Technical Report No. 9

A Study of the Feasibility of Restoring Lake Sturgeon to Lake Champlain

Lake Champlain
Basin Program

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2. *Design and Initial Implementation of a Comprehensive Agricultural Monitoring and Evaluation Network for the Lake Champlain Basin.* NY-VT Strategic Core Group. February, 1993.

3. (A) *GIS Management Plan for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc., and Associates in Rural Development. March, 1993.

   (B) *Handbook of GIS Standards and Procedures for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.

   (C) *GIS Data Inventory for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.

4. (A) *Lake Champlain Economic Database Project. Executive Summary.* Holmes & Associates. March 1993.

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   Lake Champlain Sediment Toxics Assessment Program. An Assessment of Sediment - Associated Contaminants in Lake Champlain - Phase 1. Executive Summary. Alan McIntosh, Editor, UVM School of Natural Resources. February 1994.

6. *(A) Lake Champlain Nonpoint Source Pollution Assessment.* Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

   (B) Lake Champlain Nonpoint Source Pollution Assessment. Appendices A-J. Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

7. *Internal Phosphorus Loading Studies of St. Albans Bay. Executive Summary.* VT Dept of Environmental Conservation. March 1994.

   (A) *Dynamic Mass Balance Model of Internal Phosphorus Loading in St. Albans Bay, Lake Champlain.* Eric Smeltzer, Neil Kamman, Karen Hyde and John C. Drake. March 1994.

   (B) *History of Phosphorus Loading to St. Albans Bay, 1850 - 1990.* Karen Hyde, Neil Kamman and Eric Smeltzer. March 1994.

   (C) *Assessment of Sediment Phosphorus Distribution and Long-Term Recycling in St. Albans Bay, Lake Champlain.* Scott Martin, Youngstown State University. March 1994.

8. *Lake Champlain Wetlands Acquisition Study.* Jon Binhammer, VT Nature Conservancy. June 1994.

9. *A Study of the Feasibility of Restoring Lake Sturgeon to Lake Champlain.* Deborah A. Moreau and Donna L. Parrish, VT Cooperative Fish & Wildlife Research Unit, University of Vermont. June 1994.

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A Study of the Feasibility of Restoring Lake Sturgeon to Lake Champlain

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Project Summary

Lake sturgeon (*Acipenser fulvescens*) populations have declined precipitously over the past 100 years in both Canada (Scott and Crossman 1973) and the United States, and are currently classified as endangered in Vermont and threatened in New York. Our goal in this study is to provide information regarding the feasibility of establishing a restoration program for lake sturgeon in Lake Champlain. The approach was to review available life history and ecological requirements of lake sturgeon, to determine the availability of suitable habitat characteristics (using instream flow incremental methodology (IFIM) procedures) in Lake Champlain and its tributaries, and to develop stocking guidelines based on a lake sturgeon population model. We developed recommendations for lake sturgeon restoration based on the Missouri Restoration Plan (Graham 1992), historic Lake Champlain sturgeon population information, and simulations from a lake sturgeon population model. In conducting this study, we considered alternate strategies to stocking for restoring lake sturgeon. However, because very few fish have been sighted in Lake Champlain tributaries in recent years and because of the long age to maturity, we conclude that the likelihood of achieving restoration through natural reproduction of current residents is extremely small.

Therefore, <u>If</u> a goal of restoring lake sturgeon to Lake Champlain is adopted, we recommend stocking 10,000 age-1 lake sturgeon annually for 10 years. At the end of the 10-year

period, population assessment should be conducted, and if the survival of stocked fish is low, research should be initiated to determine the causes of mortality. Continued stocking past the initial 10 years would shorten the time required to reach a stable population to 60 years rather than 250 years. To reduce the risk of exceeding carrying capacity, 10,000 juveniles should continue to be stocked annually only if age-1, second year of life, juvenile survival is < 0.1, but if survival is > 0.1, a stocking reduction to 5,000 is recommended. After 20 years, if there is evidence of spawning, stock 5,000 a year. But, if there is no evidence of spawning, studies should be initiated to address the factors contributing to a lack of reproduction by lake sturgeon in Lake Champlain tributaries.

Index

List of Figures

List of Figures (continued)

List of Tables

Introduction

Lake sturgeon (*Acipenser fulvescens*) populations have declined precipitously over the past 100 years in both Canada (Scott and Crossman 1973) and the United States, and are currently classified as endangered in Vermont and threatened in New York. Because lake sturgeon are so long-lived and have delayed maturation, any loss of quality habitat for spawning and for the juvenile phase, which can last twenty years, could contribute to the extirpation of the species in many U.S. waters. A summary of habitat suitability requirements for lake sturgeon was presented in Countryman (1986). Kempinger (1988) found that thermal regime, siltation, and water velocity influences reproductive success by affecting egg and larval survival. In addition to the quality of habitat, overfishing has clearly contributed to the decimation of many sturgeon populations.

Given the current status of lake sturgeon in Lake Champlain, our goal in this study is to provide information regarding the feasibility of establishing a restoration program for lake sturgeon in Lake Champlain. Our approach was to review available life history and ecological requirements of lake sturgeon, to determine the availability of suitable habitat characteristics in Lake Champlain and its tributaries, and to develop stocking guidelines based on a lake sturgeon population model.

Methods/Approach

This report addresses, tasks 1 through 5 of the Request for Proposal (RFP) issued by the Lake Champlain Management Conference. This project was funded by the Management Conference in May 1992 and work began in August 1992. Vermont Fish and Wildlife personnel wrote the culture requirements and associated costs sections, which are attached to this report as an addendum. So, the approach for the contracted portion of the project is as follows:

1. A complete literature review of lake sturgeon encompassing the complexity of the life cycle; specific habitat requirements related to spawning, egg-adult survival, individual growth rates, water quality, flow regimes, and substrate types; and techniques for population assessment. A listing of U.S. lake sturgeon biologists and culturists for potential egg and fry sources was compiled (Appendix I). The subject of artificial propagation, including spawning and rearing techniques, health and genetic concerns, hatchery requirements related to water quality is covered by Tom Wiggins in a separate document.

2. Available historical information and current distribution and abundance data of sturgeon in Lake Champlain was reviewed and summarized.

3. Historical, existing, and potential spawning and nursery habitats in Lake Champlain and associated tributaries was identified and quantified. From the identified available habitat, we estimated potential natural reproduction.

4. Recommendations are provided from the data summary and population model strategies for the management and restoration of lake sturgeon in Lake Champlain. Methods used in habitat assessment and model development are given in the appropriate sections of this report.

Literature Review

First, we should explain our approach in conducting and presenting our review of the lake sturgeon literature. This review occasionally incorporates information not acquired from original papers, but discussed in other reviews. Reviews used extensively were: Harkness and Dymond 1961; Priegel and Wirth 1974; Knox and Dadswell 1980; Houston 1987; Fortin et al. 1991. So, general information that is not directly cited, was derived from our assessment and resummarization of the entire information pool found in these reviews. Next, we have cited several recently published papers written in French. These papers represent much of the best ongoing lake sturgeon research in North America. Although neither of us reads French well, we were able to glean significant information from the Abstracts (in English) and data presentations. Also, we have cited many tables throughout this report. The tables provide information too cumbersome to present entirely in the review and they are the basis for the population model. Therefore, many citations can be accessed by referring to the tables. And finally, all measurements were converted to metric to enable direct comparison of the information.

Family Acipenseridae

Lake sturgeon are members of the family Acipenseridae and are very similar to their primitive ancestors of the upper Cretaceous period of nearly 100 million years ago. They retain large, bony plates, a cartilaginous skeleton, a lung-like swim bladder, a heterocercal tail and a notochord (Harkness and Dymond 1961; Scott and Crossman 1973; Priegel and Wirth 1974). There are 25 known species of sturgeon; most are anadromous, but some are strictly freshwater species (Priegel and Wirth 1974). The range of sturgeons includes northern Europe, Asia, and North America. In North America, four anadromous species of sturgeon exist: the white sturgeon (*A. transmontanus*) and the green sturgeon (*A. medirostris*) on the Pacific coast; and the Atlantic sturgeon (*A. oxyrhynchus*) and the shortnose sturgeon (*A. brevirostrum*) on the Atlantic coast. The three freshwater species of sturgeon in North America occur in the Mississippi drainage and nearby waters: the shovelnose (*Scaphirhynchus platorynchus*), pallid (*S. albus*), and lake sturgeons (Dees 1961; Priegel and Wirth 1974; Eddy and Underhill 1976).

Distribution

In North America, the lake sturgeon has one of the widest geographic ranges of all freshwater fishes. Lake sturgeon presently occur or have occurred in e.g. the Great Lakes basin, including the St. Lawrence River and Lake Champlain, the Mississippi River drainage, and the Hudson Bay drainage (Houston 1987; Figure 1). Most lake sturgeon occur in freshwater habitats, however some are found in the brackish waters of the St. Lawrence River and the Moose River (Houston 1987).

Morphology

The lake sturgeon's large body gradually tapers to a shark-like tail (Harkness and Dymond 1961). Dorsal and anal fins are in a very posterior position. The reddish brown young change to greenish olive or gray as adults (Eddy and Underhill 1976). Five rows of scutes line the body; the young bear sharp, pointed scutes that become smaller and smooth with age (Harkness and Dymond 1961). In addition, the long, tapering snout becomes shorter and blunter with age. Young sturgeon have a small suction plate on their snout, which is used to cling to vegetation for resting (Williams 1951). A bony opercle covers the gills and anterior to the ventral mouth are four sensory barbels used to search for benthic food items (Eddy and Underhill 1976). Protrusible lips are used to feed via a suction-like mechanism (Harkness and Dymond 1961; Priegel and Wirth 1974).

Teeth are present only in the very young. The gizzard-like stomach aids in maceration and digestion of aquatic invertebrates (Eddy and Underhill 1976).

Life Cycle

The life cycle of lake sturgeon includes six distinct stages: egg, larva, fry, fingerling, juvenile, and adult.

Eggs

Eggs are about 2.7 to 3.5 mm in diameter (Roussow 1957) and require from 5 to 14 days to hatch (Table 1). Natural hatching success, which is < 10% (Kempinger 1983, 1988; Czeskleba et al. 1985), greatly depends on habitat suitability (Table 2).

Larvae

Upon hatching, the larvae are about 8 mm long (Scott and Crossman 1973), but grow to 21 mm by the time the yolk sac is absorbed in 9 to 18 days (Harkness and Dymond 1961; Table 3). Larvae are negatively phototactic and reside in the interstices of the spawning substrate (Fortin 1991; Czeskleba et al. 1985). Larvae from eggs of the Des Prairies River, Quebec were concentrated in a substrate of fine gravel combined with cobble rather than in fine gravel alone (Fortin 1991). Survival rates of larvae are unknown.

Fry

Upon completion of yolk sac absorption, young sturgeon are referred to as fry. Fry become positively phototactic and begin to feed on small chironomid larvae (Harkness and Dymond 1961) and can include Baetidae nymphs (Kempinger 1988). Larval lake sturgeon swim up from the spawning substrate and drift downstream; peak drifting occurs between nine and ten days posthatch (Table 4), to areas about 0.6 to 1.2 m deep (Table 5), with pea-sized gravel substrate (Table 6).

Fingerlings

According to Kempinger (1985) an age-0 sturgeon is a fingerling when it is large enough to avoid capture in drift nets and corresponds to a total length ranging from 31 to 253 mm. Fingerlings seek out shallow water with small gravel substrate. During this riverine stage, young sturgeon feed mainly on Baetidae nymphs, and Diptera larvae and pupae (Kempinger 1984; 1983). By September, sturgeon are about 12.3 cm long (Scott and Crossman 1973) and their size and scutes render them invulnerable to predation. Fingerlings remain in the river at least until the fall of their first year of life and then enter lakes or main rivers sometime late in the fall.

Juveniles

Sturgeon are considered juveniles from the time of entering the lake until their seventh summer (Kempinger 1985). Evidence of juvenile residence in lakes is ambiguous, but as with adults, are suspected to occur in areas usually < 9.1 m deep (Priegel and Wirth 1974). Harkness and Dymond (1961) found juvenile sturgeon within river mouths or nearby on rocky, gravelly shoals in water usually from 3.0 to 4.6 m, but one was taken in 27.4 m of water. Mongeau et al. (1982) found juveniles on clay bottoms with a 10 to 30° slope of Lake des Deux Montagnes, Quebec at depths of 3 to > 21 m. Juvenile diets are presumed similar to those of adults and growth is rapid during the first five years of life (Harkness and Dymond 1961).

Adults

Sturgeon reach sexual maturity between 12 and 33 years old (Table 8). Males usually mature at 14 to 16 years and are about 1.0 to 1.1 m long and weigh between 6.8 and 8.1 kg (Probst and Cooper 1954). Females usually mature between 24 to 26 years, at which time they are about 1.3 to 1.4 m in length and weigh about 15.9 to 18.6 kg (Probst and Cooper 1954). Females live longer than males and account for most of the large (> 1.5 m) and old (> 30 years) sturgeon (Harkness and Dymond 1961; Priegel and Wirth 1974). The greatest recorded weight of a lake sturgeon is 141 kg (Harkness and Dymond 1961). Two fish have been caught, one from Lake Superior in 1922 and another from Lake Michigan in 1943, that were nearly 2.44 m long (Harkness and Dymond 1961). Most adult sturgeon range from 0.9 to 1.4 m in length and weigh from 4.6 to 36.4 kg (Houston 1987). Maximum age varies among sturgeon waters (Table 9). The oldest lake sturgeon on record, which came from Lake of the Woods, Minnesota, was 154 years old and weighed 94.6 kg (MacKay 1963). Adult annual mortality rates are about 0.013 to 0.227 (Table 10).

Adults remain on the bottom and are seldom seen except during spawning and prefer waters usually < 9 m deep, with mud or gravel substrates that provide an abundance of aquatic invertebrates (Priegel and Wirth 1974). However, sturgeon have been caught at 43 m deep (Harkness and Dymond 1961). Sturgeon search the bottoms of shallow areas with sensory barbels and upon contact with benthic organisms, the tubular mouth protrudes and sucks in food, which is then broken down in the toothless mouth (Harkness and Dymond 1961).

Adult lake sturgeon are extreme feeding opportunists. In a study of several lakes, Harkness (1923) found the diet to contain: crayfish, molluscs, insect larvae, nymphs, fish eggs, fishes, nematodes, leeches, amphipods, decapods, and vegetation. Diets of lake sturgeon from Lake des Deux Montagnes, Quebec, contain the following, in order of abundance: crustacea, molluscs, insect larvae, leeches and oligochaetes, and some unidentified prey (Mongeau et al. 1982). In two Quebec tributaries of James Bay, Magnin (1977) found sturgeon diets were dominated by molluscs in La Grande River and by insect larvae in Opinaca River. Another study by Magnin and Harper (1970) in Waswanipi lake and river, Quebec, suggested younger sturgeon fed on insect larvae (Trichoptera, Chironomids, Plecoptera) from sandy reaches, whereas older fish inhabited the softer bottoms and fed on *Hexagenia* sp. and other burrowing Ephemeroptera larvae. These studies show large variability in sturgeon diets and high dependence on food availability.

Individual Growth Rates

Presentations of immature lake sturgeon growth rates can be found accordingly: larvae are 11-20 mm within 20 days (Kempinger 1988), fingerling total length ranges between 175 and 230 mm by September 15 (Kempinger 1984), and juvenile sizes range between an average length of 406 mm (age-1) to 830 mm (age-5) (Kempinger 1985). Growth rates of juvenile and adult lake sturgeon from six water bodies were summarized by Houston (1987) and are presented here (Figure 2). In Lake Winnebago, three-year-old juveniles are about 534 mm long; six-year-olds are about 838 mm long; eight-year-olds are about 1 m long; and fifteen-year-olds are about 1.1 m (Priegel and Wirth 1974). In Lake Nipigon, Ontario, juveniles grew to 483 mm (455 g) by the end of their fifth year, but incremental growth decreases to a range of 127 to 229 mm (909-2727 g) per five year time period during their latter juvenile years (Harkness and Dymond 1961). It takes eight years for a sturgeon to reach 1.0 m in Lake Winnebago; Lake Poygan sturgeon require an additional five years to attain 1.0 m (Priegel and Wirth 1974). Growth rate varies with location and depends mostly on temperature and food availability. Harkness and Dymond (1961) found sturgeon grew faster in both weight and length in southern waters than in northern waters. Weight of females depends on reproductive state (Priegel and Wirth 1974); most weigh about 20% greater before spawning than after (Harkness and Dymond 1961). Adult sturgeon exhibit allometric growth in that incremental growth in length declines to between 76 to 127 mm per year, but is accompanied by an increase in weight gain of 1.3-8.2 kg per five year time period (Harkness and Dymond 1961).

Species Interactions

Potential competitors for spawning habitat in rivers, include the following: walleye (*Stizostedion vitreum*), suckers (*Catostomus* sp.), red-horses (*Moxostoma* sp.), and northern pike (*Esox lucius*). However, all of these species spawn at either different times or in different places than sturgeon (Harkness and Dymond 1961; Priegel and Wirth 1974). Therefore, interference competition for spawning sites is expected to be insignificant. Common suckers (*Catostomus commersoni*) and whitefish (*Coregonus clupeaformis*) are potentially serious competitors for food with sturgeon, because their diets consist mainly of molluscs, insect larvae and nymphs, and shrimp (Harkness and Dymond 1961).

Predation on sturgeon is probably limited to the earliest life stages. Eggs are probably vulnerable to cannibalism and to predation by benthic feeding species such as, carp (*Cyprinus carpio*), catfish (*Ictalurus punctatus*), and suckers (Priegel and Wirth 1974). Young sturgeon are well-protected by sharp scutes and older sturgeon are simply too large to be preyed upon (Harkness and Dymond 1961; Scott and Crossman 1973).

Water Quality

Many levels of water quality support self-sustaining lake sturgeon populations both North and South of Lake Champlain, from the St. Lawrence River in Quebec (Fortin et al. 1993) down to several lakes and rivers in Michigan, including Burt, Mullett, and Black lakes, the Menominee River, and Lake St. Clair and the St. Clair River (Baker 1980). The St. Lawrence and Ottawa river system is well-oxygenated, but contains large amounts of toxic wastes, nutrients, and microorganisms (Fortin et al. 1992). Water of the Missouri and Mississippi rivers in Missouri is assumed to be of sufficient quality to permit successful restoration of lake sturgeon (Graham 1992). Myer and Gruendling (1979) provide no evidence and we have no other information indicating water quality of Lake Champlain and its tributaries is less than the Mississippi or St.Lawrence rivers.

Movements

Residencies and movements of sturgeon throughout the year vary with location. Because Lake Winnebago is uniformly shallow, sturgeon are confined to mud flats throughout the entire year (Priegel and Wirth 1975). In Lake Huron, sturgeon chose shoal habitats in summer and water up to 18.3 m deep in spring and in the Ottawa River, sturgeon reside in deep holes during summer and migrate downstream in fall (Harkness and Dymond 1961).

Sturgeon may travel long distances during spring spawning migrations, up to 400 km (Sandilands 1987). Tagging studies have revealed a strong homing tendency in lake sturgeon. Priegel and Wirth (1974) found Lake Winnebago sturgeon migrate through two small lakes to their spawning grounds in the Wolf River and tagged adults return to their lakes of origin and the populations do not mix. Similar results have been found on the St. Lawrence River and its associated lakes. However, sturgeon have been found to wander. A sturgeon tagged in the St. Lawrence River in 1942 was recaptured 129 km away two years later and a sturgeon tagged in Lake St. Clair was recaptured 28 years later in Lake Michigan (Harkness and Dymond 1961).

A recent study by Fortin et al. (1993) of sturgeon movements in the Saint Lawrence and Ottawa River system indicates sturgeon are a sedentary species outside of spawning season. Of tagged fish, 75.8% were recaptured in the general location of tagging. Fish tagged on the spawning grounds and pre- and post-spawning concentration sites were recaptured throughout the Saint Lawrence River and its lakes. Fortin et al. (1993) suggest sturgeon migrate from various feeding grounds to common spawning grounds and return to their original feeding grounds after spawning.

Very little is known about juvenile sturgeon movements. The exception is a study by Thuemler (1988). He radiotagged juveniles from Lake Winnebago and the Menominee River and stocked them into a different section of the Menominee River. Lake Winnebago juveniles rapidly migrated downstream, whereas Menominee River juveniles remained in the stocked section.

<u>Spawning and Spawning Habitat Requirements</u>

Exact time of spawning migration varies with temperature-related factors, e.g. year and latitude (Harkness and Dymond 1961; Priegel and Wirth 1974). Spawning runs of sturgeon occur from mid-April to mid-June (Table 11), when water temperatures rise to 8 to 23° C (Table 12). Frequency of spawning differs between the sexes. Females usually spawn every four to six years, while males typically spawn every other year (Table 13). In spring, spawning adults seek out rapids below obstructions providing fast, shallow waters with rocky substrates (Harkness and Dymond 1961; Table 14). Depths up to 4.7 m are suitable (Table 15). Velocities of $< 2.0\ m \cdot s^{-1}$ are suitable (Table 16). Swift water provides a strong current minimizing clumping of eggs and egg vulnerability to predation and disease (Harkness and Dymond 1961). On the Wolf River of the Lake Winnebago system, where sturgeon usually spawn on outside river bends, installing riprap improved spawning habitat (Priegel and Wirth 1974; Folz and Meyers 1985).

Lake sturgeon spawn in lakes, if conditions simulating rapids are available. Typical lake spawning habitat is along shallow, rocky shorelines that have strong wave action and depths usually range from 0.9 to 1.2 m (Stone 1901; Harkness and Dymond

1961). Spawning occurs later in lakes, because of the delay in warming (Houston 1987; Harkness and Dymond 1961).

Sturgeon reach spawning grounds before the temperature is optimal for spawning, with males arriving before females. They wait in pools until the desired temperature is reached and then swim directly to spawning beds in groups of one female with six to eight males (Kempinger 1988; Priegel and Wirth 1974). Eggs, demersal and adhesive, are scattered over rocks, with each female depositing several batches of eggs (Kempinger 1988). Fecundity ranges from 50,000 to 885,000 eggs per female (Table 17). The spawning period is about one to two weeks in duration and ends when the temperature exceeds 23° C or water temperature decreases by 1.5-3° C (Kempinger 1988). Upon completion of spawning, sturgeon rapidly migrate downstream (Priegel and Wirth 1974).

<u>Historical Harvest and Current Fisheries</u>

In many bodies of water before 1860, sturgeon found in fishing nets were killed and dumped back in the water, piled on shore to dry and later burned, fed to pigs, or buried as fertilizer (Harkness and Dymond 1961). Commercial preparation of caviar and later, smoked sturgeon were the principal reasons for the sudden intensification of the U.S. and Canadian fisheries. Isinglass, from sturgeon swim bladders, became a source of gelatin (Scott and Crossman 1973). Also, skin was made into leather and oil was extracted from flesh (Harkness and Dymond 1961).

Human uses spurred an intense fishery that contributed to the depletion of sturgeon populations, from which they have never recovered (Scott and Crossman 1973). Early fishery statistics reveal a consistent pattern of high initial yield followed by a sharp and rapid decline to only 2-3% of the maximum yield (Harkness and Dymond 1961; Houston 1987; Table 18). The U.S. fishery peaked in about 1880 and declines began by 1890 (Harkness and Dymond 1961; Priegel and Wirth 1974).

The following accounts of sturgeon declines were given in Harkness and Dymond (1961) and Priegel and Wirth (1974). In Lake Erie, catch dropped more than 80%; from > 2,272 mt to < 454 mt in a short, ten-year period between 1885 and 1895. During the last five years of fishing activity (1952 to 1956) in Lake Erie, average catch was only 0.3% of the 1885 maximum catch. Similarly, in Lake of the Woods, Minnesota, catch declined 70% between 1893 and 1900 and harvest declined 90% from a maximum of almost 818 mt in 1893 to almost nothing by 1920. The Lake Huron fishery experienced a slower decline of 56% in ten years; but during the final years of the fishery, average annual catch was only three percent of the maximum harvest.

Attempts to halt the decline in sturgeon populations began in 1892 with an international fisheries commission of the United States and Canada proposing management recommendations, which eventually were enacted (Harkness and Dymond 1961). These regulations protected spawning fish, fishing licenses were limited to specified capture methods and numbers and sizes of fish, obstructions and pollution of habitats was prohibited, and spawning grounds and juveniles were protected. Some fisheries were closed for 10 to 20 years to permit recovery of populations. But, closures usually failed to restore sturgeon populations because of length of time for sturgeon to reach harvestable size. The best method for limiting harvest proved to be shortening the fishing season (Harkness and Dymond 1961).

At present, population numbers are low in most sturgeon waters in the U.S. The Lake Winnebago system has sustained a significant sturgeon population (Ronald Bruch, Wisconsin Department of Natural Resources (WDNR), personal communication), despite many years of intensive fishing, probably because of good foraging habitat (water < 6.4 m deep) throughout the entire basin and abundant spawning habitat in the major tributaries (Probst and Cooper 1954). About 1950, the State of Michigan opened a very limited fishery during January and February (Williams 1951).

In Canada, the geographical range of lake sturgeon remains similar to that of historic times, however populations have seriously declined in most areas (Houston 1987). According to Fortin (1991), Canadian commercial fisheries in the St. Lawrence River and several other Quebec river drainages show high annual yields. However, Lake St. Francis yields are low, because of overexploitation and reduced recruitment (Fortin 1991). A commercial fishery in Manitoba permits a marketable quota of 18.1 metric tons, but only about 6.3 metric tons are commercially harvested each year, because of low sturgeon numbers (Houston

1987). One case of sustained populations is in Alberta, where sturgeon stock numbers are similar to those of historic levels (Houston 1987).

Restoration Problems

Restoration of sturgeon is a difficult process for several reasons; many pertaining specifically to life history. From life history theory, we know sturgeon are *K*-selected species because they mature late, grow slowly, and exhibit infrequent spawning (Pianka 1970). These *K*-selected factors dictate that recovery programs should only be implemented where a long-term commitment can be guaranteed.

Habitat alterations compound biological problems of restoration. Dams on tributaries can block migration to potential upstream spawning grounds and may destroy spawning habitat immediately below. However, many dams occur at natural barriers to spawning sturgeon (Harkness and Dymond 1961), and sturgeon may be able to spawn in the rapids below the lowest dams. The major impact of dams on spawning success lies in flow regulations from April to mid-June. If dams do not release enough water to provide a downstream depth of at least 1.5 m (Table 15), spawning habitat may not be suitable. Low summer and fall flows may destroy fry and fingerling habitat.

Recovery of lake sturgeon populations may also be hampered by pollution from industrial and domestic effluents. Pulp and paper mill effluent negatively impacts spawning, hatching, and survival of lake sturgeon by smothering eggs and food sources and by releasing toxic sulphite waste (Harkness and Dymond 1961). Many spawning grounds experience a high degree of disturbance related to construction and nearby roads, which has sometimes resulted in sturgeon abandoning those spawning grounds (Harkness and Dymond 1961).

Apparently, from the sparseness of literature pertaining to health issues in lake sturgeon populations, restoration efforts are not likely affected by parasites or diseases in the wild. Recorded parasites include several species of trematodes, acanthocephalids, nematodes, cestodes, and crustaceans (Harkness and Dymond 1961; Scott and Crossman 1973). Another obvious parasite is the sea lamprey, which attaches to the skin of the sturgeon and causes sores and scars. However, scutes probably protect the body cavity from wounds (Harkness and Dymond 1961; Priegel and Wirth 1974).

Two types of diseases are known to affect sturgeon eggs, lipoid degeneration and development of an egg 'cement'. Lipoid degeneration occurs when ripe females cannot find suitable spawning conditions. In 'cement', a greyish liquid results in flotation of the remaining eggs and ovarian cysts appear as clusters on the ovarian tissue (Harkness and Dymond 1961).

Genetic concerns of lake sturgeon in the wild are based on low population numbers coupled with stock homogeneity. In Quebec, Fortin et al. (1991) have identified sturgeon from Lac des Deux Montagnes, Lac Saint-Louis, Lac Saint-Pierre and Saint-Laurent River downstream from Lac Saint-Pierre as distinct stocks based on their high degree of sedentariness and differences in growth and total mortality. These results were initially corroborated by the movements and biological statistics determined by Fortin et al. (1993). Sturgeon in Lac des Deux Montagnes had more restricted movements, slower growth, and lower condition factor than sturgeon from Lac Saint-Louis and Lac Saint-Pierre. Lac Saint-Pierre sturgeon had lower lengths, weights, ages, and survival rates than Lac Saint-Louis sturgeon. Overall movements of sturgeon were very limited outside of the spawning season. Fortin et al. (1993) conclude that sedentariness of lake sturgeon, combined with the effects of fisheries and environmental conditions, results in differences in population parameters of sturgeon in different places within the same hydrographic system. Common spawning grounds of Lac Saint-Louis and Lac Saint-Pierre sturgeon suggests those fish may be members of the same gene pool, but restricted movements of Lac des Deux Montagnes sturgeon probably results in a distinct genotypic stock (Fortin et al. 1993). However, surprisingly Guenette et al. (1993) found, according to mitochondrial DNA analysis, the St. Lawrence river sturgeon form a homogeneous genotypic group that is not significantly different from Lac des Deux Montagnes sturgeon. The low index of heterogeneity for sturgeon in the St. Lawrence system suggests that sturgeon should be considered a single population (Guenette et al. 1993).

Population Assessment

Lake sturgeon population assessment is usually based on survival and growth rates, age-at-maturity, condition factors, age structure, and ratio of males to females. Eggs and larvae have been sampled effectively in only a few studies (Kempinger 1988; LaHaye et al. 1992). Kempinger (1983, 1984, 1985) sampled fingerlings in summer and fall 1982-1984 with seines, trawls, scuba diving, canoe observation, electroshocking, and gillnetting. Electroshocking was the most effective method of sampling, with a total of 188 fingerlings captured (Kempinger 1983, 1984, 1985). Adults can be sampled by a variety of methods including spearing (Folz and Meyers 1985; Priegel and Wirth 1975), trap nets and otter trawls (Folz and Meyers 1985), gillnets (Cuerrier 1966, Jolliff and Eckert 1971, Threader and Brousseau 1986), trot and trammel lines (Missouri Department of Conservation (MDOC) 1981), and longlines (Threader and Brousseau 1986). In recent Canadian studies (e.g. Fortin et al. 1993), most fish were collected from commercial and/or sport fisheries. Mark-and-recapture studies can be conducted to determine growth rates, population estimates, survival rates, and movement patterns when there are sufficient numbers.

Sampling of juvenile sturgeon has occurred in very few studies; thus, methods for assessing the status of juvenile lake sturgeon have not been developed. One study in Wisconsin involved radiotagging one year old sturgeon to determine movements (Thuemler 1988). Lake sturgeon, ages 2 to 25 ranging in length from 38.8 to 127.0 cm were captured in gill nets in the Saint Lawrence and Ottawa River systems, but those < 80 cm (mean age = 10 years) were captured less effectively than larger ones (Fortin et al. 1993). Lack of good population assessment methods for lake sturgeon has led Missouri's restoration program to develop sampling strategies, so assessment criteria can be established (Graham 1992). We anticipate that Missouri's findings will be helpful in establishing assessment criteria for sturgeon in Lake Champlain.

Restoration Programs

Stocking

Restoration of lake sturgeon populations requires artificial culture in most areas because of extremely low numbers of fish in remnant populations. Early culture attempts in the late 1800's and early 1900's failed because of difficulties in finding ripe individuals of both sexes simultaneously, difficulties of gamete collection, adhesivity of eggs, fungal disease of eggs, and poor feeding of larvae and juveniles (Harkness and Dymond 1961). WDNR renewed attempts to culture sturgeon in 1979 as a tool for conservation and restoration. Wild Rose State Fish Hatchery in Wisconsin hatched 135,200 lake sturgeon eggs in 1982, and thus marked the beginning of successful lake sturgeon culture (Czeskleba et al. 1985). These embryos were stocked into the Red Cedar River. In the Menominee River for population restoration, 291 sturgeon (18 cm) were stocked in September 1982 and an additional 11,000 yearlings were stocked into the river in June 1983.

Wisconsin DNR began reestablishment efforts on the St. Louis River, Minnesota, in 1983 with the stocking of 82,000 eight-day-old embryos in May and an additional 11,000 yearlings in August 1983 (Czeskleba et al. 1985). Electrofishing was used to monitor survival of these fish (Thuemler 1985), which was 71% in 1985 and 90% in 1986 (Thuemler 1988). In addition to the efforts by Wisconsin DNR, the St. Louis River has been stocked heavily by the Minnesota Department of Natural Resources (Anderson 1987). Lake sturgeon fry were collected from Wisconsin and raised to the fingerling stage at the St. Paul hatchery resulting in 5,700 coded-wire tagged fingerlings (13 to 18 cm) that were stocked into the St. Louis River in 1985 and another 500 in 1986 (Anderson 1987). An additional 20,000 fingerlings were stocked in 1988 (Schrank 1989).

MDOC has recently undertaken an extensive restoration program in the Mississippi and Missouri rivers. The following is a brief outline of the Missouri plan given in Graham (1992). Goals are to reestablish self-sustaining lake sturgeon populations, to gain public support for sturgeon restoration, and to eventually have a population that will support limited sport harvest. Missouri stocked 23,500 fingerlings in 1984 and 1986, and 21,500 fingerlings in 1988 and 1990. Reports of 2.3 to 3.6 kg sturgeon netted by commercial fishermen suggest substantial survival of these stocked fingerlings. MDOC plans to stock

30,000 (20.3-25.4 cm) fingerlings annually for ten years. A population of ten year-classes is assumed to be sufficient for successful natural reproduction. A major component of the Missouri plan is to develop appropriate sampling methods that will enable biologists to evaluate stocking success and to monitor the population. When 15 to 20% of the population reaches at least 127 cm long, which is unlikely to occur during the 10 years of the plan, a hook-and-line limited sport fishery will be initiated. If a fishery is opened, creel surveys will be used as a means of assessing success of the restoration program.

Hatchery Genetic Concerns

The number of parental sources of gametes required to provide sufficient genetic variability for viable populations has not been addressed by culture or restoration programs to date. Graham (1992) states that longterm rarity of lake sturgeon in the Mississippi and Missouri rivers has resulted in an insufficient number of adult fish in the existing populations to establish a significant, viable, and naturally reproducing population. The Missouri restoration program assumes that 10 year classes from an annual stocking of 30,000 fingerlings is sufficient for the development of a naturally sustaining population (Graham 1992). But, Missouri does not address the issue of numbers of adults needed in the collection of gametes for introducing enough variability to avoid problems of introgression when these fish eventually attempt to reproduce.

Lake Champlain Sturgeon History

Lake Champlain (Figure 3), historically supported a small, but stable lake sturgeon population. Halnon (1963) documented the sturgeon fishery, which began in the late 1800's and consistently produced between 50 and 200 fish annually until the late-1940's (Figure 4). Biomass of these harvests showed a similar pattern (Figure 5). Primary methods of harvest were gillnets, haul seines, and tip-ups (Cobb 1905). Locations of fishing grounds were recorded by Vermont Fish and Game from 1901-1906 (Appendix II). Lake Champlain followed the typical pattern of high yields of lake sturgeon and then a rapid decline. By 1952, the annual harvest plummeted to ten fish; however, note that no data were recorded for the years 1914-1939 (Figure 4). The sturgeon fishery on Lake Champlain was officially closed in 1967, although the last recorded harvest was in 1962. The population has never recovered and sturgeon are now very infrequently sighted or caught. Vermont Fish and Wildlife has recorded sightings or catches up to 12 sturgeon annually between 1980 and 1993, but most years, sightings are considerably less (Table 19). Based on fishery data, we estimate an historic population of 3,000 adult sturgeon in Lake Champlain. (Regression for calculating population size is given in the population model section).

Not only have sturgeon been much more abundant on the Vermont side of the lake (Harkness and Dymond 1961), but there is no evidence that sturgeon presently spawn or spawned in the past in the New York waters of Lake Champlain (Lawrence Nashett, NY DEC, personal communication). Historical spawning grounds were located in the Missisquoi and Lamoille rivers (Carter 1904; Stone 1901; Stone 1900). Since the installation of the Swanton dam on the Missisquoi River in the early 1900's, sturgeon have been limited to spawning in the rapids below the dam (Halnon 1963). However, sturgeon historically migrated further upstream to other spawning grounds at the base of Highgate Falls (Michael Delaney, Abenaki tribal judge, personal communication). On the Lamoille River, sturgeon historically spawned in the Sturgeon Hole below Woods Falls (Carter 1904; Stone 1901). Since the installation of Peterson Dam in 1948 at the Sturgeon Hole, potential spawning habitat has been limited to the rapids below the dam (Halnon 1963). Spawning runs of sturgeon were at one time large enough that the Missisquoi and Lamoille rivers were chosen for early efforts at artificial propagation (Harkness and Dymond 1961). Sturgeon also migrated to spawning grounds in the Winooski River and Otter Creek, but the specific locations were not documented (Harkness and Dymond 1961). Before the Vergennes dam, located 12.5 km from the lake (Jenkins and Zika 1988), was installed on Otter Creek, the falls at Vergennes limited spawning migrations. Winooski Falls, located 14.9 km from Lake Champlain (Jenkins and Zika 1988), limited sturgeon spawning migrations on the Winooski River even before the existing dam was installed.

Lake Champlain Habitat Assessment

Habitats used by sturgeon in lakes can be related to lake productivity. Especially important to sturgeon success are shallow areas that provide an adequate benthic forage base. For example, long ago the shallow Lake Erie produced 75 times as many sturgeon as the much deeper Lake Superior; however, when expressed in terms of the area of water < 18.3 m deep, lake sturgeon production was only 10 times greater in Lake Erie (Harkness and Dymond 1961). Water < 9.1 m deep is the lake habitat most conducive for supporting lake sturgeon. Lake Champlain has 441 km^2 of < 9.1 m deep (Myer and Gruendling 1979). Where populations exist, adult lake sturgeon numbers range from 5 to > $500 \cdot km^{-2}$ (Appendix III). Assuming an historic population of 3000 adults, the concentration of adults in shallow water areas of Lake Champlain would be $\approx 7 \cdot km^{-2}$.

Riverine habitat is critical for lake sturgeon spawning and early life residence. To determine the availability of suitable spawning grounds for lake sturgeon, quality and quantity of the current habitat was characterized for two historic spawning tributaries, the Lamoille and Missisquoi rivers. Spawning habitat requirements for lake sturgeon have been described (LaHaye et al. 1992; LaHaye and Fortin 1990; Kempinger 1988). Sturgeon spawn at depths up to 4.7 m, with a peak between 0.4 and 1.5 m. Velocities are optimal between 0.15 and 1.0 $m \cdot s^{-1}$, but are suitable up to 2.0 $m \cdot s^{-1}$. Substrates of sand to boulder are suitable for spawning; but gravel, cobble, and boulder are best.

(Substrates were classified according to the Wentworth scale (Bovee 1982)). These spawning requirements for depth, velocity, and substrate (Tables 14-16) were converted to probability-of-use (SI) curves to assess riverine habitat for lake sturgeon during spring and early summer (Figure 6).

Probability-of-use curves relate the number of eggs deposited by lake sturgeon to specific habitat values. These relations between number of eggs deposited and habitat variable values were then converted to an index where values that support the maximum density of eggs are scaled to a value of one, representing optimal habitat conditions for the variable in question. Habitat values for which no eggs were found are scaled to an index value of zero, representing totally unsuitable habitat conditions for that variable. Thus, values for each individual habitat variable are normalized to probability-of-use indices between zero and one.

Probability-of-use curves have three primary assumptions. First, individuals of a species are assumed to select areas that provide the most favorable combination of hydraulic conditions. For lake sturgeon spawning habitat, these hydraulic conditions are based on depth, velocity, and substrate. The second assumption is that individuals will use less favorable conditions with a decreasing probability as the favorability of the hydraulic conditions diminishes. The final assumption is that individuals will leave an area before its hydraulic conditions become lethal (Bovee and Cochnauer 1977).

The instream flow incremental methodology (IFIM) uses probability-of-use curves to evaluate the suitability of riverine habitat to support a species under a variety of flow regimes (Bovee 1982; Bovee and Cochnauer 1977). To do this, a section of river, defined as a stream reach, is subdivided into transects which are subdivided into cells. The habitat variables are measured in each cell of each transect at a constant flow. Probability-of-use curves are then used to convert actual habitat measurements to values between zero and one. Finally, these index values can be used in calculations that describe both the habitat quality and quantity of the stream reach.

Habitat information for each transect is used to characterize a subsection of the stream reach under study. The length of this subsection is taken as half the distance to the closest upstream transect and half the distance to the closest downstream transect. The area of the subsection equals the product of the transect width and length. Habitat within each subsection is characterized according to its cells. Each cell describes the habitat for an area equal to the product of cell width by cell length. Thus, transect habitat is described by its cell habitat characteristics, and stream reach habitat is described by the habitat characteristics of its transects.

Habitat quality is described for each cell in each transect by a composite probability; i.e., the product of the probability-of-use indices for each habitat variable measured. For example, for lake sturgeon, the composite probability is the product of the probability-of-use indices for depth, velocity, and substrate. The overall habitat quality of the stream reach is then described by the distribution of the composite probabilities of its component cells.

Habitat quantity is described for the stream reach by a weighted usable area (WUA). In other words, WUA is calculated by first multiplying each cell's composite probability by its associated cell area, then summing the results for all cells in the stream reach (Bovee and Milhous 1978). WUA calculations (m^2 and m^2 per 10 m) show the Lamoille River has more suitable habitat per m^2 than the Missisquoi River (Figures 7 and 8).

IFIM was used to describe lake sturgeon spawning habitat for the Lamoille and Missisquoi rivers. An IFIM study of the Missisquoi River was conducted in 1987 by Vermont Hydroelectric, Inc. Data for this river was collected at a flow of 34 $m \cdot s^{-1}$, which is typical of Spring conditions at the time of lake sturgeon spawning. The stream reach was located immediately below the lowest dam on the river at Swanton. This dam is a barrier to lake sturgeon spawning migrations, but lake sturgeon historically spawned below that area (Stone 1900). The reach consisted of transects that subdivide a 183-m section of riffle, run, and pool habitat directly below the dam. Rationale for stream reach and transect selections are described by Vermont Hydroelectric, Inc (1987).

An IFIM study of the Lamoille River was conducted by Central Vermont Public Service Corporation during 1987. The study site was located below Peterson dam, the lowest dam on the river. The stream reach for the study was located from 82 to 365 m below the dam and consisted of seven transects. Habitat data was collected at a flow of 20.6 $m^3 \cdot s^{-1}$. Habitat information from the 20.6 $m^3 \cdot s^{-1}$ flow was extrapolated to a flow of 36.8 $m^3 \cdot s^{-1}$, the expected flow at spawning time, by hydraulic simulation modeling.

Hydraulic simulations describe the changes in the distribution of velocities, depths, and substrates as a function of flow (Bovee and Milhous 1978). These simulations are based on the Manning equation, which defines the relationship between channel features and the velocity in a channel as:

$$Q = (1.486 * R^{2/3} * S_e^{1/2} * A)/n$$

where: Q = discharge ($m^3 \cdot s^{-1}$)

R = hydraulic radius

S_e = slope of the energy grade line

A = cross sectional area of flow (m^2)

n = coefficient of roughness, Manning's n

For a given flow regime, Manning's n can be calculated for each cell. The equation of continuity states that $Q = A * V$ (V = average velocity of flow through the cross section $m \cdot s^{-1}$). Manning's equation can thus be redefined as:

$$V = (1.486 * R^{2/3} * S_e^{1/2})/n.$$

This form of the equation permits the determination of cell velocities for other flow conditions.

Flow is directly proportional to total area. Flows of individual cells can thus be calculated by multiplying the total flow by the fraction of the total area that each cell comprises. With Manning's n and flow known for each cell, the velocity and depth can be calculated from hydraulic simulation modeling. Therefore, the predicted hydraulic conditions can be described as the probability-of-use indices and WUAs for various flow conditions.

The Lamoille River provides a minimum of 79 meters of sturgeon spawning habitat in the rapids from 119 to 198 m below Peterson dam. At a Spring flow of 36.8 $m^3 \cdot s^{-1}$, this section contains 59% highly suitable habitat, 12% semi-suitable habitat, and 29% poor habitat. Although there is a large percentage of highly suitable habitat, the area in the Lamoille for sturgeon is not large (Figure 9). The Missisquoi River provides spawning habitat in about 183 m of riffle, run, and pool habitat below the Swanton dam. At a Spring flow of 34 $m^3 \cdot s^{-1}$, this section contains approximately equal proportions of highly suitable, semi-suitable, and poor habitats; however, sizes of specific transects show variability in habitat quality (Figure 9). The Missisquoi River has less spawning area available than the Lamoille River (Figure 9).

The Winooski River historically provided sturgeon spawning habitat below Winooski Falls and in the Salmon Hole and nearby shoal areas. Chace Mill hydroelectric project site studies suggest that this area may still provide suitable sturgeon spawning habitat during Spring flows of 28.3 to 42.5 $m^3 \cdot s^{-1}$. Otter Creek may provide sturgeon spawning habitat below the

Vergennes dam; however, no IFIM studies have been conducted.

In summary, suitable sturgeon spawning habitat exists in both the Missisquoi and Lamoille rivers. The Winooski River and Otter Creek may also provide suitable spawning habitat.

Population Model and Potential Stocking Strategies

A discrete-time, age-specific model for lake sturgeon populations was developed. The purpose of the model was to identify various stocking strategies that would lead to a stable population of adult lake sturgeon similar in size to historical populations in Lake Champlain. In this model, 60 age classes (lake sturgeon live 60 years, Sandilands 1987) were treated separately and survivorships of juveniles and adults were density independent. Density dependence was incorporated into the model in egg survivorship because spawning habitat is limited (previously addressed in the section on habitat assessment), thus, egg survivorship will decline as sturgeon densities increase. A stocking component is included in the model that allows for stocked fish to enter the age-1 lifestage. The age-specific population model was run using Stella II software (Appendix IV).

Model Characteristics

Estimates of Historic Population Size

Carrying capacity for adult lake sturgeon in Lake Champlain was determined from the historical population estimate. Historic population levels are assumed to be the maximum number of adult sturgeon that Lake Champlain can support. Harvest data are available from the Lake Champlain commercial fishery through the years 1896-1962. Population size was estimated from the relation between fishing success and cumulative catch using the Leslie method (Ricker 1975; Figure 10). The catch equation is:

$$C_t/f_t = qN_o - qK_t$$

where: C_t/f_t = number of sturgeon caught per license

K_t = cumulative catch of sturgeon

q = catchability = slope of C_t/f_t vs. K_t

N_o = estimated original population size

The regression of C_t/f_t as a function of K_t results in the following equation:

$$C_t/f_t = 50.5 - 0.016573K_t,$$

which yields values for q and N_o, $q = 0.016573$ and $N_o = 50.5/0.016573 = 3047$.

Although the regression equation had a low correlation coefficient ($r^2 = 0.34$), the relation was significant ($P = 0.0014$). Therefore, we set the maximum Lake Champlain population size to 3,000.

Model Parameters

We used various lake sturgeon studies to estimate some parameters. Yearly survival probabilities of age 2 to age 45 fish (0.988) and age 46 to 60 fish (0.866) were taken from the literature (Sandilands 1987). Survival of age-1 juveniles was highly uncertain; therefore, a series of survival probabilities were tested (see below) under each stocking strategy. Reproduction begins at age 21 when lake sturgeon reach sexual maturity (Table 8). Beginning at age 21, female fish spawn every five years (Table 13) for the next 39 years producing 250,000 eggs per female (Table 17). Density dependence reduces this 250,000 eggs/female by factors relating to fish density and spawning habitat (see below). After eggs are successfully laid (density dependence has reduced their number), eggs have a survival probability to hatch of 0.01 (Table 2).

The logistic equation was used to describe the relationship between the total number of eggs spawned (density of female sturgeon x effective fecundity of an individual) and eggs successfully laid. This equation yields

$$Eggs_{t+1}=b*N_t*f*(1-(N_t*f)/K)$$

where N_t is the density of females at time t, f is the effective fecundity of a female (250,000/5; 250,000 eggs per female spread over 5 years), K is the egg carrying capacity, and b is the probability of survival of eggs during the spawning process. Note that the number of eggs successfully laid is close to the maximum when N_t*f is much less than K. As N_t*f increases the number of eggs successfully laid decreases. As such, this equation regulates population size in our model because of limited spawning habitat availability.

Values of K and b that gave stable populations of lake sturgeon of about 3,000 adults (historical carrying capacity, see above) were estimated using the full model. Probabilities of survival of an egg during spawning of 0.0001 and 1.0 and carrying capacities between 5 and 500 million eggs were modeled. Five hundred age-1 fish were stocked once. A probability of survival of 0.0005 and an egg carrying capacity of 125 million resulted in an equilibrium population of 2,900 adults in 180 years. Thus, the density dependent equation used in further tests of the model was

$$Eggs_{t+1}=0.0005*N_t*250,000/5*(1-(N_t*250,000/5)/(1.25 \times 10^8))$$

(parameters defined as above).

Experiments with the model

The goal of the model was to determine stocking strategies that produced stable populations of about 3,000 adult lake sturgeon. Annual stocking into the age-1 class of 500, 5,000, and 10,000 were simulated for stocking 10 consecutive years and for continuous stocking. Stocked fish are subject to the age-1 survival rate, which is highly uncertain. These uncertainities were incorporated into a wide variation in the survival of age-1 juveniles. Each stocking strategy was tested under five different age-1 survival rates (0.01, 0.05, 0.10, 0.50, and 0.90).

Explanation of Model Results

For Lake Champlain sturgeon, spawning habitat limitation is defined as an egg carrying capacity of 125 million. When too many eggs are produced, egg survival is lower because of density-dependent effects such as disease, increased predation rate, and disturbance of spawning grounds from overcrowding of adult spawners. Therefore, the rate of change in egg abundance is always negative (decreasing) when egg production is in excess of 125 million eggs (the egg carrying capacity). Egg production of < 125 million results in increased rate of survival because the environment can adequately support the development of these eggs. The rate of egg production is stabilized at 125 million. This level of egg production corresponds to an adult population of about 3000, if the survival of age-1 fish is 0.90.

Stocking fingerlings bypasses the egg stage. Therefore, no density-dependent effects occurred until the stocked fish begin to naturally reproduce after 20 years. When the population of sexually mature fish from the stocking of fingerlings exceeds 3000, their egg production is unsuccessful because of overtaxing the available habitat.

This situation occurred in a very pronounced manner for the simulated annual stocking of 5,000 and 10,000 fingerlings for 10 years. The population of stocked fish appear as adults between years 20 and 60. Their excessive egg production (much greater than 125 million) causes the survival of these eggs to be zero because of too high densities in the spawning habitat.

Therefore, when the stocked fish die out (between years 60 and 70), no naturally-produced adults exist to replace them because of their unsuccessful egg production. Egg survival becomes positive only when egg production is < 125 million, which finally occurs during the final years of the stocked sturgeons' lives. Therefore, growth of a new population is dependent on eggs produced between years 65 and 70. Survival of these eggs is still low, however, because there is still a relatively large adult population that is producing quantities of eggs approaching carrying capacity (125 million).

At this point, successfully hatched eggs (2nd generation) produce fish that reach sexual maturity 20 years later and produce eggs (3rd generation) between years 85 and 130. (By this time, there is a smaller adult population producing eggs because of the decline in the numbers of stocked sturgeon. Therefore, numbers of eggs spawned has declined.) Eggs of the third generation in turn mature and an increase in the rate of egg production to the egg carrying capacity is reached. At that level, the rate of egg production ceases to increase and a stable annual egg production of 125 million is sustained. This corresponds to a stable adult population of about 3000. The time required to reach this level is about 250 years. As stated above, this time is required because of densities in the spawning habitat beyond the capacity of 125 million eggs. In addition, the population rebounds slowly because of the low probability of egg survival of 0.0005.

The time requirement could be bypassed with continued stocking of fingerlings past the 10-year mark. However, the population would be based on stocked fish rather than naturally-reproduced fish because of the continued excessive egg production by the huge population of mature fish of stocked origin that by-pass the density-dependent egg lifestage. Stocking of 500 fish annually avoids overtaxing of the environment, and thus results more quickly in a naturally reproducing and self-sustaining population. However, because of the huge degree of uncertainty involved in lake sturgeon restoration, it is probably best to err on the safe side of stocking 5,000 or 10,000 fish annually until a survival estimate of the fingerlings through sexual maturation is determined.

Potential Stocking Strategies

A control was run with 500 fingerlings stocked once to determine the baseline population growth pattern. Results showed adult populations ranging from 4 to 320 would develop by year 30 (Figure 11). Age-1 survival rates of 0.01, 0.05, and 0.10 do not sustain these populations; very few adults are extant after 100 years. If the age-1 survival rate is 0.50, a population of about 560 adults develops by year 250. The 0.90 age-1 survival rate results in an adult population of about 2,935 by year 180.

Annual stocking of 500 fingerlings produces populations of adult sturgeon within 30 years that range from 38 to 3,390 for age-1 survival rates of 0.01 to 0.90. If stocking was terminated after 10 years, only the 0.50 and 0.90 age 1 survival rates produce significant populations (Figure 12). A survival rate of 0.50 produces an adult population of about 1,290 after 100 years. The 0.90 survival rate produces a stable population of about 2,935 adult sturgeon after 100 years. With continuous stocking, these populations increase to between 108 and 9,513 adult sturgeon in about 100 years (Figure 13), depending on age-1 survival.

If the stocking rate is increased to 5,000 fingerlings, in 30 years adult populations of 377 to 33,900 develop, for age-1 survival rates ranging from 0.01 to 0.90. If fish were stocked for only 10 years, population sizes for the low age-1 survival rates (0.01, 0.05, 0.10) would be 377 to 18,800 fish by year 30 (Figure 14), but would not be sustained. Few adults are present after year 60. For an age-1 survival rate of 0.50, a stable population of about 665 adults develops around year 230. The 0.90 age-1 survival rate again results in a stable population of about 2,950 adults after 230 years. With continuous stocking of 5,000 fingerlings, stable populations of 1,060 to 95,200 develop within 60 years (Figure 15), depending on age-1 survival rate.

Maximum stocking density tested with this model was 10,000 fingerlings. This strategy produces large populations of adults within 30 years. Numbers range from 750 to 67,800 for age-1 survival rates between 0.01 to 0.90. If 10,000 fingerlings are stocked annually for just 10 years, low age-1 survival rates produce populations that peak about year 30 and collapse by year

70 (Figure 16). With a 0.50 age 1 survival rate, a large population of about 37,670 adults develops by year 30, temporarily declines by year 70, and rebounds to 500 adults by year 230. Age-1 survival of 0.90 shows a pattern similar to that of the 0.50 survival rate. At 30 years, an extremely large population of about 67,800 adults exists. This population experiences a temporary decline during the years 70 through the 80s. By year 250, a renewed population of about 2,950 adults is established. With continuous stocking, these populations reach from about 2,125 to 190,260 adults by year 60 (Figure 17). We show the trade-offs of various stocking strategies at the 0.1 (Figure 18) and 0.5 (Figure 19) juvenile survival rates.

Study Recommendations

In the section on restoration programs, we presented a brief outline of the plan to reestablish lake sturgeon in Missouri (Graham 1992). Because lake sturgeon are endangered in Vermont and in Missouri, we find more parallels with the Missouri plan to reestablishing lake sturgeon in Lake Champlain than any other ongoing program. We based our recommendations for restoration on the Missouri Restoration Plan (Graham 1992), historic Lake Champlain sturgeon population information, and simulations from a lake sturgeon population model. In conducting this study, we considered alternate strategies to stocking for restoring lake sturgeon. However, because very few fish have been sighted in Lake Champlain tributaries in recent years and because of the long age to maturity, we conclude that the likelihood of achieving restoration through natural reproduction of current residents is extremely small. We submit the following strategies and rationale for restoring lake sturgeon to Lake Champlain, to be used wholly or in part in a restoration plan, <u>if</u> a goal is adopted to reestablish a self-sustaining population of lake sturgeon in Lake Champlain.

Thus, <u>IF</u> the above stated goal is established, we would recommend the following strategies as guidelines:

<u>Initial 10 Year Stocking</u>

<u>Strategy</u>: Annual stocking of 10,000 fingerlings into Lake Champlain tributaries for 10 years.

<u>Rationale</u>: In Missouri, the Mississippi River is stocked at a density of 494 $fish \cdot km^{-2}$ and the Missouri River is stocked at about 371 $fish \cdot km^{-2}$ (Graham 1992). Approximately two-thirds of Lake Champlain, which contains 441 km^2 of water $<$ 9 m deep, is in Vermont. Stocking densities for Lake Champlain should be based on the area of water $<$ 9 m deep that is located in Vermont for the following reasons: historically, lake sturgeon were known to have spawned only in tributaries located on the Vermont side of the lake; and the population model, which is based on Vermont data only, assumes spawning habitat is limiting. Assuming uniform proportions of water $<$ 9 m deep in both Vermont and New

York, Vermont contains about 294 km^2 of this depth of water. Stocking densities of 371-494 $fish \cdot km^{-2}$ would require annual stockings of 10,897-14,529 fingerlings for ten years.

The population model was used to simulate annual stocking strategies of 500, 5,000, and 10,000 fingerlings for ten years. Stocking for ten years has an initial peak in an adult population at about 30 years, which then crashes at about 60 years because of termination of stocking. Natural reproduction eventually produces new, stable adult populations in about 250 years. Stocking 10,000 fingerlings for ten years results in a density of about 346 $fish \cdot km^{-2}$ in Vermont. A stable population of about 2,900 adults results after 250 years, if survival is 0.90. If survival is 0.50, the population will only reach 500 fish in 250 years. Lower survival rates (< 0.01) would be insufficient to produce any significant adult population.

Assessment

Strategy: After ten years of stocking, status of juvenile lake sturgeon should be determined. If survival of stocked fish is low, research should be initiated to determine the causes of mortality. After 20 years, status of adults and spawning should be determined. If there is no evidence of spawning, studies should be initiated to address the factors contributing to a lack of spawning success.

Rationale: Stocking evaluation procedures will need to be established to facilitate documenting success of the initial stocking strategy. An extensive sampling program to address, e.g. survivorship, movements, habitat usage, and growth rates, will need to be implemented. Research should determine causes of mortality and indicate alternative approaches to restoring lake sturgeon if initial stocking strategy is not successful.

Continued Stocking

Strategy: Continued stocking would shorten the time required to reach a stable population to 60 years rather than 250 years. After 10 years, if age-1 juvenile survival is < 0.1, stock 10,000 annually, but if survival is > 0.1, stock 5,000. Stocking strategies after 20 years will rely on information from population assessments and from research studies.

Rationale: Annual stocking of 5,000 fingerlings would result in about 10,700 to 52,900 adults in 60 years, if age-1 survival was between 0.1 and 0.5. If 10,000 were stocked annually, the population at 60 years would be between 21,000 and 106,000 for survival rates of 0.1 to 0.5. Because the historic population of Lake Champlain is estimated at 3,000, very large populations may overtax the forage base. Therefore, if population assessment indicates survival of stocked fingerlings at > 0.1, continued stocking after the ten-year mark should be limited to 5,000 annually. After 20 years, numbers of spawning adults should be assessed and adjustments should be based on the combination of spawning status and juvenile survival.

Potential Fishery

Strategy: In this initial phase of restoration planning, we have chosen not to address a fishery strategy, since about 60 years are required to establish a significant lake sturgeon population. However, a limited fishery could be initiated, if numbers of lake sturgeon allowed for removal from any protected fish list.

Rationale: Population studies of Wisconsin suggest a maximum harvest of 5% of the adult population to prevent overharvesting (Priegel and Wirth 1974) and Missouri's plan recommends a limited harvest when 15-20% of the population is 127 cm (Graham 1992). These conservative guidelines or similar ones, should prevent any possibility of declining population numbers through harvest.

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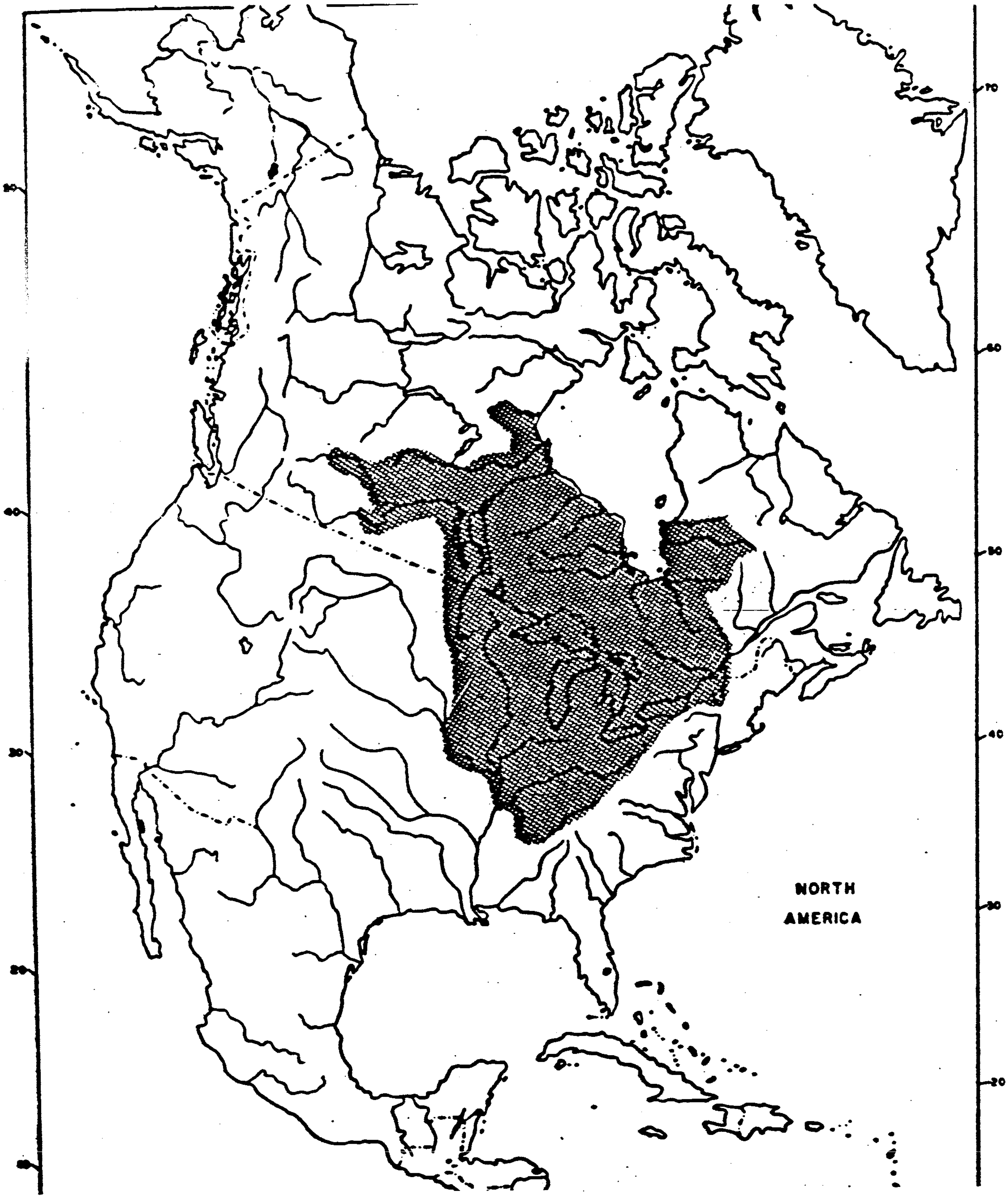


Figure 1. North American distribution of the lake sturgeon (from Houston 1987).

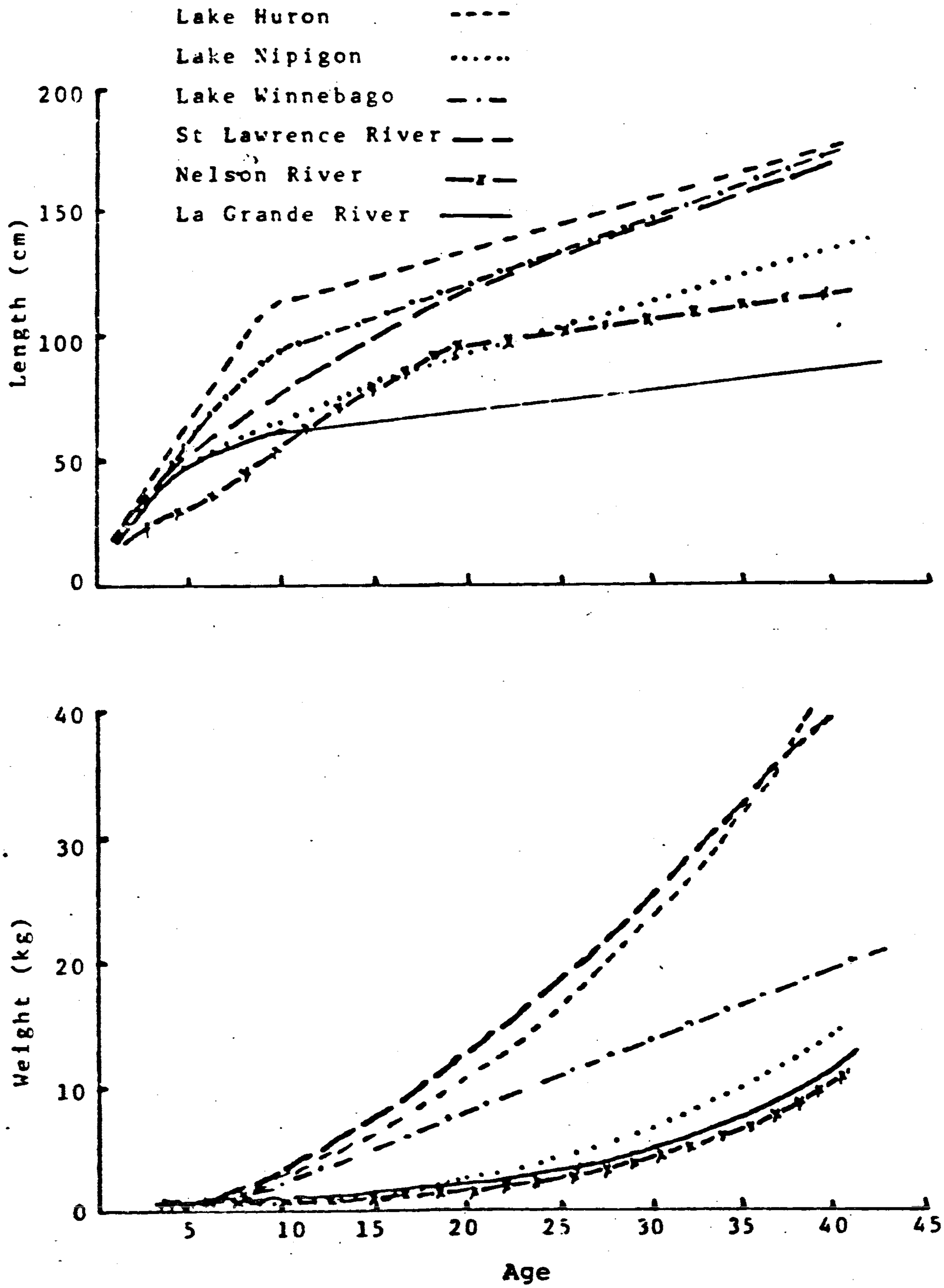


Figure 2. Growth rates of lake sturgeon in North American lakes and rivers (from Houston 1987).

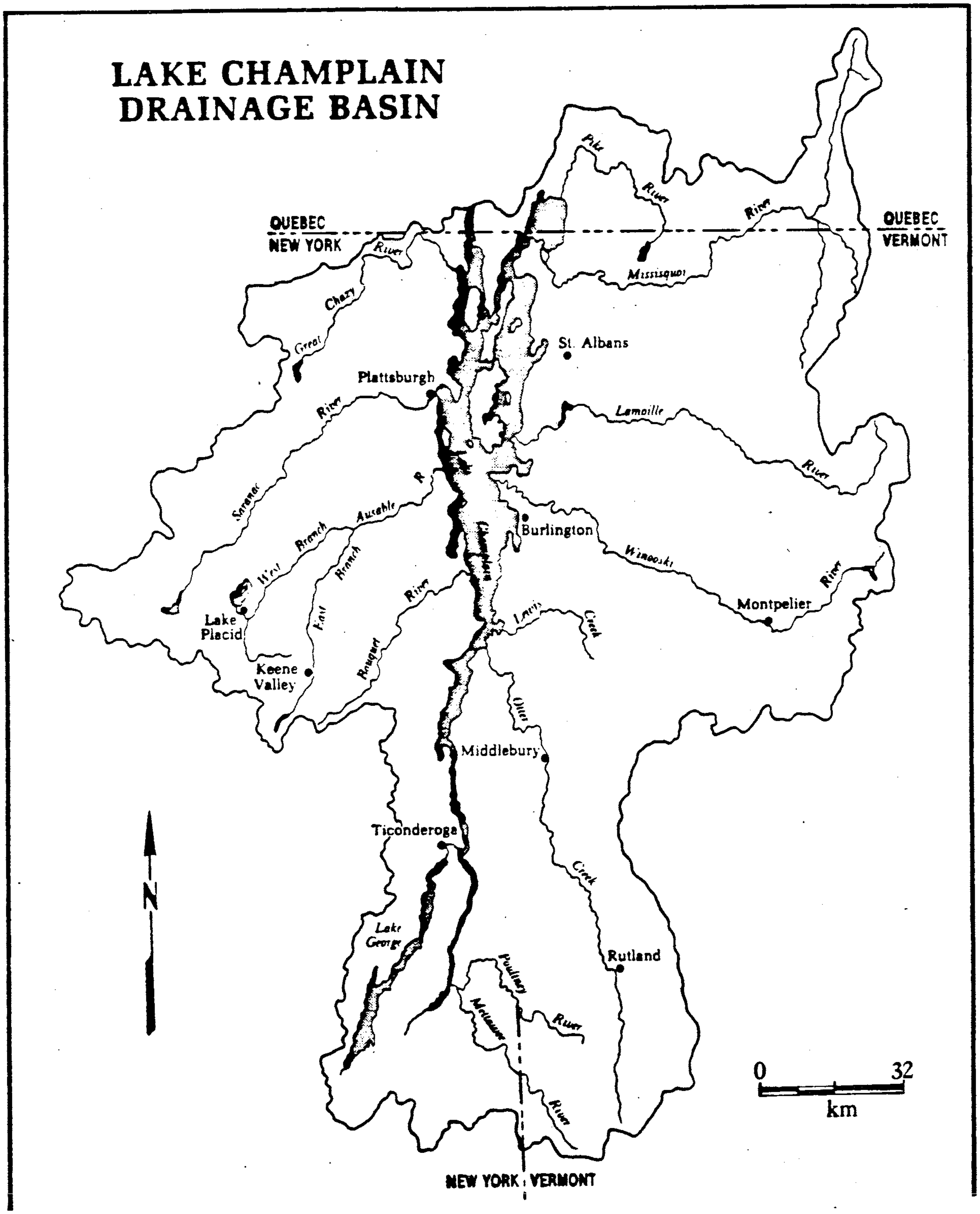


Figure 3. Map of the Lake Champlain drainage basin (adapted from Versteeg 1987).

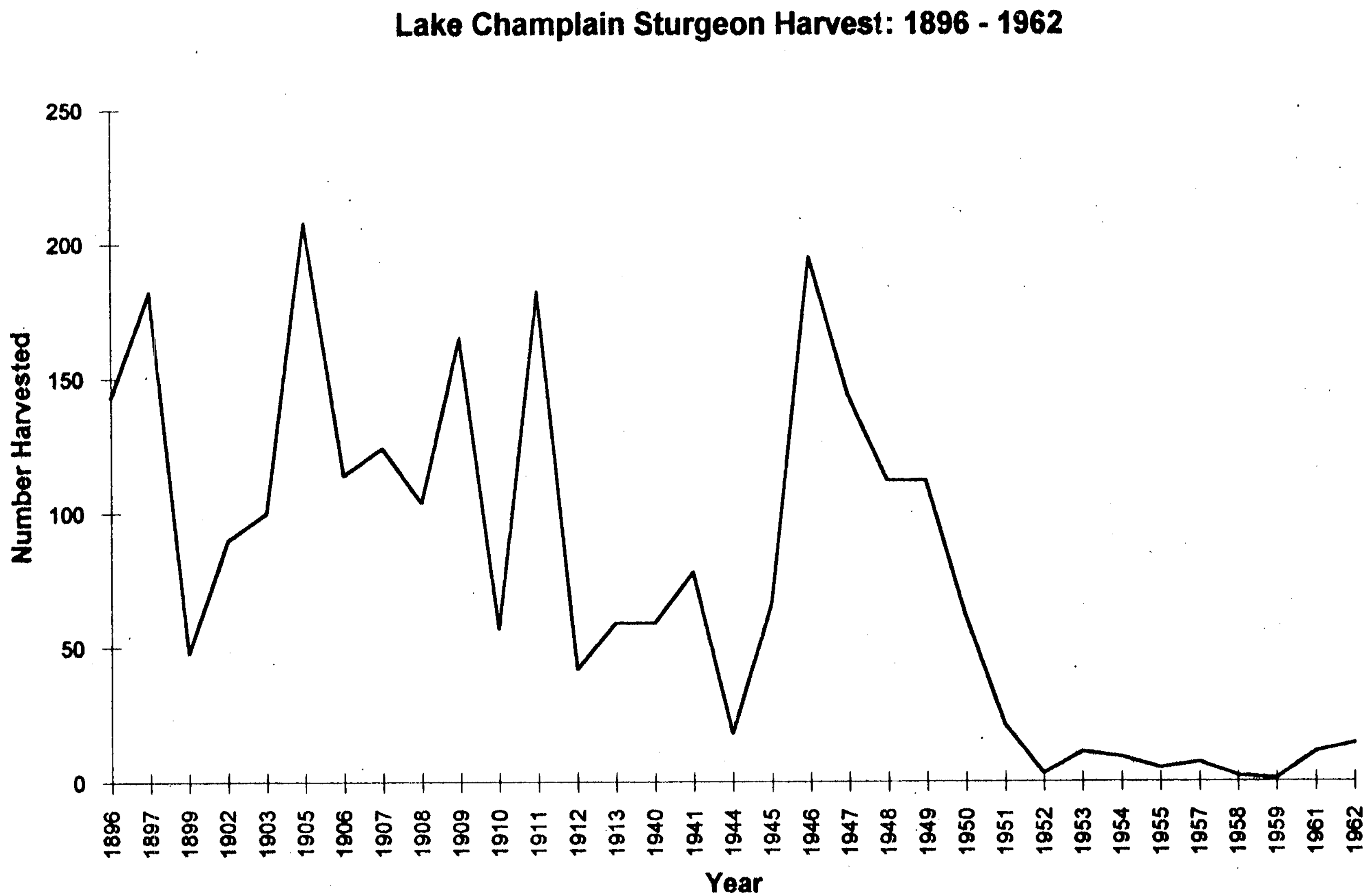


Figure 4. Numbers of Lake Champlain sturgeon harvested from 1896 to 1962.

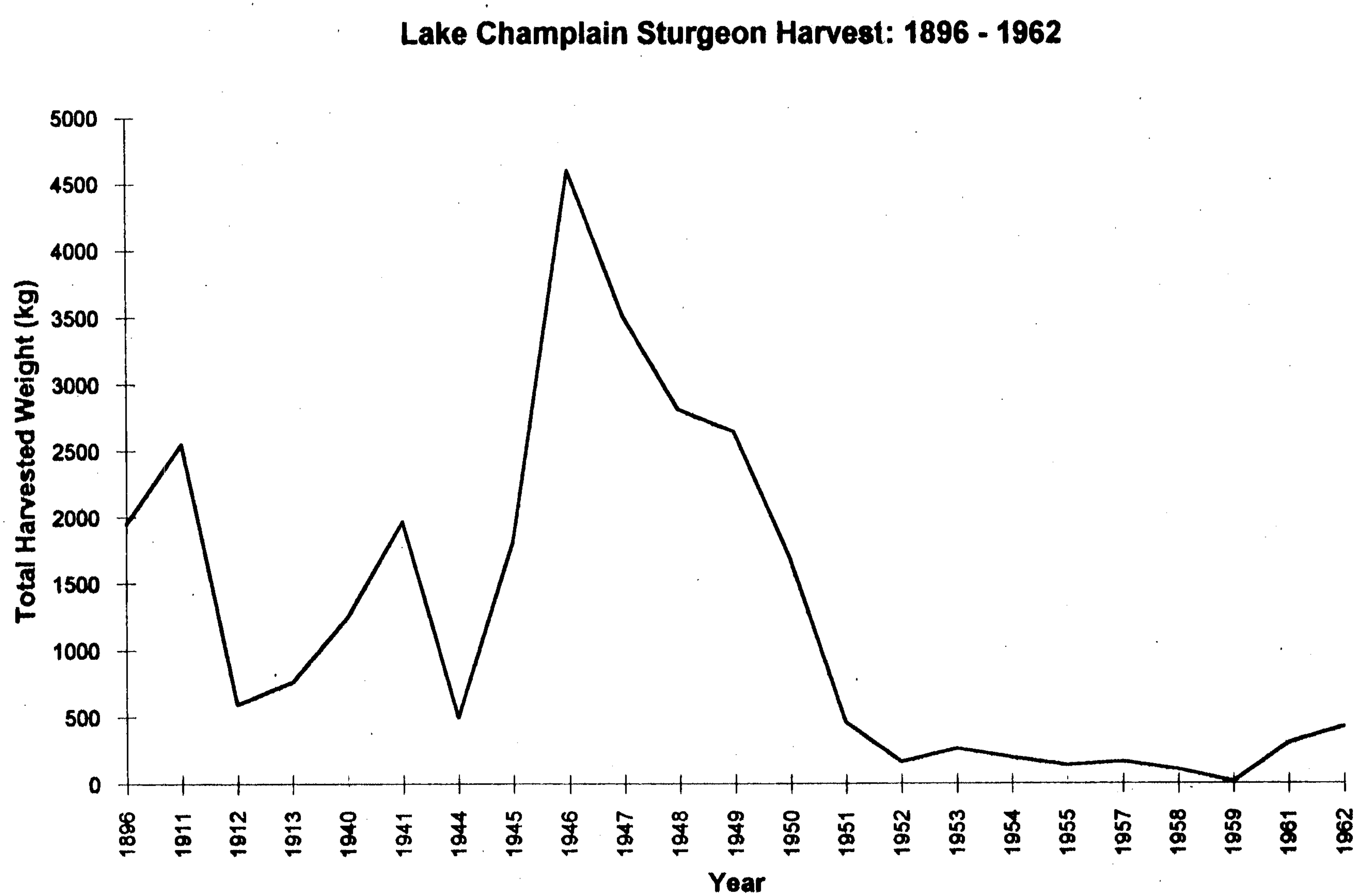


Figure 5. Biomass of Lake Champlain sturgeon harvested from 1896 to 1962.

Lake Sturgeon Spawning Habitat

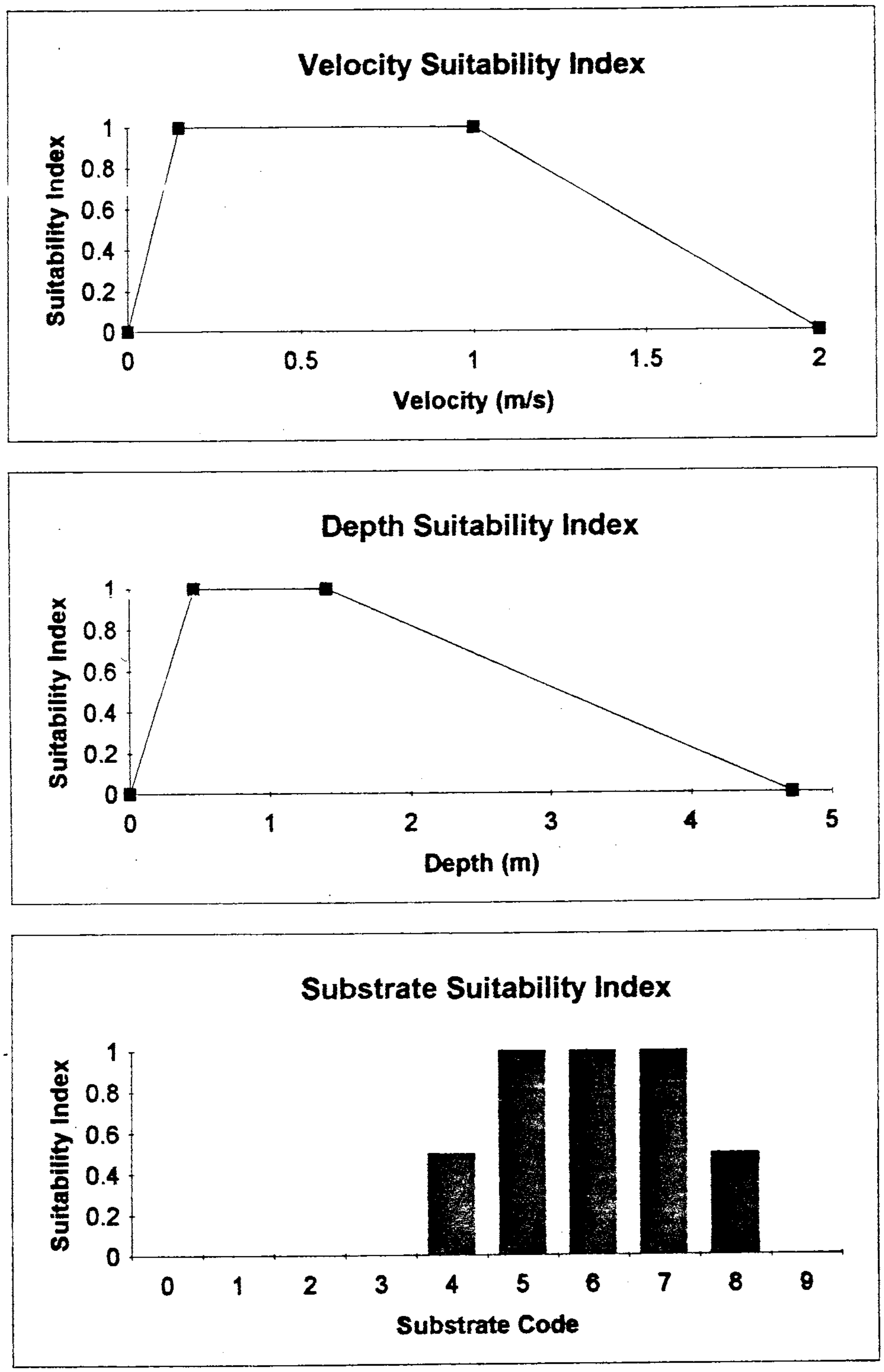
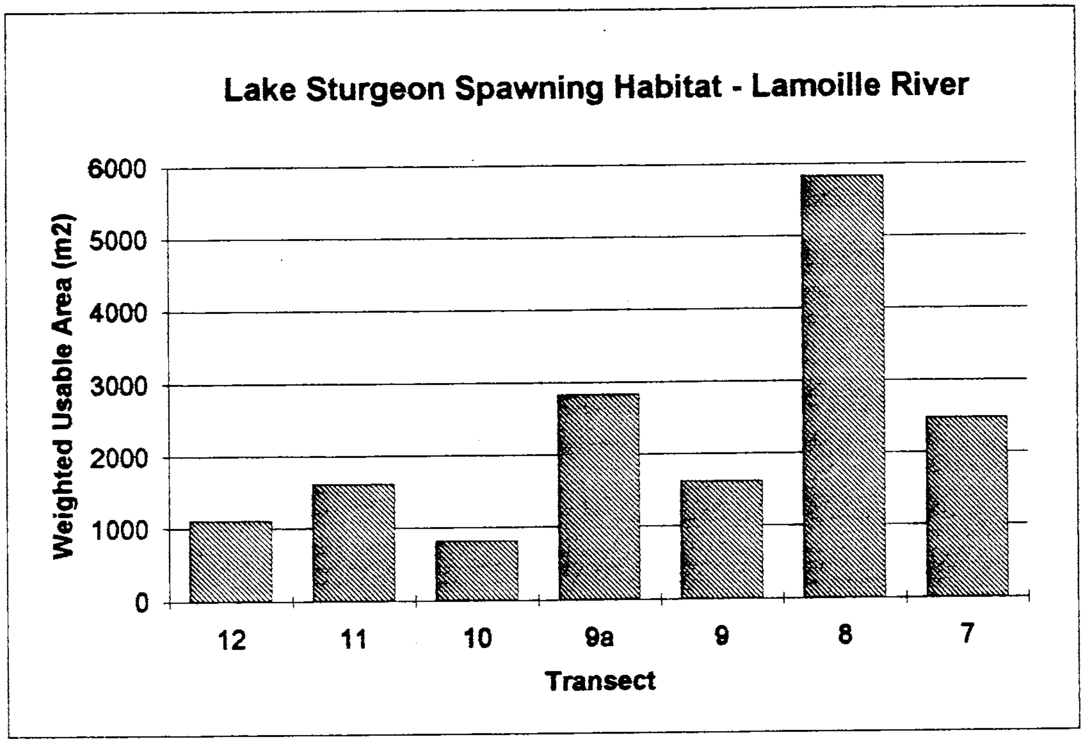


Figure 6. Probability-of-use (SI) curves determined for lake sturgeon spawning habitat.



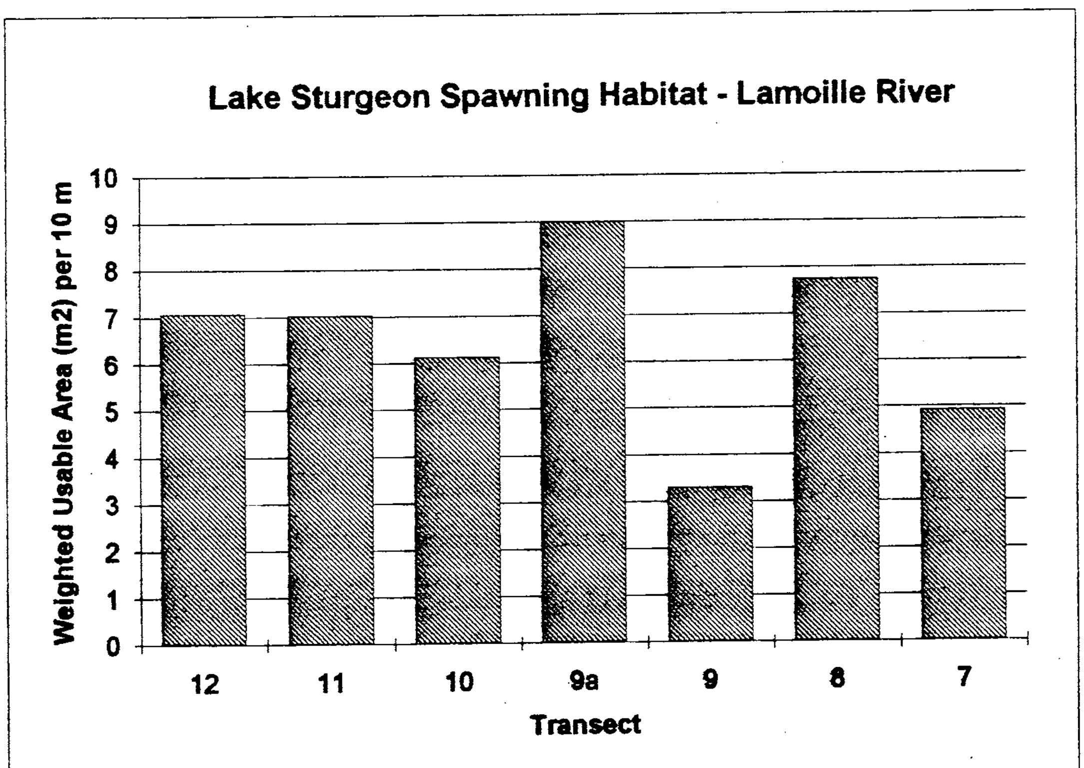


Figure 7. Weighted usable area (WUA) (upper) and WUA per 10 m (lower) of lake sturgeon spawning habitat in the Lamoille River.

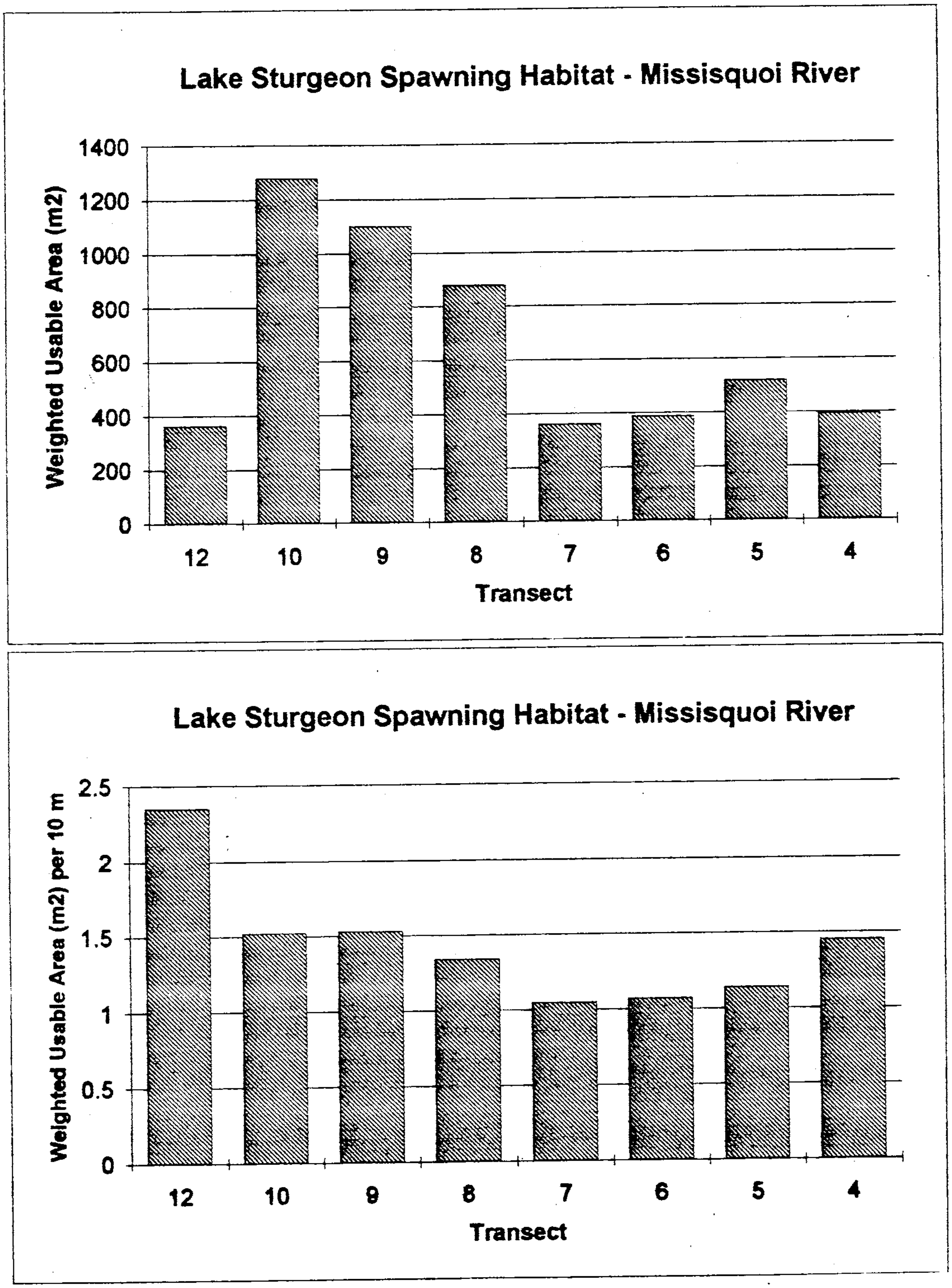


Figure 8. Weighted usable area (WUA) (upper) and WUA per 10 m (lower) of lake sturgeon spawning habitat in the Missisquoi River.

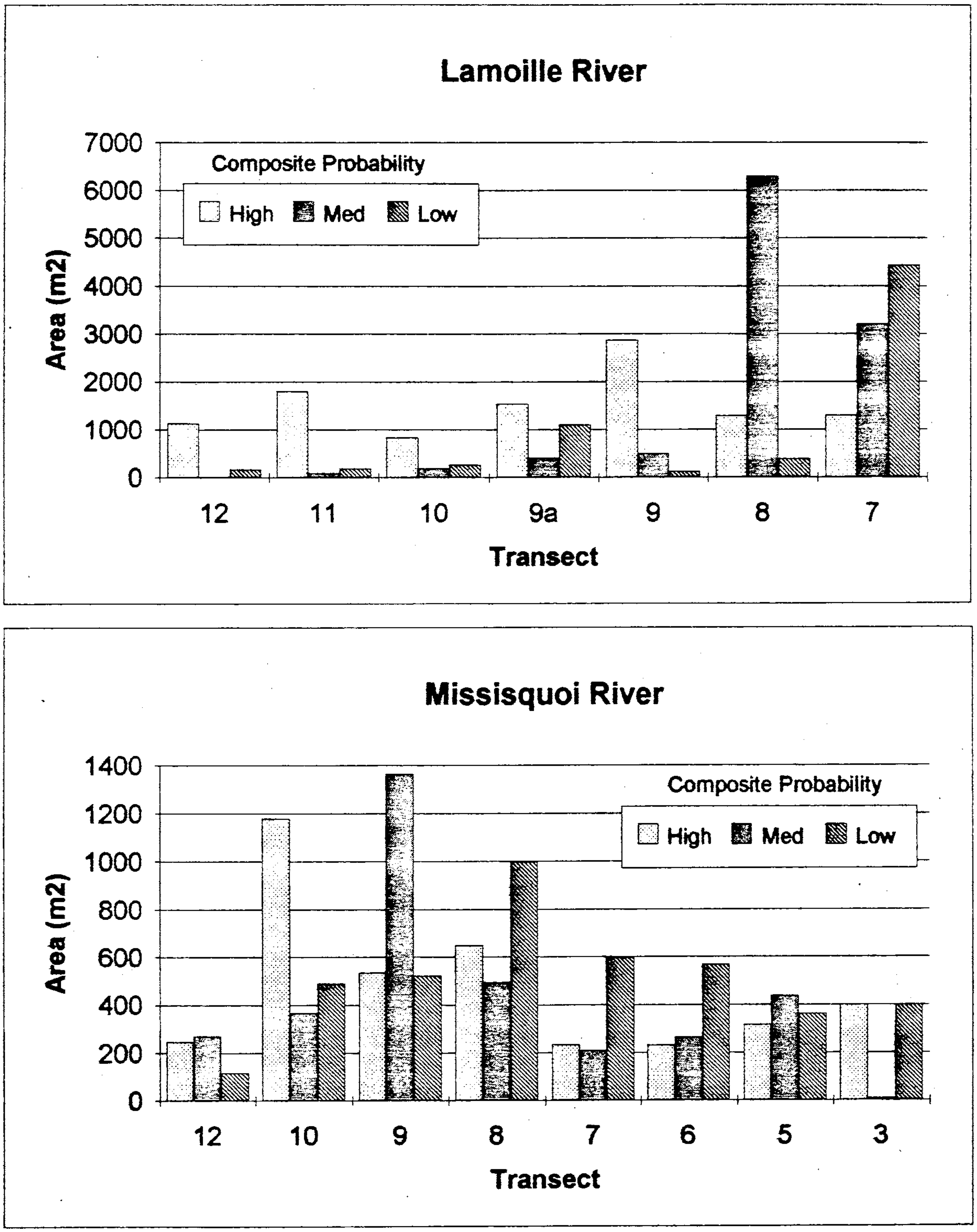


Figure 9. Areas of composite probabilities for lake sturgeon spawning habitat in the Lamoille (upper) and Missisquoi (lower) rivers.

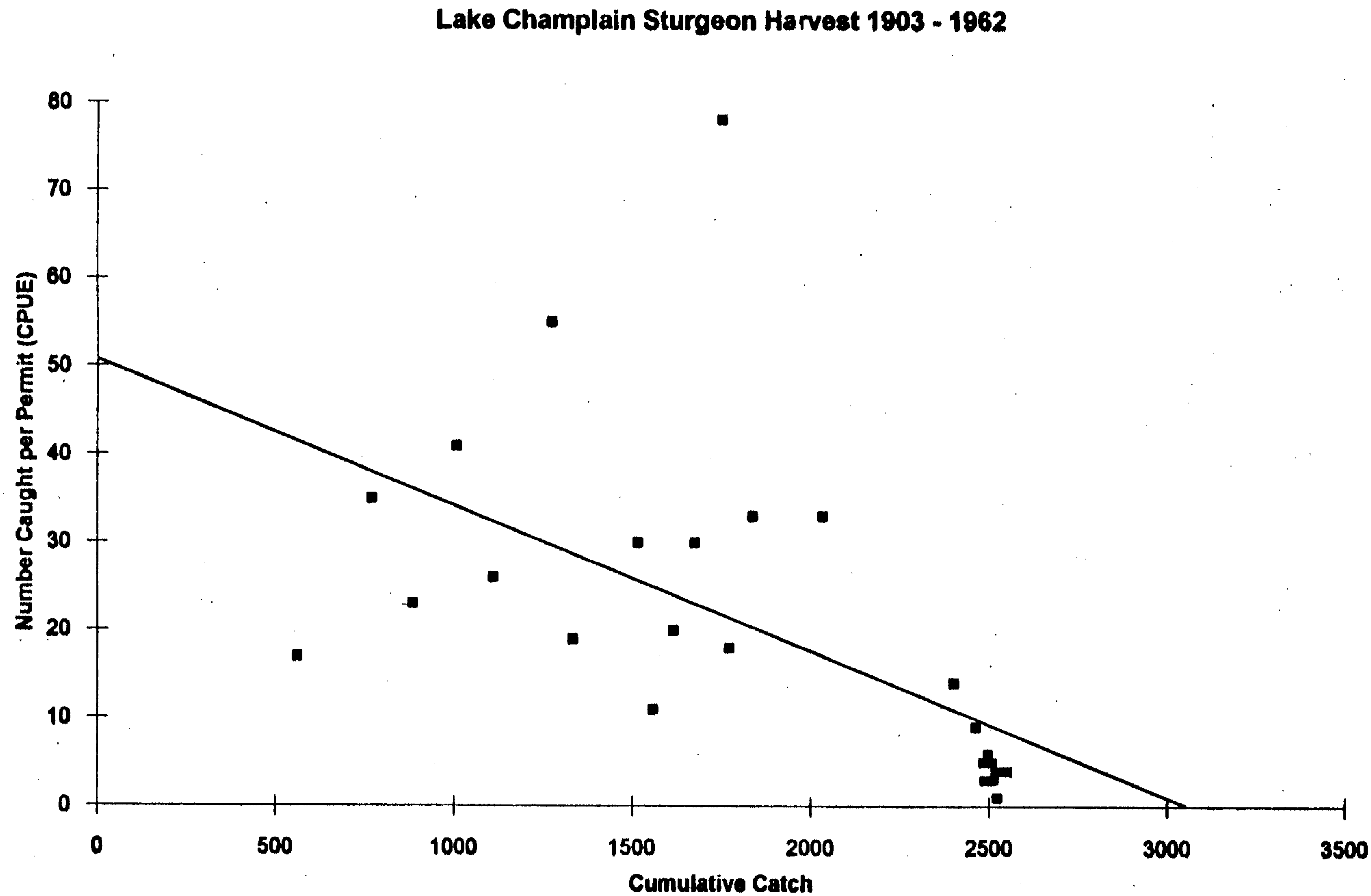


Figure 10. Harvest (CPUE) of lake sturgeon from Lake Champlain between 1903 and 1962 using the Leslie method to estimate total population size. The regression line meets the x-axis at the total population size.

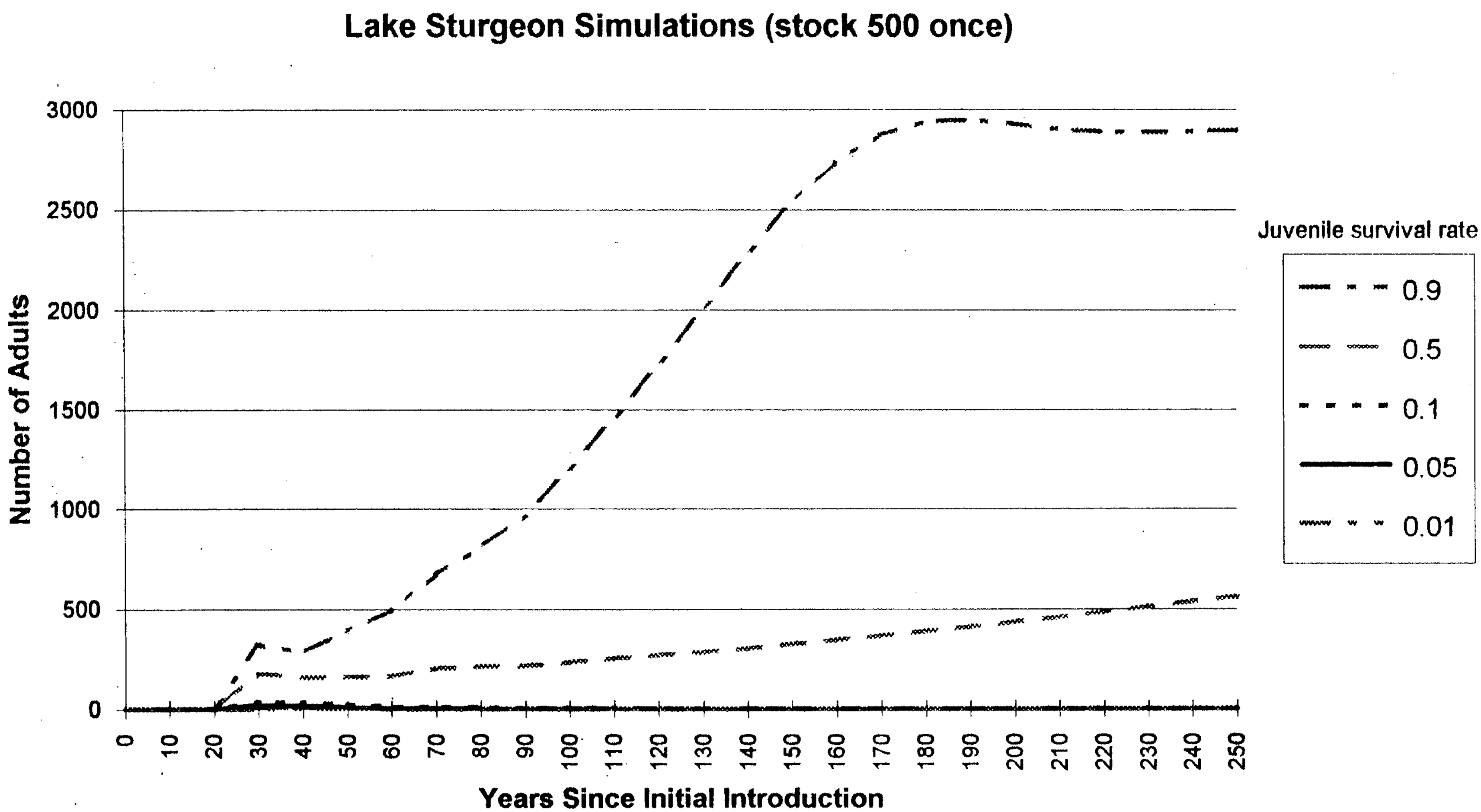


Figure 11. Lake sturgeon stocking simulation for stocking 500 juveniles one time.

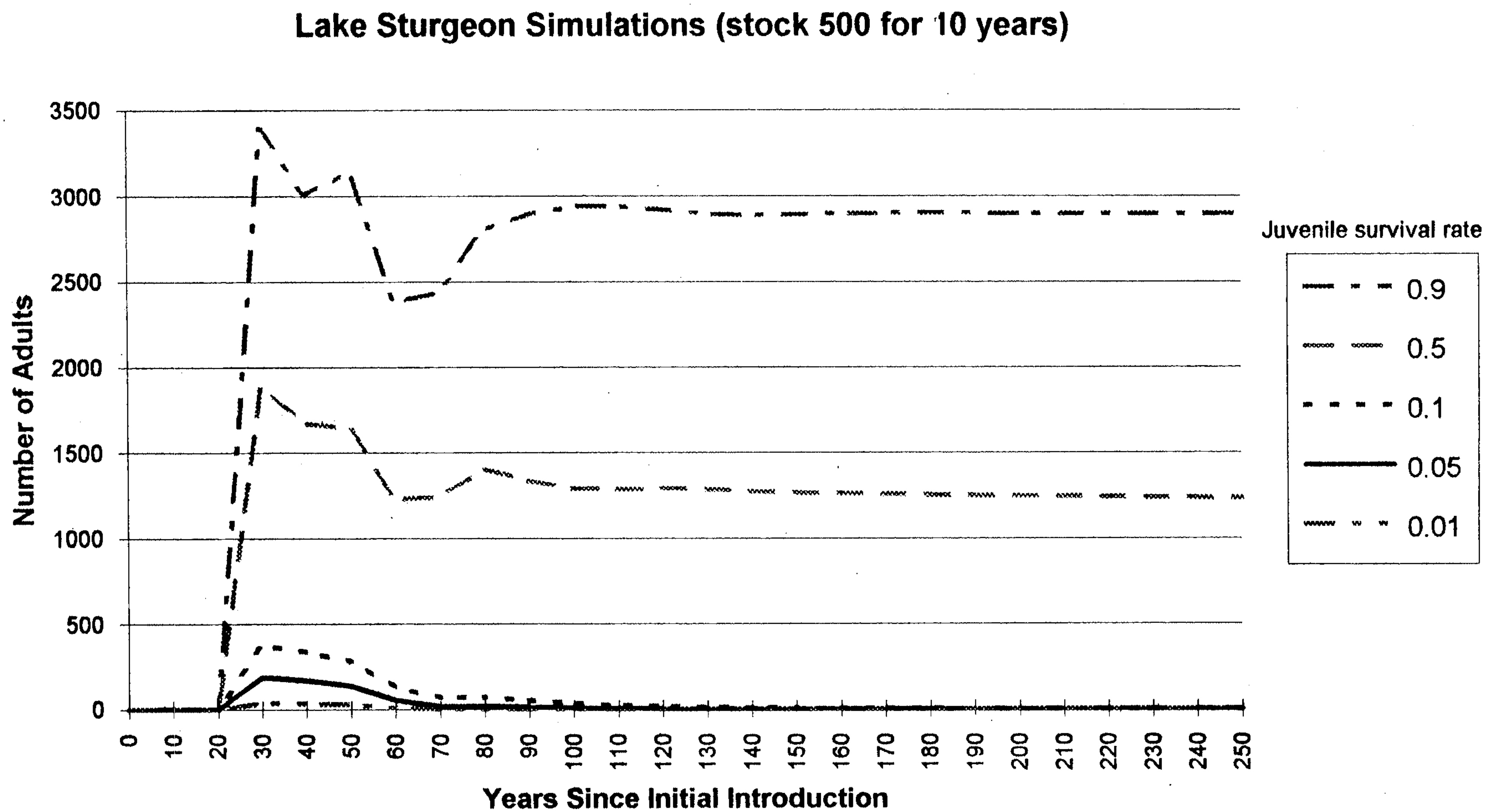


Figure 12. Lake sturgeon stocking simulation for stocking 500 juveniles annually for 10 years.

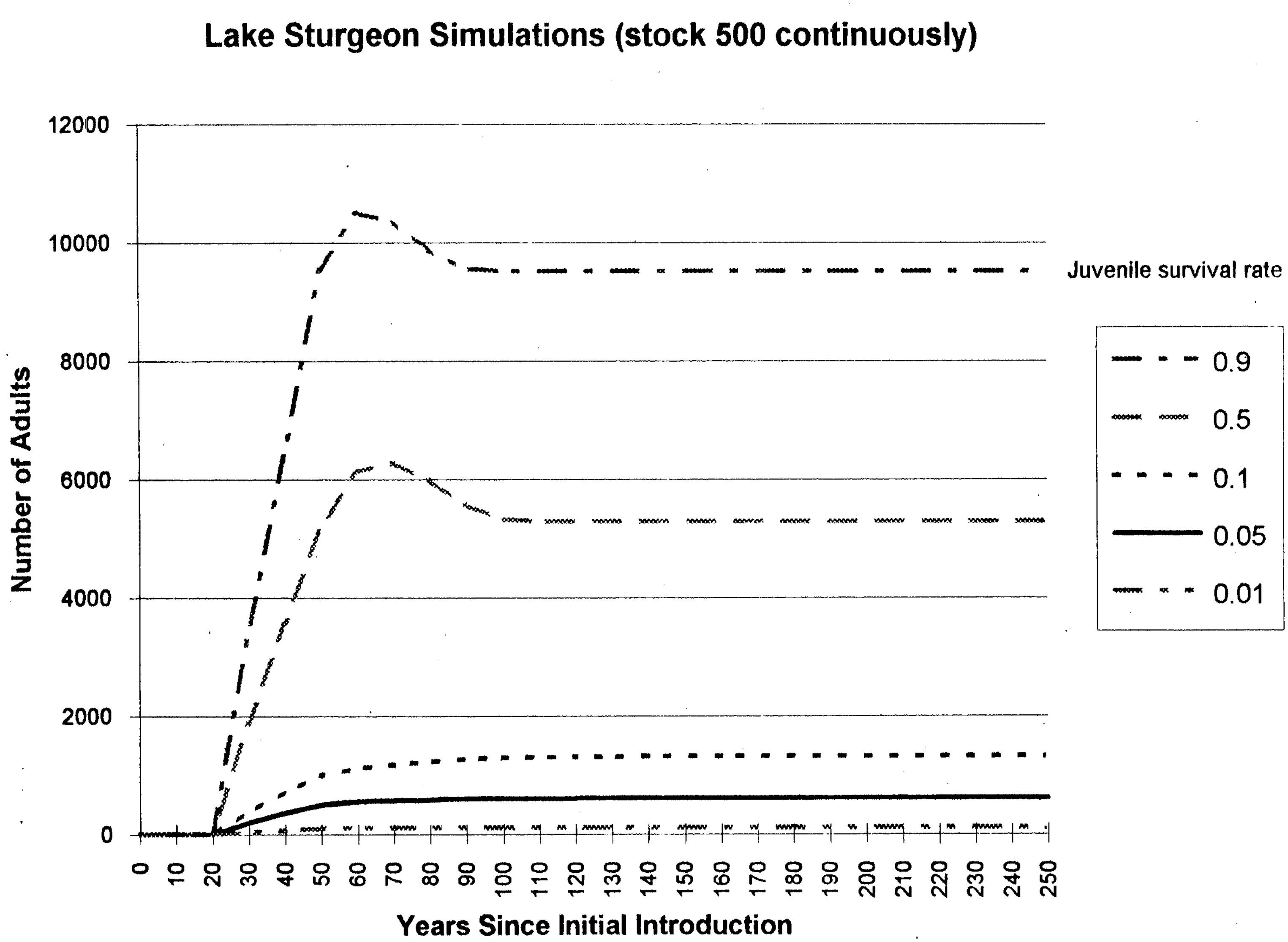


Figure 13. Lake sturgeon stocking simulation for continuous stocking of 500 juveniles annually.

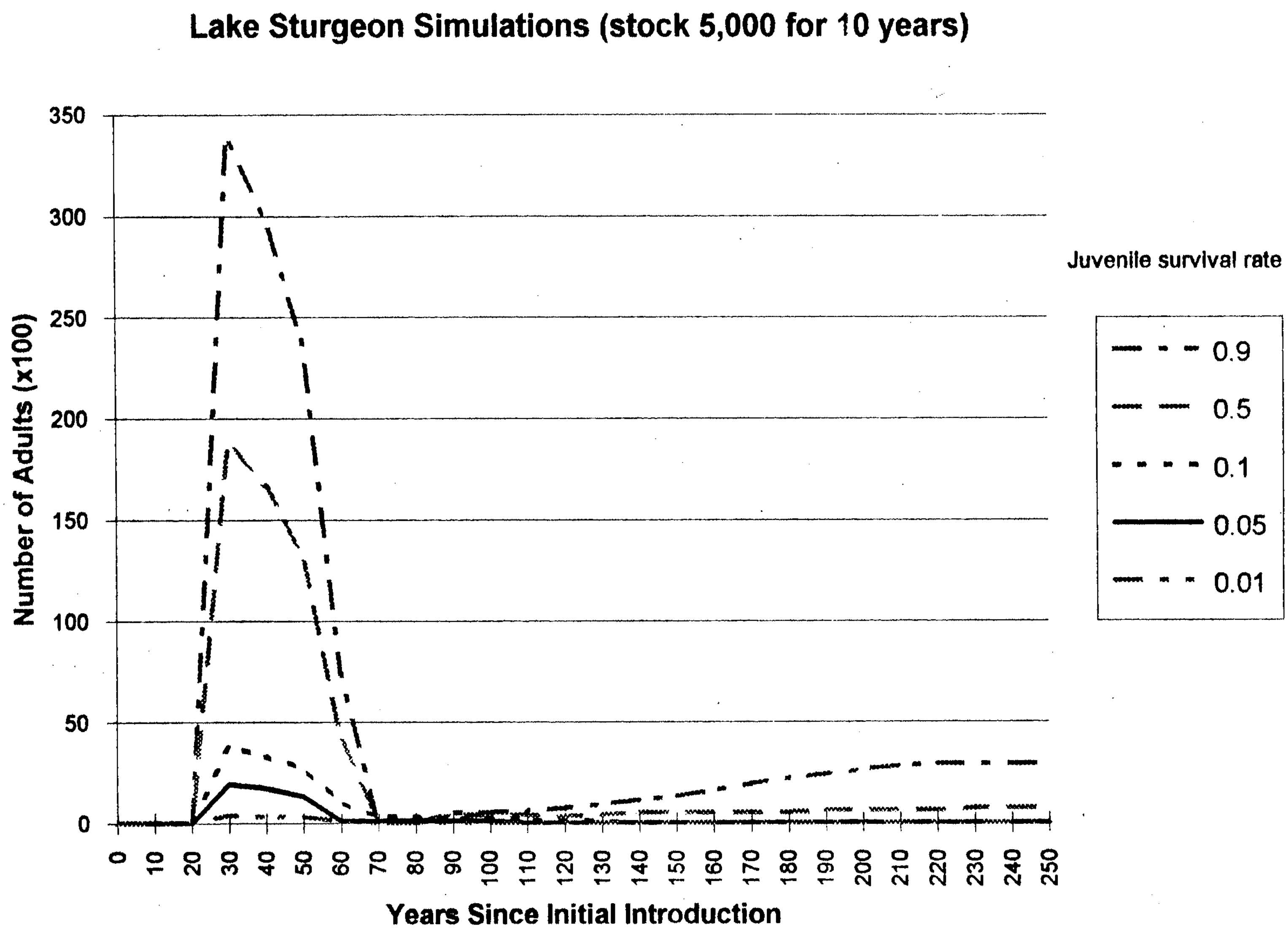


Figure 14. Lake sturgeon stocking simulation for stocking 5,000 juveniles annually for 10 years.

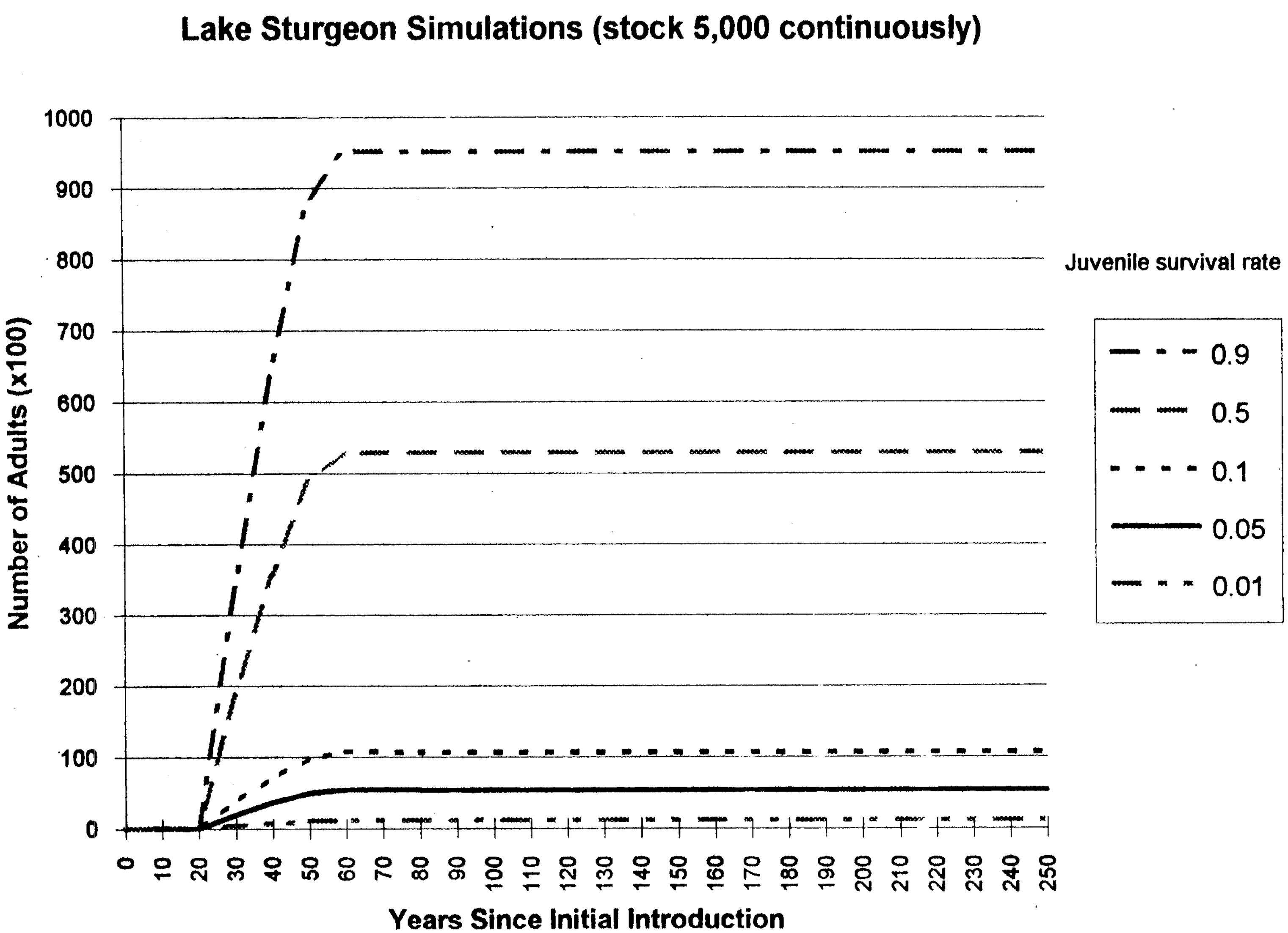


Figure 15. Lake sturgeon stocking simulation for continuous stocking of 5,000 juveniles annually.

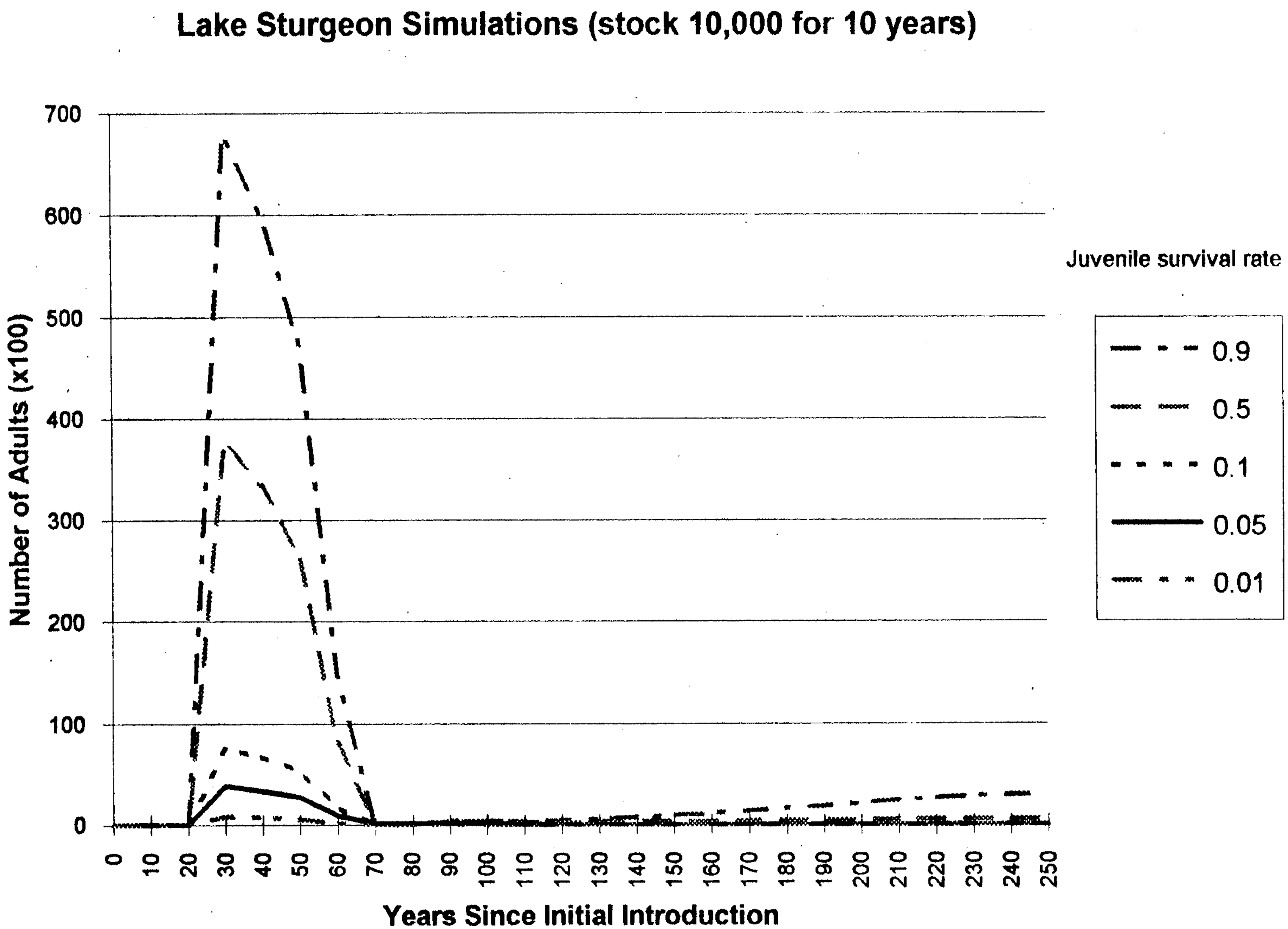


Figure 16. Lake sturgeon stocking simulation for stocking 10,000 juveniles annually for 10 years.

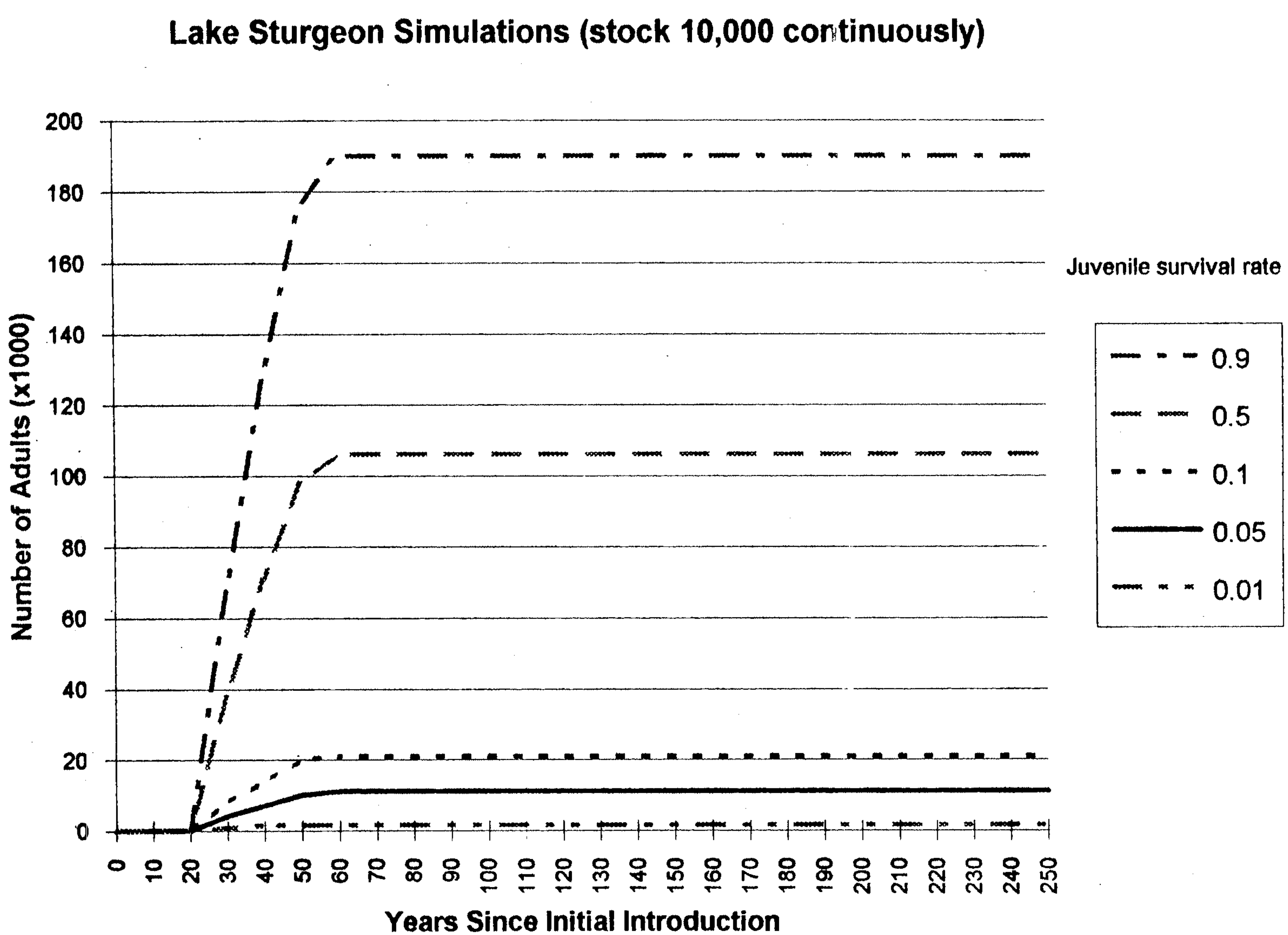


Figure 17. Lake sturgeon stocking simulation for continuous stocking of 10,000 juveniles annually.

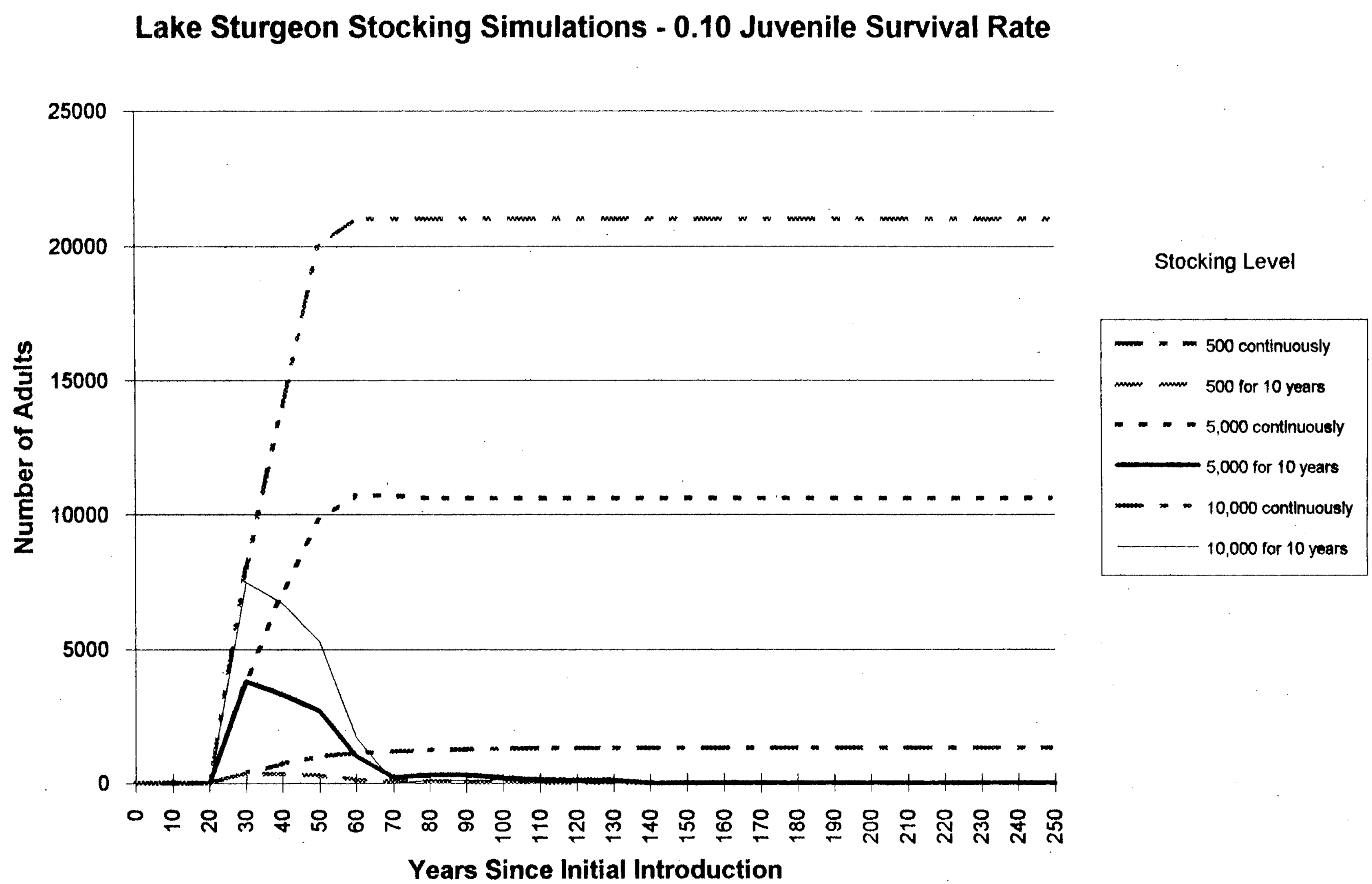


Figure 18. Lake sturgeon stocking simulation at a 0.1 juvenile survival rate for six strategies.

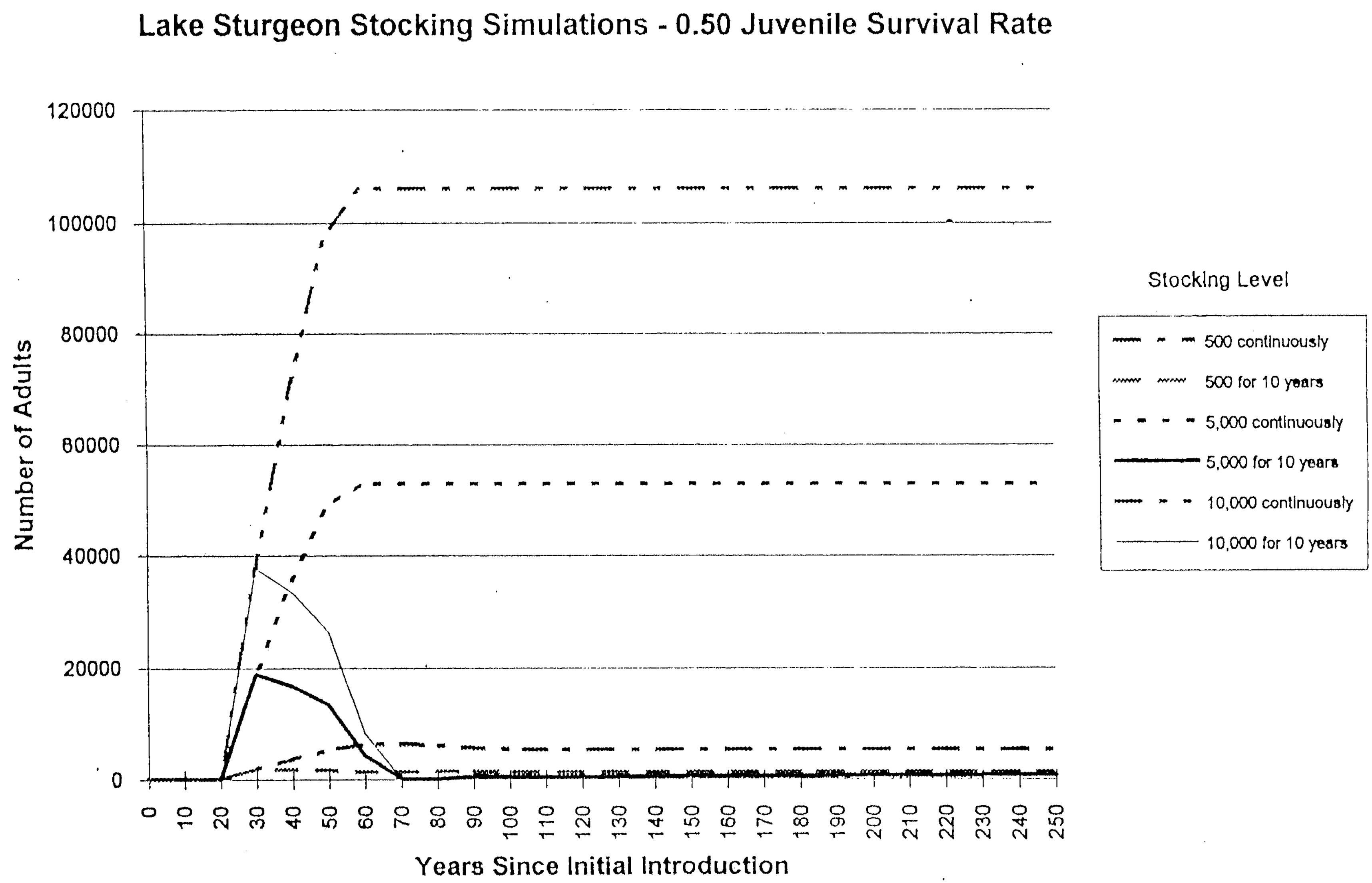


Figure 19. Lake sturgeon stocking simulation at a 0.5 juvenile survival rate for six strategies.

Table 1. Incubation periods of lake sturgeon eggs.

days	location	source
10	L'Assomption River (Quebec)	LaHaye & Fortin 1990
14	Des Prairies River (Quebec)	LaHaye & Fortin 1990
8 - 14	Wolf River (Wisconsin)	Kempinger 1988
8	L'Assomption River (Quebec)	LaHaye, et al. 1992
14	Des Prairies River (Quebec)	LaHaye, et al. 1992
about 5	Central Wisconsin	Priegel 1971
5 - 7	general	Countryman 1986
5 - 8	Central Wisconsin	Priegel & Wirth 1974
5 - 8	Canada	Harkness & Dymond 1961

Table 2. Egg survival to hatching.

survival	source
< 0.00517	Czeskleba et al. 1985
0 - 0.0147	Kempinger 1983
0 - 0.099	Kempinger 1988

Table 3. Days required to complete yolk sac absorption for lake sturgeon eggs.

days	temperature (C)	source
10	>= 20	Priegel and Wirth 1974
12 - 14	< 68	Priegel and Wirth 1974
9	19.2	Kempinger 1985
10 - 14		Priegel 1971

Table 4. Dates of downstream migration of lake sturgeon larvae.

dates	days posthatch	location	source
April 29 - June 3	11 - 14	Wolf River (Wisconsin)	Kempinger 1988
variable	about 14	Des Prairies River (Quebec)	Provost, et al. 1982
May 29 - June 20	18	Des Prairies River (Quebec)	LaHaye, et al. 1992
	10 - 14	Central Wisconsin	Priegel & Wirth 1974

Table 5. Water depths of lake sturgeon larvae habitat.

depth (meters)	location	source
0.6 - 1.2	Wolf River (Wisconsin)	Kempinger 1985
shallow	Mississippi & Missouri Rivers (Missouri)	Graham 1992

Table 6. Substrate composition of lake sturgeon larvae habitat.

dominant substrate	location	source
sand & pea-sized gravel	Wolf River (Wisconsin)	Kempinger 1988
sand, gravel, or rubble	Mississippi & Missouri Rivers (Missouri)	Graham 1992
gravel	Central Wisconsin	Priegel & Wirth 1974
gravel & sand	general	Houston 1987

Table 7. Duration of riverine residence of young lake sturgeon.

time period	location	source
until mid-June	Des Prairies & L'Assomption Rivers (Quebec)	LaHaye, et al. 1992
first year	Wolf River, Wisconsin	Kempinger 1988
first summer	Wolf River, Wisconsin	Kempinger 1985
first year	Wisconsin	Becker 1983

Table 8. Lake sturgeon ages (years) to first spawning.

males	females	source
15 - 20	15 - 20	Carlander 1969
14 - 20	20 - 25	Harkness and Dymond 1967
14 - 16	24 - 26	Priegel and Wirth 1974
12 - 19	14 - 23	Roussow 1957
	24 - 26	Becker 1983
17	25	Priegel and Wirth 1971
14	25	Cuerrier 1949
20	20	Probst and Cooper 1954
22	22	Harkness 1923
19 - 20	26	Dubreuil and Cuerrier 1950
15	23	Cuerrier and Roussow 1951
22	25	Wirth and Cline 1955
14	25	Schultz 1958
15 - 20	25 - 33	Sunde 1959
	20	Threader and Brousseau 1986
16	24 - 26	Priegel 1973
15 - 25	15 - 25	Williams 1951
20	25	Scott and Crossman 1973
18 - 20	20 - 23	Magnin 1966
25	20	Threader 1981
21 - 25	25 - 31	Sandilands 1987
20	25	Mosindy 1987

Table 9. Maximum age (years) of lake sturgeon.

maximum age	source
100	Carlander 1969
82	Priegel and Wirth 1974
152	Probst and Cooper 1954
80	Magnin 1966
80	Scott and Crossman 1973

Table 10. Annual adult lake sturgeon mortality.

range	mean	source
0.11 - 0.33		Dumont et al. 1987
	0.227	Cuerrier and Roussow, 1951
	0.254	Jolliff and Eckert 1971
0.064 - 0.107		Fort 1986
0.054 - 0.134		Priegel and Wirth 1978
	0.115	Nowak and Jessop 1987
0.047 - 0.105		Priegel and Wirth 1975
	0.013	Threader and Brousseau 1986
0.012 - 0.134		Sandilands 1987
	0.129	Threader 1981
0.113 - 0.181		Dumont et al. 1987
0.093 - 0.097		Baker 1980

Table 11. Dates of lake sturgeon spawning periods.

range	peak	location	source
April 14 - May 6	late April	Wolf River	Kempinger 1988
weeks 3 - 4 of May		Southern Quebec	Fortin 1991
week 4 of May week 3 of June		Des Outaouais River	Roussow 1957
June		Nottaway River	Magnin 1966
May 14 - May 27	May 19 - May 21	Des Prairies River	LaHaye et al 1992
May 15 - May 22	May 18	L'Assomption River	LaHaye et al 1992
mid-April - early May		Lake Winnebago System	Folz & Meyers 1985
late April - May 20	May 13	Missisquoi River	Stone 1901
mid-May - late May	May 22 - May 23	Lamoille River	Stone 1901
week 1 of June		Lake Champlain	Stone 1901
May 1 - mid-June		Missisquoi, Lamoille, & Winooski Rivers	Carter 1904
May 25 - mid-June		Lamoille River	Carter 1904
late April - early May		Central Wisconsin	Priegel & Wirth 1974
May - June		Michigan	Baker 1980
week 1 of May		Wolf River	Wirth 1959
June 12 - June 13		Pigeon River	Rodd 1924
	May 31	Detroit River	Meehan 1909
May 25 - June 13		Gull River, Lake Nipigon	Dubreuil & Cuerrier 1950
weeks 1 - 3 of June		Northern Quebec	Dubreuil & Cuerrier 1950

Table 12. Water temperatures during lake sturgeon spawning periods.

range (°C)	optimum (°C)	location	source
8.3 - 23.3	10.0 - 14.0	Wolf River (Wisconsin)	Kempinger 1988
	14.0 - 16.0	Lake Winnebago System (Wisconsin)	Folz & Meyers 1985
	11.1 - 11.7	Michigan	Baker 1980
9.0 - 21.5	11.0 - 15.0	Quebec	Fortin 1991
11.6 - 15.4	12.0 - 15.0	Des Prairies River (Quebec)	LaHaye, et al. 1992
11.7 - 14.7	13.0	L'Assomption River (Quebec)	LaHaye, et al. 1992
> 11.0		Quebec	Gendron 1988
> 11.7		Central Wisconsin	Priegel & Wirth 1974
	15.6	Missisquoi River (Vermont)	Stone 1901
	18.9	Lamoille River (Vermont)	Stone 1901
	14.0 - 17.0	General	Wang, et al. 1987

Table 13. Frequency (years) of lake sturgeon spawning.

males	females	source
2	4 - 5	Cuerrier 1966
4 - 7	7 - 9	Roussow 1957
	9	Goyette 1988
2	4 - 6	Harkness and Dymond 1961
2	4 - 6	Priegel and Wirth 1974
2	4 - 6	Becker 1983
4 - 5	4 - 5	Sunde 1959
	4 - 7	Roussow 1957
	4 - 5	Werner 1980
	4 - 6	Magnum and Priegel, unpublished
2		Kempinger 1988
2 - 3	4 - 6	Magnin 1966

Table 14. Substrate composition of lake sturgeon spawning habitat.

dominant substrate	location	source
fine gravel to fractured or unfractured bedrock; rocks and boulders with gravel	Quebec	Fortin 1991
fine gravel to boulders	Des Prairies & L'Assomption Rivers (Quebec)	LaHaye, et al. 1992
fine gravel to boulders	Des Prairies & L'Assomption Rivers (Quebec)	LaHaye & Fortin 1990
cobble to boulders	General	Countryman 1986
cinders, rubble, sand, boulders	Wolf River (Wisconsin)	Kempinger 1988
rocks & large clean boulders	Michigan	Baker 1980
boulders, rocks, concrete	Central Wisconsin	Priegel & Wirth 1974
gravel	Missouri	Pflieger 1975
rocky ledges	Canada	Houston 1987

Table 15. Water depths (meters) of lake sturgeon spawning habitat.

range (m)	optimum (m)	location	source
0.25 - 3.00	1.40	Quebec	Fortin 1991
0.00 - 1.10		L'Assomption & Des Prairies Rivers (Quebec)	LaHaye & Fortin 1990
0.00 - 2.50	1.00	Wolf River (Wisconsin)	Kempinger 1988
0.25 - 0.85	0.46 - 0.85	L'Assomption River (Quebec)	LaHaye, et al. 1992
0.10 - 1.58		Des Prairies River (Quebec)	LaHaye, et al. 1992
0.30 - 4.70		Central Wisconsin	Priegel & Wirth 1974
0.60 - 4.70		Canada	Harkness & Dymond 1961
	>= 0.90	Missisquoi & Lamoille Rivers (Vermont)	Stone 1901

Table 16. Water velocities of lake sturgeon spawning habitat.

range ($m \cdot s^{-1}$)	optimum ($m \cdot s^{-1}$)	location	source
0.25 - 1.77	0.98	Quebec	Fortin 1991
0.00 - 2.00		L'Assomption & Des Prairies Rivers (Quebec)	LaHaye & Fortin 1990
0.02 - 1.39	0.61 - 0.84	L'Assomption & Des Prairies Rivers (Quebec)	LaHaye, et al. 1992
> 0.10	> 0.15	Wolf River (Wisconsin)	Kempinger 1988

Table 17. Fecundity of lake sturgeon.

fecundity	source
181,720 - 670,450	Cuerrier 1966
64,580	Magnin 1977
667,472	Harkness and Dymond 1961
50,000 - 700,000	Priegel and Wirth 1971
49,835 - 667,472	Dubreuil and Cuerrier 1950
180,000 - 680,000	Werner 1980
121,000	Sandilands 1987
107,510 - 885,360	Cuerrier 1949

Table 18. Lake sturgeon harvest declines in North America.

years of decline	decline (%)	location	source
1885 - 1895	80	Lake Erie	Harkness and Dymond 1961
1885 - 1895	56	Lake Huron	Harkness and Dymond 1961
1893 - 1900	89	Lake of the Woods	Scott and Crossman 1973
1880's to 1987	97 - 98	Province of Ontario	Houston 1987
1900 - 1910	97	Lake Winnipeg	Houston 1987
1898 - 1907	77	Ottawa River	Dymond 1939

Table 19. Lake Champlain sturgeon sightings from 1980 to 1992.

Number of Sightings	Year	Location
1	1980	North side of Sand Bar
1	1985	Sampson Point
1	1986	Lamoille River
1*	1986	Winooski River
8	1986	Mouth of washout at Enosburg
2	1986	Missisquoi River
5	1987	Missisquoi River
4	1988	Missisquoi River
1	1989	Lamoille River
2	1990	Missisquoi River
1	1990	Missisquoi Bay
3	1991	Lamoille River
1*	1991	Lamoille River
2	1992	Lamoille River

* fish caught by angler

Table 20. Modified Wentworth substrate codes (from Bovee 1982).

Code	Substrate	Sizes
1	plant detritus	--
2	clay	0.000239mm-0.0041mm
3	silt	0.00401mm-0.0620mm
4	sand	0.0620mm-0.2cm
5	gravel	0.2cm-6.35cm
6	cobble	6.35cm-25.4cm
7	boulder	>25.4cm
8	bedrock	--

Appendix I.

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Wellsboro, Pennsylvania 16901
(717) 724-3322
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Appendix I. continued

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-early life history and adult movement patterns

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Green Bay, Wisconsin 54307
(414) 492-5834
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Charles F. Saylor
Tennessee Valley Authority
Land and Forest Resources
Ridgeway
Norris, Tennessee 37828
(615) 494-9800
-restoration and culture

Thomas F. Thuemler
Wisconsin Department of Natural Resources
Industrial Parkway
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Marinette, Wisconsin 54143
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-culture

Potential Egg Sources

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Mr. David Ives (Fish Culture Chief) or Mr. Lee Kevnen
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Madison, WI 53707

New York
Al Sciavone (315-785-2266)

Appendix II.

Historic Lake Champlain Sturgeon Legal Fishing Grounds*

(summarized from the 16th, 17th, and 18th Biennial Reports of the Commissioners of fisheries and Game of the State of Vermont for the years 1901 to 1906)

Between Sand Bar Bridge on the north and the Rutland R. R. bridge on the south.

Bounded on the north by light house opposite Rouses Point and on the south by south end of Isle La Motte.

East side of North Island, City Bay, and from North Island Bridge to south end of South Island.

Between Knight's Island on the north and Sand Bar Bridge on the south, east of North and South Hero Islands, west of Georgia and Milton.

Bounded on the north by the Central Vermont Railway bridge between Alburgh and West Swanton, and on the south side of Knight's Island.

From Stevenson's Point, south to Old Woman's Island, thence to the south point of Knight's Island, thence west to Wood's Island.

From south end of Hog Island to Long Point, due east to Cherry Point on the west shore of Maquam Bay, to place of beginning.

From C. V. R. R. bridge, between Hog Island and Alburgh, north to Canadian line.

Enclosed by Sand Bar Bridge, north on Milton shore to a point directly east of the south end of Savage Island; thence from the south end of Savage Island due west to Grand Isle, south to point of beginning.

From Colchester Point south to Apple Tree Point; from Wagner's Point south to end of Alburgh Point, and west of Canadian R. R.

From south end of Hog Island to north end of Stevenson's Point, north to R. R. bridge, east to Hog Island, back to point of beginning.

From Long Point, south to west shore of North Hero Island, opposite Butler's Island; east to Samson's Lake View House; north to Cherry Point on the east shore of Maquam Bay, and to point of commencement.

From Samson's Lake View House to south end of Old Woman's Island; south to Ladd's Point; east to Burton Island, north to place of beginning.

* After 1904, licenses were issued for any water in Lake Champlain within the confines of the State of Vermont.

Appendix III.

Density estimates of lake sturgeon·km^{-2} for major lakes and rivers in North America.

citation	------------------------------------
year	1902 - 1949
location	Lake Champlain, Vermont
maximum depth (m)	122 m
age classes	21 - 60 years
surface area (km^2)	1,130 km^2
population estimate	3,000 adult sturgeon
density estimate (#/km^2)	3 adult sturgeon per km^2
citation	------------------------------------
year	1902 - 1949
location	Lake Champlain, Vermont
maximum depth (m)	9.1 m
age classes	21 - 60 years
surface area (km^2)	441 km^2
population estimate	3,000 adult sturgeon
density estimate (#/km^2)	7 adult sturgeon per km^2
citation	Folz and Meyers 1985
year	1976 - 1982
location	Lake Winnebago, Wisconsin
maximum depth (m)	6.4 m
age classes	> 15 years
surface area (km^2)	558 km^2
population estimate	18,081 adult sturgeon
density estimate (#/km^2)	32 adult sturgeon per km^2

citation	Folz and Meyers 1985
year	1955 - 1959
location	Lake Winnebago, Wisconsin
maximum depth (m)	6.4 m
age classes	> 15 years
surface area (km^2)	558 km^2
population estimate	7,497 adult sturgeon
density estimate (#/km^2)	13 adult sturgeon per km^2

citation	Baker 1980
year	1975
location	Black Lake, Michigan
maximum depth (m)	------------------------------------
age classes	> 20 years
surface area (km^2)	------------------------------------
population estimate	1,599 adult sturgeon
density estimate (#/km^2)	------------------------------------

citation	Baker 1980
year	1974
location	Black Lake, Michigan
maximum depth (m)	------------------------------------
age classes	> 20 years
surface area (km^2)	------------------------------------
population estimate	2,478 adult sturgeon
density estimate (#/km^2)	------------------------------------

citation	Baker 1980
year	1973
location	Black Lake, Michigan
maximum depth (m)	------------------------------------
age classes	> 20 years
surface area (km^2)	------------------------------------
population estimate	1,666 adult sturgeon
density estimate (#/km^2)	------------------------------------

citation	Mongeau, et al. 1982
year	
location	Lake des Deux Montagnes
maximum depth (m)	
age classes	>= 35 cm
surface area (km^2)	
population estimate	22,997
density estimate (#/km^2)	

citation	Thuemler 1985
year	1978
location	Menominee River, Wisconsin-Michigan
maximum depth (m)	5 m
age classes	> 16 years
surface area (km^2)	6 km^2
population estimate	206 adult sturgeon
density estimate (#/km^2)	34 adult sturgeon per km^2

citation	Thuemler 1985
year	1970
location	Menominee River, Wisconsin-Michigan
maximum depth (m)	5 m
age classes	> 16 years
surface area (km^2)	6 km^2
population estimate	185 adult sturgeon
density estimate (#/km^2)	31 adult sturgeon per km^2

citation	Thuemler 1985
year	1969
location	Menominee River, Wisconsin-Michigan
maximum depth (m)	5 m
age classes	> 16 years
surface area (km^2)	6 km^2
population estimate	243 adult sturgeon
density estimate (#/km^2)	40 adult sturgeon per km^2

citation	Priegel 1973
year	1970
location	Menominee River, Wisconsin-Michigan
maximum depth (m)	6 m
age classes	> 15 years
surface area (km^2)	22 km^2
population estimate	185 adult sturgeon
density estimate (#/km^2)	8 adult sturgeon per km^2

citation	Priegel 1973
year	1969
location	Menominee River, Wisconsin-Michigan
maximum depth (m)	6 m
age classes	> 15 years
surface area (km^2)	22 km^2
population estimate	243 adult sturgeon
density estimate (#/km^2)	11 adult sturgeon per km^2
citation	Sandilands 1987
year	1985
location	Kapeesawatan Lake and 15 km of downstream Kenogami River, Ontario
maximum depth (m)	7.5 m
age classes	> 21 years
surface area (km^2)	1.128 km^2
population estimate	4 adult sturgeon
density estimate (#/km^2)	5 adult sturgeon per km^2
citation	Sandilands 1987
year	1984
location	Kapeesawatan Lake and 15 km of downstream Kenogami River, Ontario
maximum depth (m)	7.5 m
age classes	> 21 years
surface area (km^2)	1.128 km^2
population estimate	45 adult sturgeon
density estimate (#/km^2)	40 adult sturgeon per km^2

citation	Sandilands 1987
year	1985
location	Ogahalla Rapids, Kenogami River, Ontario
maximum depth (m)	5 m
age classes	> 21 years
surface area (km^2)	0.264 km^2
population estimate	25 adult sturgeon
density estimate (#/km^2)	95 adult sturgeon per km^2
citation	Sandilands 1987
year	1984
location	Ogahalla Rapids, Kenogami River, Ontario
maximum depth (m)	5 m
age classes	> 21 years
surface area (km^2)	0.264 km^2
population estimate	45 adult sturgeon
density estimate (#/km^2)	170 adult sturgeon per km^2
citation	Sandilands 1987
year	1984
location	Kapeesawatan Lake to Ogahalla Rapids, Kenogami River, Ontario
maximum depth (m)	7.5 m
age classes	> 21 years
surface area (km^2)	1.572 km^2
population estimate	82 adult sturgeon
density estimate (#/km^2)	52 adult sturgeon per km^2

citation	Sandilands 1987
year	1985 - summer and fall combined
location	Mammamattawa section of the Kenogami River, Ontario
maximum depth (m)	4.5 m
age classes	> 21 years
surface area (km^2)	3.5 km^2
population estimate	695 adult sturgeon
density estimate (#/km^2)	199 adult sturgeon per km^2

citation	Sandilands 1987
year	1985 - summer only
location	Mammamattawa section of Kenogami River, Ontario
maximum depth (m)	4.5 m
age classes	> 21 years
surface area (km^2)	3.5 km^2
population estimate	354 adult sturgeon
density estimate (#/km^2)	101 adult sturgeon per km^2

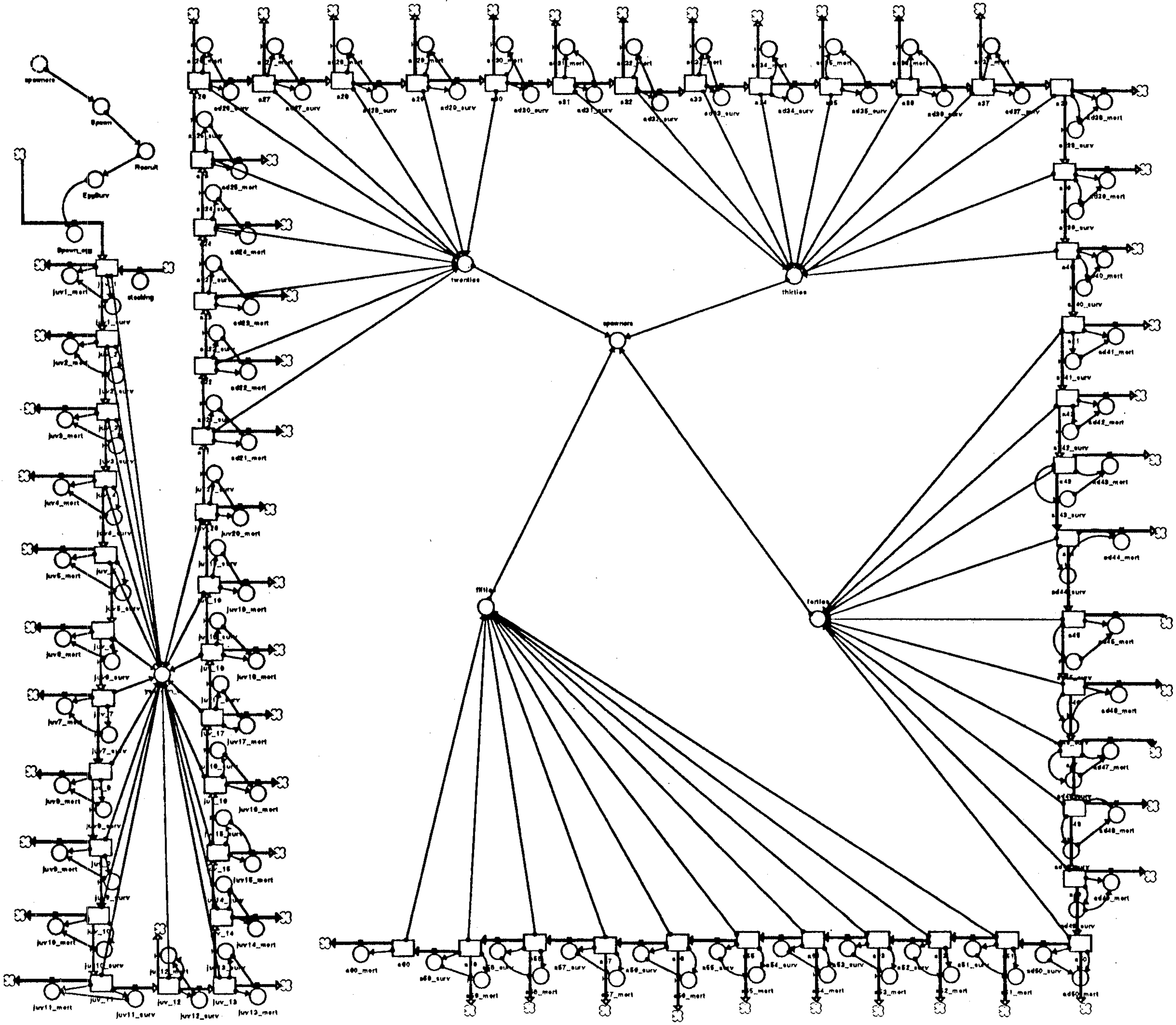
citation	Payne 1987
year	1985
location	upper reach of the Mattagami River, Ontario
maximum depth (m)	------------------------------------
age classes	all
surface area (km^2)	3.88 km^2
population estimate	114 sturgeon
density estimate (#/km^2)	29 sturgeon per km^2

citation	Payne 1987
year	1985
location	lower reach of the Mattagami River, Ontario
maximum depth (m)	------------------------------------
age classes	all
surface area (km^2)	1.8 km^2
population estimate	33 sturgeon
density estimate (#/km^2)	18 sturgeon per km^2
citation	Payne 1987
year	1984
location	Island Falls to Abitibi Canyon Dam on Abitibi River, Ontario
maximum depth (m)	------------------------------------
age classes	all
surface area (km^2)	1 km^2
population estimate	994 sturgeon
density estimate (#/km^2)	994 sturgeon per km^2
citation	Payne 1987
year	1983
location	Frederick House River, Ontario
maximum depth (m)	------------------------------------
age classes	all
surface area (km^2)	0.98 km^2
population estimate	186 sturgeon
density estimate (#/km^2)	190 sturgeon per km^2

citation	Payne 1987
year	1981
location	Frederick House River, Ontario
maximum depth (m)	------------------------------------
age classes	all
surface area (km^2)	0.98 km^2
population estimate	125 sturgeon
density estimate (#/km^2)	128 sturgeon per km^2

citation	Nowak and Jessop 1987
year	1984
location	Groundhog and Mattagami rivers, Ontario
maximum depth (m)	------------------------------------
age classes	9 - 49 years
surface area (km^2)	11.7 km^2
population estimate	6,724 sturgeon
density estimate (#/km^2)	575 sturgeon per km^2

citation	Threader and Brousseau 1985
year	1980 - 1982
location	Moose River, Ontario
maximum depth (m)	<shallow>
age classes	> about 16 years
surface area (km^2)	52 km^2
population estimate	about 3,898 adult sturgeon
density estimate (#/km^2)	about 75 adult sturgeon per km^2



Appendix IV. Age-structured lake sturgeon population model run using Stella II software.

ADDENDUM

Artificial Propagation of Lake Sturgeon

Acipenser fulvescens (Rafinesque)

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Background

Attempts to artificially culture lake sturgeon began in 1883 and 1887 (Carter 1904). The efforts were unsuccessful because of the inability to collect ripe females (Carter 1904). In general, other early problems in sturgeon culture included: difficulties in finding ripe individuals of both sexes simultaneously, difficulties of gamete collection, adhesiveness of eggs, fungal disease, and poor feeding of larvae and juveniles (Harkness and Dymond 1961). Culture was undertaken in Vermont by Livingston Stone between 1899 and 1901, using eggs collected from sturgeon that were spawning in the Missisquoi and Lamoille rivers (Stone 1900, 1901). However, these efforts were also unsuccessful.

Successful artificial propagation programs began in Wisconsin in 1979 and stocking began in 1982 in the Menominee River (Thuemler 1985). Difficulties still exist in finding enough ripe adults, inducing egg ripening in confinement, and collecting gametes; but, many of the problems have been overcome by fish culture stations in Wisconsin, Missouri, and Michigan. The following describes the most current techniques used to culture lake sturgeon.

<u>Capture of Adults</u>

For culturing purposes, lake sturgeon are captured at spawning sites. Female sturgeon are frequently surrounded by several males. Typically large, long handled dip nets are used to capture mature lake sturgeon, but in Wisconsin electroshocking with DC current has been successful (S. Fajfer, Wisconsin Department of Natural Resources (WDNR), personal communication). The net frames are approximately 76 cm long by 61 cm wide; netting 2 cm bar mesh, 10 cm stretch; the bag approximately 91 cm deep; and a handle 1.5 to 2.4 m long. Males and females are generally distinguishable in shallow clear water, because females are larger (Anderson 1984). When a sturgeon is netted, it is brought to shore and transferred to a stretcher for collection of eggs or milt. The stretcher is approximately 1.5 m long made of a plastic tarp material that is folded over providing a place for the fish's head. Two people are needed to conduct the spawning procedure. The person holding the fish's head spawns the fish, if the fish is manually spawned, and collects of the leading ray of the pectoral fin, which is used for aging purposes. The other person holds the tail end and tags the fish.

The fish is tagged with cattle ear tags placed over, and attached just below, the dorsal fin. Tag retention for males is 90% for 3 years and 80% for females (R. Bruch, WDNR, personal communication).

Collection of Milt

Several males (generally four to five) are collected in nets, taken to shore and placed ventral side up in a stretcher. The fish's head is inserted into the envelope of the stretcher and water is poured into the mouth or over the gills every few minutes, providing some oxygen and keeping the gills moist. The area around the vent is dried completely (Anderson 1984) then milt is collected manually using a massaging movement beginning anterior of and moving toward the vent. Milt is drawn into a 50 cc syringe from the depression around the vent (Anderson 1984; Czeskleba et al. 1985). After three or four massaging movements, milt is transferred to a dry graduated cylinder (or retained in the syringe) and stored on ice for 15 minutes to 2.5 hours (Czeskleba et al. 1985); however, milt has been stored up to 48 hours (S. Fajfer, WDNR, personal communication). Care must be taken not to contaminate milt with water.

Collection of eggs

After collecting milt from several males, a female is captured and evaluated for ripeness by palpation of the abdomen and visual inspection of eggs (Anderson 1984). To ensure collecting females with ripe eggs, they should be captured while in the act of spawning.

Because captured females contract the sphincter muscles and eggs cannot be stripped easily (Anderson 1984), eggs are removed by cesarean-section (Anderson 1984). The sturgeon is placed in a stretcher and the vent area is dried. A heavy surgical scalpel is used to make a 3.8 to 5 cm incision 10 cm anterior and to left of vent (Anderson 1984). When the incision is made the fish is rotated dorsally, allowing eggs to flow from the incision into a collection basin (Anderson 1984). In Wisconsin, small plastic buckets (1.9 liter) were used to collect eggs, with care given to keeping the buckets dry. Ripe eggs flow freely and typically, 70,000 to 80,000 eggs are collected per fish. To reduce the time fish are kept out of the water, which is between 13 and 19 minutes, there is no attempt to collect every egg (S. Fajfer, WDNR, personal communication). Following egg collection, the incision is closed with 3-0 dissolving suture material (Anderson 1984). A triangular shaped cutting needle is used because of the tough skin of the fish, and a suture clamp or needle holder is used properly manipulate the needle (Anderson 1984; Czeskelba et al. 1985). The fish is sutured using a standard mattress pattern with 0.3 cm spaces between sutures (Anderson 1984). Anderson (1984) reported good success with the healing of these incisions (Anderson 1984).

Currently, an alternative nonsurgical technique for stripping the eggs is being developed (R. Bruch, WDNR, personal communication). This technique involves an artificial method of hand-stripping the eggs. The fish was placed in a stretcher and eggs were forced out with a strenuous massaging motion; first to the vent from just forward of the pectoral fins, then with a slightly less strenuous motion pulling back towards the region of the opening of the ovaries midway on the sides. This technique was partially successful in obtaining eggs; however, additional efforts were tested to enhance or improve egg collection. For example, a flexible tube (1.27 cm diameter and approximately 61 cm long) can be inserted into the vent and pushed into and along the oviduct until the tube passes through the sphincter muscle. At this point, some eggs can possibly be stripped into a basin. Connecting the tube to a volumetric flask with suction aids the flow of eggs and to increase numbers of eggs collected, the tube can be inserted into the second oviduct.

Fertilization of Eggs

Fertilization takes place immediately after eggs and sperm are collected. The dry method of fertilization (milt added directly to eggs and mixed for 10 seconds) is used (Anderson 1984) and then enough water is added to dilute the milt 10 to 15 times. The fertilized eggs are rinsed after they sit for two to four minutes. After 4 minutes post-fertilization eggs become adhesive (Anderson 1984); so, a bentonite clay solution is added to the eggs to prevent clumping. Bentonite clay powder is suspended in water to a "milk-shake" consistency prior to use, then two cups of the bentonite mixture are added to 11.3 L pan of eggs and stirred for 5 to 10 minutes, until eggs are not adhesive (Anderson 1984;

Czeskleba et al. 1985). Finally, the eggs are rinsed again, allowing a very light concentration of bentonite solution to remain. During the following one hour period, eggs will water-harden. Fertilized eggs are left in spawning buckets and transported on ice in coolers to the fish culture station. In Wisconsin, the period of holding and transport was three to four hours. In the past eggs have been transported in plastic bags (Czeskleba et al. 1985).

<u>Egg Incubation</u>

Upon arrival at the fish culture station, eggs are screened through 4-mm mesh nylon net to separate egg clumps (Czeskelba et al. 1985). Eggs are enumerated using the Von Bayer Method. There are usually 26,400-31,700 eggs per L; therefore, 50,000-60,000 eggs are put into each 1.9-L jar (Anderson 1984). After four days incubation at 13°C, eggs ranged from 3.0-3.5 mm in diameter, while eggs incubated at 16°C ranged from 4.0-4.5 mm in diameter (Czeskleba et al. 1985). At the Wild Rose Hatchery in Wisconsin, eggs of each female are incubated separately (S. Fajfer, WDNR, personal communication).

Water flow in each egg incubation jar should initially be set at 7 L per min (Anderson 1984; Czeskelba et al. 1985). After embryos have developed neural grooves, flow through incubation jars can be increased to 10 to 11 L per min (Wang et al. 1985). Greater flows near the end of incubation reduce problems with fungus by maintaining good water circulation around the eggs; however, higher flows cause eggs to roll more (Anderson 1984). To contain larvae when they hatch, Michigan has placed eggs in vertical flow incubators with flow rates of 3.8 L per minute (Anderson 1984).

Because eggs are dependent on water quality, they are treated one or two days for 15 minutes with 1667 PPM of formalin to prevent fungal infection (Anderson 1984; Czeskelba et al. 1985). However, eggs are not treated with formalin the first day, because embryos are sensitive to formalin while eggs are water hardening (S. Fafjer, WDNR, personal communication). Newly hatched larvae are also sensitive to formalin; therefore, treatments are stopped prior to hatching (S. Fafjer, WDNR, personal communication). Salt is frequently used as an alternative measure to prevent fungal infection during this time.

Wang et al. (1985) studied the effect of temperature on embryonic survival and found that 14-17°C was optimum with incipient mortalities occurring at 20°C. No effect of low incubation temperature was evident. Czeskleba et al. (1985) incubated eggs at two water temperatures, which resulted in egg hatches of 59% at 13° and 55% at 16°C.

Time of egg hatch seems somewhat variable. Czeskelta et al. (1985) reported that embryos incubated at 13°C began hatching after 8 days (194 accumulated temperature units, one temperature unit is defined as 0.6°C above 0°C for 24 hours (Piper et al. 1982), and hatching was complete in just over 12 days. These embryos had well-defined eye spots, mouths, and rudimentary development of the dorsal fin at time of hatch (Czeskleba et al. 1985). Another set of embryos incubated at 16°C, began hatching after 4 days (141 temperature units), and hatching was completed within 6 days (169 temperature units). However, these embryos had no eye spots, poorly developed mouths and no dorsal fin development (Czeskleba et al. 1985). In a second year of incubating eggs, Czeskleba et al. (1985) reported an overall hatching success of 65.4%. Eggs began hatching after 9 days, an average of 230 temperature units, and completed hatching between 11 and 12 days (272 temperature units). Anderson (1984) reported at 15°C, egg hatching began on day 9 and was complete within 24 hours. Eye-up of lake sturgeon eggs in recent years ranges from 60 to 90% with a mean of 75%; however, occasionally eggs from a single female have no viability (S. Fafjer, WDNR, personal communication).

Egg Development

Initially when eggs are removed from the fish, they are very dark in color (green-black) with a small buff colored spot (germinal vesicle) visible on one pole (Anderson 1984). After water-hardening, eggs change color progressively turning lighter until the eggs are almost transparent at time of hatching (Anderson 1984). After eggs clear, hatching usually occurs within 36 hours at 15°C (Anderson 1984).

Hatching and Early Rearing

Newly hatched lake sturgeon larvae, approximately 2.54 cm total length, swim constantly after hatching until the yolk-sac is absorbed (Anderson 1984). In Wisconsin, newly hatched embryos reared in MacDonald egg incubation jars are allowed to swim out of the jars into rearing units (Czeskleba et al. 1985). In Michigan, egg lots were reared in vertical flow incubators and fry were transferred to holding tanks after hatching (Anderson 1984). In Missouri, fry swim out of incubation jars into 133 L aquaria, with each aquarium receiving about 0.95 L of fry and inflow of 15.6°C water directed to the bottom (J. Hamilton, Missouri Department of Conservation (MDOC), personal communication). Fine screen is placed over outlets and air lines are directed over them to prevent impinging fish on the screen. Until swim-up and completion of mouth development, fry are reared in these aquaria then they are transferred to a large rearing unit.

Early larvae are negatively phototactic (Anderson 1984; Czeskleba et al. 1985; Wang et al. 1985). At the Wild Rose Hatchery in Wisconsin each rearing unit has an astroturf mat, folded in half (grass to grass) and bound with a rubber band, floating on the surface. As fry hatch and swim into the rearing unit, they swim into this mat to escape the light. Fortunately, this also permits easy tank cleaning. As fry initiate feeding they swim out of the mat. At this point the remaining fry can be collected from the mat and the mat removed (S. Fajfer, WDNR, personal communication). If protection from light is not provided, fry will congregate in the corners of the tank.

Early Development

Czeskleba et al. (1985) described early development of the lake sturgeon from hatch through initial feeding of the larvae. At hatching, fry eyes were poorly pigmented and there was no mouth or fin development; however, eyes are well-pigmented one day after hatching. Infolding for the mouth began and appeared well-developed by day 5. Dorsal fin rays began to develop on day 3 and began to protrude by day 6. Barbels and pectoral fins were evident by day 7. Pectoral, pelvic and dorsal fins and barbels were well developed by 15 days. Yolk sac absorption occurred between 8 and 10 days. After 10 days larvae became positively phototactic and swam, actively searching for food. A black intestinal plug, observed just posterior to the yolk sac in newly hatched embryos, had moved to the vent area in 10 days and was absent by day 12.

Culture Techniques

Many types of rearing units have been used for culturing lake sturgeon. Rearing unit design does not appear to significantly impact success in culturing this species. Anderson (1984) reared lake sturgeon in rectangular fiberglass tanks, 2.7 m x 51 cm x 30 cm. Each tank had a single pass flow-through water system with a flow rate of 7.5 L per min at 19.4°C. Sturgeon fry (N=2,000) were placed into each rearing unit. Tanks can be cleaned with a feather attached to a small handle that is used to sweep wastes together and then wastes can be removed with a syphon. Juvenile sturgeon reside on the bottom of tanks, so care should be given to avoid inflicting injury.

In Wisconsin, fry are initially hatched into small 127 L fiberglass rearing units. Approximately 2000 fry are reared in each unit. Water flow is 4.7 L per min and is increased to 11.4 L per min as amount of feed fed increases. Water temperature at hatching is between 12.2 and 13.3°C. As fry initiate feeding, water temperature is increased to 14.4°C, but later the sturgeon are reared at 15.6 to 18.3°C. Water temperatures are increased at a rate of 0.6°C per day (S. Fajfer, WDNR, personal communication). When fingerlings attain a total length of 3.8 cm, they are moved to larger rearing units.

Both circular and rectangular fiberglass rearing units are used at the Wild Rose Hatchery to rear 400 to 500 fingerlings in each unit (S. Fajfer, WDNR, personal communication). The rectangular units used are 5.5 m x 61 cm x 61 cm. Water level is maintained at 51 cm with a water flow of 18.9-22.7 L per min at 15.6°C. Water flow is single pass and limited by heating ability.

Round tanks have some advantages over rectangular ones because of the slight, but constant current. Currents keep feed, and to some extent the fry, moving and improves feeding. This appears to improve growth of the fry. In addition, circular tanks, which are approximately 1.8 m in diameter and have a water level of 61 cm, are easier to clean. Each unit is initially provided a water flow of 18.9 to 22.7 L per min at approximately 15.6°C (S. Fajfer, WDNR, personal communication). As the fingerlings increase in size the flow can be increased to 37.8 L per min.

Because fingerlings are reared in moderate water velocity, fine screens must be used on all rearing units while using brine shrimp and plankton as feed to prevent the food from being swept from the tank. Fingerling sturgeon 3.8-5 cm can be gently graded for size with a bar grader, although there will be a range of sizes. Fingerlings can also be sorted by simple examination, if numbers reared are not great. Although predation is rarely a problem, sorting to size permits providing feed of a uniform size (S. Fajfer, WDNR, personal communication). In Wisconsin, problems with gas supersaturation and disease can begin when water temperatures reach 21°C.

Missouri rears fingerlings in raceways upon reaching 7.6 cm in length (J. Hamilton, Missouri Department of Conservation (MDOC), personal communication). Raceways are 15.2 m x 1.5 m x, with a 91 cm water depth. Each raceway is stocked with approximately 10,000 fingerlings, but fish densities are reduced as fish grow, achieving a final density of approximately 3,000 lake sturgeon with each about 22.8 cm total length. Water flow has a turnover rate of once per hour. Fingerlings have tolerated water temperatures as high as 32.2°C; however, they have begun to show signs of stress at 33.3°C. Overall survival averages 65 to 70% with the greatest percentage of loss occurring while training fry to feed.

Anderson (1984) reported early efforts to feed lake sturgeon. Zooplankton were introduced several days prior to yolk-sac absorption. Fry were initially fed zooplankton that were mainly Daphnia pulex and various stages of copepods. Zooplankton were collected twice daily from a local lake using a plankton net. During the first 10 days of feeding, zooplankton were screened through Nitex (333 microns) to permit only the smallest zooplankton to enter the tanks. Subsequently, zooplankton were added directly into rearing units. Nitex screens were used on the effluent to prevent loss of zooplankton from the tank. This feeding regime was continued until fry were observed feeding on the zooplankton (16 and 31 days dependent on strain). Anderson (1984) observed the yolk sac was fully absorbed at 15-19 days post-hatch, and approximately 40% of the fry should began to feed. At 28 days, 70% of the fry had zooplankton in their stomachs (Anderson 1984). A natural diet was then presented twice daily, morning and evening, combining both zooplankton and annelids until approximately 25 days post-hatch when only worms were used. Worms were eaten readily at a rate of approximately 150 ml (170 g) per day per tank fed until about 53 days post-hatch when quantity of worms was increased to 300 ml (340 g). Fish did not appear to be satiated at these levels. Fry fed most actively during evening hours, and were often observed feeding from the surface and water column.

Mean survivals of two strains of lake sturgeon were 54% and 75%. Fish grew from 1.6 cm to 8.4 cm total length (0.07 g to 2.26 g in weight) during the 9-week period. Little survival was obtained using artificial diets.

Since Anderson's initial work a great deal of progress has been made in using natural diets. Reports on feeding regimes used at the Wild Rose Hatchery, Wisconsin and the Blind Pond Hatchery, Missouri follow. There still has been little progress in the use of artificial diets.

Wild Rose Hatchery Feeding Program (S. Fajfer, WDNR, personal communication)

Culturists have identified their biggest problem as finding sufficient food of appropriate size. Fry can initially feed on brine shrimp, fed 5 to 6 times daily. Czeskleba et al. (1985) reported 40% of the embryos had begun feeding on brine shrimp by day 12 and 100% by day 15. However, early fry should be introduced to zooplankton as soon as they are capable of feeding on zooplankton, because brine shrimp do not appear to provide sufficient nutrition over a long period of time. This problem is compounded because fry also eat brine shrimp cysts, which provide little or no nutrition. As fish grow feed size must increase proportionally. For this reason, lake sturgeon are initially fed brine shrimp, followed by Daphnia, then tubifex worms, and finally, adult brine shrimp.

Tubifex worms can generally be found on the bottom of settling ponds. In the early morning, worms are found clumped on the pond bottom and can be easily netted. Worms are cleaned using a strainer, then held in water and fed as needed. Fingerlings should never be overfed with tubifex worms, because they will overfeed, which will result with bloating and finally, fish can float to the surface. If this occurs, feeding should cease until the fish regain equilibrium.

As fish continue to grow, they are fed adult brine shrimp that are purchased frozen. Brine shrimp are cut up until the fish are capable of feeding on whole shrimp. Currently, only San Francisco brand adult brine shrimp produces consistent results. (Source: Beldts Aquarium Inc., PO Box 4006, Hazelwood, Missouri 63042; 1-800-937-9907).

Blind Pond Hatchery Feeding Program (J. Hamilton, MDOC, personal communication)

Missouri initially holds lake sturgeon at high densities while training the fish to feed, (50,000 fry in a rectangular rearing unit 2.7 m x 61 cm x 30). Fry are fed four times a day both brine shrimp and zooplankton that are collected in a 7.6-m zooplankton seine. When fry first feed, generally within a couple of days, fry are separated reducing densities to half. This is necessary because, lake sturgeon distribute horizontally, rather than vertically in rearing units. Therefore, each fish needs space on the bottom of the tank or they will not feed.

At a total length of between 3.8 and 5.1 cm, fingerlings are fed frozen adult brine shrimp. As fingerlings grow, grinding shrimp is no longer necessary. At 7.6 cm total length, fingerlings are moved to raceways, where they continue to feed on adult brine shrimp. Although other brands of shrimp have been used, only San Francisco Brand provides consistent results.

Fish Health

Little research has been done regarding health in cultured lake sturgeon. The following are some general observations. Lake sturgeon are very sensitive to supersaturations of gases, high ammonia levels and water temperatures above 33.3°C (J. Hamilton, MDOC, personal communication). Chemicals such as potassium permanganate and copper sulfate are apparently harmful to the lake sturgeon. Formalin should not be used on fry, but can be used on eggs and fingerlings. MS-222 is effective as an anesthetic.

Genetic Concerns

In any restoration effort using cultured fish, the source of brood fish can have significant and long term impacts. For example, in Pacific salmon (*Oncorhynchus* sp.) it has been demonstrated that as the geographical or ecological distances increase between the source of stock and the stream where juveniles are planted, juvenile to adult survival rates decline (Reisenbichler 1988). It has been assumed that behavioral and physiological adaptation to native stream conditions become problematic when juveniles are stocked in different waters (Reisenbichler 1988). Lake sturgeon from various tributaries of a river system have been shown to be morphologically and genetically different (Guenette et al. 1992). Therefore, some restoration programs do not use stocks from other drainages (S. Fajfer, WDNR, personal communication).

Conservation genetics should be integrated into the recovery program of any endangered fish species, but this is particularly important in the case of lake sturgeon because of their longevity. Meffe (1986) stated:

> *"Genetic aspects of small populations must be considered at the outset of management programs in order to maximize probability of their long-term survival and continued adaptability. Total genetic variance of a species consists of within population genetic diversity, and the differences found among populations; both types of variance should be maintained to maximize adaptive flexibility of endangered fishes. Forces that erode genetic variation include small population size, population bottlenecks, genetic drift, inbreeding depression, artificial selection in captivity and mixing of distinct genetic stock. These can lead to increased homozygosity, loss of quantitative variation, and exposure of deleterious recessive alleles, all of which may reduce fitness."*

Potential Eggs Sources

Currently three potential egg sources have been identified. The availability of eggs from any of these sources for a Lake Champlain restoration program has not been confirmed. Possibly, some combination of the following three sources might be used in a restoration program.

The Wisconsin Department of Natural Resources (WDNR) is one potential source of lake sturgeon eggs. A WDNR management goal is to "cooperate with other states in their efforts to reestablish lake sturgeon populations in appropriate waters within the original range". Eggs would be collected from the Lake Winnebago system, where spawning adults are readily accessible and eggs are abundant. A distinct advantage of this egg source is that eggs could be collected from a large number of spawning sturgeon. Therefore problems with genetic drift and inbreeding depression would be reduced. A disadvantage of this egg source is the geographical or ecological distance of Lake Winnebago from Lake Champlain.

A second potential egg source is from the St. Lawrence river sturgeon population. The New York Department of Environmental Conservation (NYDEC) and the United States Fish and Wildlife Service (USFWS) are cooperating on a project to reestablish lake sturgeon in New York tributaries of the St. Lawrence River. NYDEC was recently issued a five year permit by Quebec that allows them to annually spawn two females and three males captured from the Ottawa River, a tributary to the St. Lawrence. A Lake Champlain restoration program may be able to obtain eggs from the current cooperative project or could apply to Quebec for a permit to spawn lake sturgeon collected from the St. Lawrence River watershed. Using a small number of fish as the source of eggs for a restoration program would raise concerns about genetic diversity.

A third potential source of eggs is from remaining Lake Champlain. An advantage is that the restoration effort would use the original stock. The disadvantage is that the population of lake sturgeon in Lake Champlain is very small. Lake Champlain lake sturgeon are listed as endangered by Vermont's Agency of Natural Resources. In addition to the potential difficulty of collecting spawning adults annually and the genetic implications of using a small population as the broodstock for a restoration program, an endangered species permit would be required.

Estimated Costs for Rearing Lake Sturgeon

Sturgeon need to be reared in a coolwater production station with personnel trained in coolwater production techniques. Fish culture techniques for rearing lake sturgeon are similar to other coolwater species, but quite different from cold water species such as trout and salmon. A coolwater facility's water supply would be appropriate for rearing lake sturgeon in quality (chemical parameters, gas levels, temperature regimes, etc.) and quantity.

The costs for rearing lake sturgeon would initially require the purchase of additional equipment, and subsequently an annual operating budget. Equipment such as egg incubation units, rearing units and feeders would be required to rear lake sturgeon. The cost for the additional equipment and installation has been estimated to be $10,513 (Table 1). Rearing lake sturgeon would also require the use of some of a coolwaters stations existing facilities and resources (hatchery building, heated water supply, productions ponds for harvesting zooplankton and annelids, raceways, etc.). The use of these facilities for rearing lake sturgeon would have to be accommodated within the current production requirements of the fish culture station being used.

The annual cost for rearing lake sturgeon can not be adequately estimated until the egg source, and cost of that egg source is determined. The estimated annual cost of rearing lake sturgeon at the VTDFW Bald Hill Fish Culture Station once eggs have been obtained is about $24,000. The major annual expense is personnel costs. A great deal of time is spent raising and obtaining feed, feeding and cleaning rearing units. In addition, it is important that feeding, grading and in some instances cleaning rearing units be done by, or under the supervision of, trained staff.

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Personal Communications

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Potential Egg Sources

Wisconsin
Mr. David Ives (Fish Culture Chief) or
Mr. Lee Kevnen
Department of Natural Resources
P.O. Box 7921
Madison, WI 53707

New York
Al Sciavone (315-785-2266)

Table 1. Estimated costs of culturing lake sturgeon at the VTDFW Bald Hill Fish Culture Station

	STAFF DAYS	COST CAPITAL	ANNUAL
Program administration	7		
Eggs (collection and/or purchase and transport)	unknown	unknown	
Eggs/Set-up	.5		
Eggs incubation units (3 jars)		$ 300	0
Plumbing of incubation units		$ 50	
Egg treatment units treatment	1.0	$ 10	$ 50
Plumbing to rearing unit		$ 500	
30 gal. aquarium (5 units -2,000 fish/unit)		$ 300	
Astroturf		$ 50	
Rearing unit cleaning (4 hrs/day x 160 days)	80		
Circular (500 fish/unit-20 units)		$6,000	
Water/Heat			$ 100
Brine Shrimp Feeder (20)		$1,200	
Brine Shrimp Cysts (6 can)			$ 300
Feeding (1½ hour/day x 160 days)	30		
Frozen Brine Shrimp ($10/lb plus ship)			$1,500
Dalphnia (1 hour/day x 30 days)	3.75		
Annelids (1 hour/day x 60 days)	7.5		
Harvesting Stocking	2		
subtotal	131.75	$8,410	$1,950
Miscellaneous (25%)		2,103	
(Average salary for Supervisor, Assistant and Culturist = $15.12/hr includes 27% benefits)			15,936
subtotal			17,886
Administrative Overhead (34%)			6,081
Totals		$10,513	$23,967