformed lamprey; blocking upstream spawning migrations; and destroying the larvae.

Experiments aimed at blocking the downstream migration of transformed lampreys was attempted but failed. Flood waters carrying the peak number of downstream migrants overflowed the traps designed to stop the lampreys, therefore, the majority of parasites continued their journey to the lakes.

The use of mechanical and electrical barriers designed to block the spawning runs were successful, and for several years served as the major control against the lampreys. The major drawback of this control was that four or five years' crops of larvae had to pass through the parasitic phase before the control could effectively reduce the parasitic population.

Authorities agreed that the best method of destroying the larvae would be by the use of a selective poison. Such a chemical, the sodium salt of 3-trifluormethyl-4-nitrophenol, was discovered after several years of research. This chemical proved to be lethal to lamprey larvae at very low concentrations, but harmless to fish and other marine life at similar concentrations.

After laboratory, simulated stream, and natural stream tests verified the differential toxicity of T F M; a large scale control program was completed in Lake Superior tributaries in 1960. A similar program is in progress in the Lake Michigan drainage; and pre-treatment, preliminary surveys have been completed in Lake Huron tributaries.

The early results of the initial Lake Superior treatment are encouraging. The number of lampreys appearing at the spawning barriers has been drastically reduced. The number of fresh lamprey scars on lake trout has declined by as much as 90 per cent. There has been an increase in the survival of larger trout, which are usually more susceptible to lamprey attack.

Control of the lampreys will require periodic application of the larvicide. However, if the resident trout population responds as expected and large scale stocking continues, an adequate brood stock should be built up in about six years (Burrows, 1963). From this brood stock, Lakes Michigan and Huron can be restocked when the treatment programs for these lakes has been completed.

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