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Selective Control of Eurasian Watermilfoil in Houghton Lake, Michigan: 2002–2006

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Abstract

Houghton Lake is the largest inland water body in Michigan, covering a surface area of nearly 9,000 ha (22,000 acres). The lake is a major natural and recreational resource for the region with activities including sport fishing, boating, snowmobiling, and habitat for migratory water birds.

Problems resulting from the proliferation of the submersed invasive plant, Eurasian watermilfoil, in Houghton Lake led to the development and implementation of a plan for managing that invader and restoring the native vegetation of the lake. The Houghton Lake Management Plan offered several alternative strategies for managing Eurasian watermilfoil within the limits of available funding. The Houghton Lake Improvement Board adopted an integrated strategy for managing Eurasian watermilfoil in the lake. The first phase of the strategy occurred from 2002 to 2004. The selected strategy used a whole-lake application of the aquatic herbicide fluridone in the first year to selectively control Eurasian watermilfoil. A second phase (2004–2006) employed targeted, relatively small-scale treatments of systemic herbicides (i.e., 2,4-D and triclopyr). As Eurasian watermilfoil populations recovered in subsequent years, milfoil weevils were introduced to help maintain control. Native plants, particularly elodea, were to be replanted if the initial impact of the whole-lake fluridone application warranted such re-vegetation.

In 2005, the diversity of aquatic plants was manifested by the occurrence of 23 species of aquatic plants in lake-wide surveys, while in 2006, 27 aquatic plant species were recorded. Overall, less than 3% of the total lake area was treated with herbicides for Eurasian watermilfoil control in 2006, indicating success of the maintenance control strategy. Because of the success of this management strategy, a second year of whole-lake fluridone applications was unnecessary.

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Preface

The work reported herein was conducted as part of the Aquatic Plant Control Research Program (APCRP). The APCRP is sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), and is assigned to the U.S. Army Engineer Research and Development Center (ERDC) under the purview of the Environmental Laboratory (EL), Vicksburg, MS. Funding was provided under Department of the Army Appropriation No. 96X3122, Construction General. Support was also provided by the U.S. Army Engineer District, Detroit, coordinated through Charles Uhlarik, Detroit District. The APCRP is managed under the Civil Works Environmental Engineering and Sciences office, Dr. Al Cofrancesco, EL, Technical Director. Dr. Linda Nelson, EL, was Assistant Technical Director and Program Manager for the APCRP. Program Monitor during this study was Timothy R. Toplisek, HQUSACE.

The Principal Investigator of this work was Dr. Kurt D. Getsinger, Environmental Processes Branch (EPB), Environmental Processes and Engineering Division (EPED), EL. This work was conducted and the report prepared by Dr. Craig S. Smith, Everglades National Park, Homestead, FL; Dr. Getsinger, Angela G. Poovey, William F. James, and Dr. Michael D. Netherland, EPB; R. Michael Stewart, U.S. Army Engineer District, Vicksburg; Dr. Mark Heilman, SePRO Corporation; Dr. Scott McNaught, Central Michigan University, Mt. Pleasant, MI; and Anthony Groves, Pam Tyning, and Paul Hausler, Progressive AE, Grand Rapids, MI.

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Summary

Houghton Lake is the largest inland water body in Michigan, covering a surface area of nearly 9,000 ha (22,000 acres). In conjunction with nearby Higgins Lake (3,900 ha), it forms the headwaters of the Muskegon River. Although quite large in surface area, the lake is very shallow, with an average depth of 2.6 m and a maximum depth of only 6.7 m. The lake is a major natural and recreational resource for the region, with activities including sport fishing, boating, snowmobiling, and habitat for migratory water birds.

Problems resulting from the proliferation of the submersed invasive plant, Eurasian watermilfoil, in Houghton Lake led to the development and implementation of a plan for managing that invader and restoring the native vegetation of the lake. Plan development included: (1) a review of previous studies of Houghton Lake, (2) surveys of the aquatic vegetation, insect biocontrol abundance, and water quality in the lake, and (3) identification of alternatives for selectively managing Eurasian watermilfoil and restoring the native vegetation of the lake. A pre-management survey in July and August 2001 found that Eurasian watermilfoil was the most abundant plant in the lake. It was detected in approximately 4,400 ha of the lake and was common or dense in approximately 2,200 ha. Stands of the exotic plant curlyleaf pondweed were also detected in several locations. Approximately 20 native aquatic plants were encountered during vegetation surveys. The most abundant native was elodea, which had been the most abundant plant in the lake prior to the expansion of Eurasian watermilfoil. The milfoil weevil (insect biocontrol agent) exhibited a clumped distribution, with only a few areas having populations above thresholds shown to impact Eurasian watermilfoil, though many areas of the lake had weevil densities below these thresholds. Water quality data indicated that the lake was mesotrophic, and problems associated with eutrophication (e.g., nuisance algal blooms, high turbidity, and oxygen depletion) were not present.

The Houghton Lake Management Plan offered several alternative strategies for managing Eurasian watermilfoil within the limits of available funding. Each of these alternatives was designed to significantly reduce the abundance of Eurasian watermilfoil to a level where negative impacts from

that plant on the biology and use of the lake would be minimized. In addition, the alternatives were designed to preserve critical resources provided by the lake, specifically a healthy native plant community, good water quality, and a productive sport fishery. From these choices, the Houghton Lake Improvement Board adopted an integrated strategy for managing Eurasian watermilfoil in the lake. The selected strategy used a whole-lake application of the aquatic herbicide fluridone in the first year to selectively control Eurasian watermilfoil. As Eurasian watermilfoil populations recovered in subsequent years, milfoil weevils were introduced to help maintain control. Native plants, particularly elodea, were to be replanted if the initial impact of the whole-lake fluridone application warranted such re-vegetation.

From 2002 to 2004, the first phase of the Houghton Lake management strategy, whole-lake applications of the aquatic herbicide Sonar® A.S. (fluridone), were conducted to control Eurasian watermilfoil and provide an opportunity for the native vegetation to recover. Prior to these applications, plant susceptibility to fluridone was measured using a physiological assay to evaluate the response of plants from the lake to varying concentrations of the herbicide. Based on results of the susceptibility assay, the herbicide was applied in 2002 to provide an initial whole-lake aqueous concentration of 6 $\mu g\ L^{-1}$ to a depth of 3 m. Two weeks after the initial application, measured aqueous herbicide residues triggered a second whole-lake application to return the aqueous fluridone concentration to approximately 6 $\mu g\ L^{-1}$. Post-treatment herbicide concentrations were monitored at 30 locations in the lake and several locations downstream from the lake. Plant responses to the herbicide application were monitored using the physiological assay to determine whether plants had received a lethal herbicide dose.

The whole-lake fluridone applications were extremely successful in controlling Eurasian watermilfoil with minimal, mostly short-term impact on most native plant species. After the 2002 treatments, Eurasian watermilfoil was not detected during 2003, and only a very small amount had returned to the lake by 2004; therefore, no additional fluridone applications were necessary. The treatments initially reduced native plant abundance, though a number of plant species were relatively unaffected or increased during the year of treatment. Most native plant species had recovered by 2004.

Native plant species exhibited a range of responses to the whole-lake fluridone treatments. Many species were relatively unaffected or increased during the year of treatment or shortly thereafter. Elodea, which was very abundant prior to treatment, was drastically reduced by the treatment but had nearly recovered by 2004. Wild rice, which had been absent from the lake prior to treatment, reappeared in the lake during 2003 and expanded from 2003 to 2004. Longer-term adverse effects of the treatments were confined to wild celery, which decreased following the treatments and had not recovered by 2004, and to coontail, northern watermilfoil, and white water crowfoot, which were apparently eliminated from the lake and had not reappeared by 2004.

The overall frequency of native vegetation declined only slightly from 2001 to 2002, then more rapidly from 2002 through 2004. By 2004, the frequency of vegetation had declined to 47%, or only 61% of the pre-treatment frequency. Total cumulative cover of aquatic plant species declined by about two-thirds from 2001 through 2002 and 2003, then increased by more than double from 2003 to 2004. Total cumulative cover of native plants in 2004 was approximately 1.5 times that in 2001. Most of the initial loss of cumulative cover resulted from the elimination of Eurasian watermilfoil; cumulative cover of native species declined only slightly from 2001 to 2003, then increased rapidly from 2003 to 2004.

No adverse impacts on water quality were measured during 2002 following the herbicide applications. Dissolved oxygen (DO), which can become depleted in bottom waters as a result of rapid plant decomposition, remained above 5 mg L^{-1}. Slow death and decomposition of target vegetation is the typical response to fluridone-sensitive plants, which prevents DO depletion. Turbidity remained very low (<4 NTU) at all stations and depths throughout the summer, suggesting minimal re-suspension of sediments following the herbicide applications. Chlorophyll and nutrient (N and P) concentration patterns during the summer of 2002 differed little from concentrations observed prior to treatment, suggesting that the treatments had little impact, if any, on the productivity of the lake.

Following the 2002 whole-lake fluridone applications, a second phase of the Houghton Lake management strategy was implemented (2004–2006) employing targeted, relatively small-scale (several hundred hectare) treatments of systemic herbicides (i.e. 2,4-D and triclopyr). This chemical treatment was supplemented by the stocking of nearly 40,000 biocontrol weevils at selected locations. These targeted applications and stockings were part of an integrated strategy designed to sustain long-term control of Eurasian watermilfoil in the lake. In 2005, the diversity of aquatic plants was manifested by the occurrence of 23 species of aquatic plants in lake-wide surveys, while in 2006, 27 aquatic plant species were recorded. Overall, less than 3% of the total lake area was treated with herbicides for Eurasian watermilfoil control in 2006, indicating success of the maintenance control strategy. Because of the success of this management strategy, a second year of whole-lake fluridone applications was unnecessary.

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
acre-feet	1,233.5	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters
hectares	1.0 E+04	square meters
microns	1.0 E-06	meters
pounds (mass)	0.45359237	kilograms
pounds per acre	1.12	kilograms per hectare

1 Introduction

This resource management project was initiated in response to concerns from stakeholders in the lake community and from the public about the proliferation of the exotic invasive plant Eurasian watermilfoil (*Myriophyllum spicatum* L.) in Houghton Lake. Lake-wide surveys conducted in 1999 and 2000 indicated that up to 4000 ha of the water body was infested with Eurasian watermilfoil (Pullman 2000), with nearly 2000 ha of dense stands (ReMetrix LLC, unpublished data). Eurasian watermilfoil fragmentation and accumulation of these shoots on the shoreline, suppression of native aquatic macrophyte species, and the overall decline in recreational quality, and fish and wildlife habitat prompted escalating local concern. In 2001, the lake was evaluated to develop a feasibility study for management of Houghton Lake with a focus on selective control of Eurasian watermilfoil. Recommendations from this study were incorporated into the final resource management plan adopted by the Houghton Lake Improvement Board (HLIB). This plan was based in part on guidance developed in a workshop held in 2001 to identify alternatives for managing Eurasian watermilfoil and restoring the native vegetation of the lake (Getsinger et al. 2002a). Based on information presented in the workshop and on other considerations, the HLIB elected to manage the Lake Houghton milfoil infestation in various phases over several years. In year 1, low-dose, whole-lake herbicide applications were employed to selectively remove Eurasian watermilfoil.

From 2002–2006, a scientific and operational team, including personnel from the U.S. Army Engineer (USAE) Research and Development Center (ERDC), USAE Detroit District, SePRO Corporation, ReMetrix LLC, the Michigan Water Research Center, and Progressive AE monitored this management program. These assessments included monitoring the initial whole-lake fluridone treatments in 2002–2003 and maintenance control efforts in 2004–2006, including the response of target and non-target aquatic vegetation and overall water quality.

Objectives

The objectives of this report are to:

1. Review data used to generate management options for selective control of Eurasian watermilfoil in Houghton Lake.
2. Describe the process used to achieve selective control.
3. Present results of various evaluations that monitored target weed control and changes to water quality and plant community composition.
4. Summarize results of management plan implementation from 2002–2006.

Description of Houghton Lake

Location, morphometry, and origin

Houghton Lake is located in the lower peninsula of Michigan, about 55 km north of Clare (Figure 1), in Roscommon County. Houghton is the largest inland lake in Michigan, with a surface area of approximately 9,000 ha (20,000 acres). The lake is very shallow, having a maximum depth of 6.4 m and an average depth of 2.3 m (U.S. Environmental Protection Agency (USEPA) 1975) or 2.6 m (Pecor et al. 1973a). The volume of the lake is approximately 2.10×10^8 m^3 (170,000 acre-ft) (Pecor et al. 1973b).

Houghton Lake was formed as a depression in the Grayling Outwash Plain, a large, thick, poorly drained area of glacial outwash. Soils of the outwash plain are typically sand or sands mixed with gravel and most are excessively drained. Layers of clay are found at the southern and western edges of the lake, indicating that the lake is probably underlain by deposits of lacustrine clays.

Hydrology

Houghton Lake and its watershed comprise the headwaters of the Muskegon River, which flows west across the state to enter Lake Michigan at the city of Muskegon (Figure 1). Water enters the lake through four major tributaries ("The Cut," Backus Creek, Denton Creek, and Knappen Creek) plus a number of minor tributaries and drains. Water level of the lake is maintained by a dam along the northwest shore, which is the outlet into the Muskegon River.

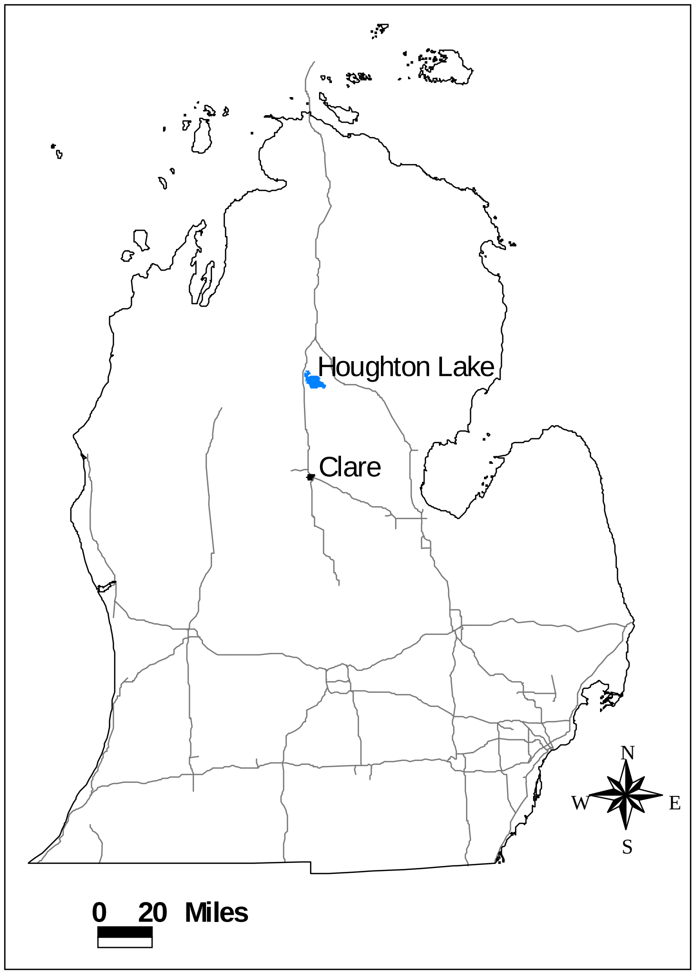


Figure 1. Location of Houghton Lake, Michigan, and associated watershed.

Average annual outflow from the lake into the Muskegon River is 4.4 $m^3 s^{-1}$ (Novy and Pecor 1973). The nearest U.S. Geological Survey gauging station is located at Evart, Michigan, about 80 km downstream from the outlet of the lake. Upstream from Evart, the Muskegon River drains 3711 km^2 (1,433 mi^2); thus, the Houghton Lake watershed represents only about 15% of the area drained by the river at that point. The average, maximal, and minimal flow rates observed at Evart during the 70-year period from 1930 through 1999 are plotted in Figure 2. Average annual flow is 30 $m^3 s^{-1}$. Stream flow varies seasonally, with a seasonal maximum average flow of approximately 7 $m^3 s^{-1}$ in the spring (March–April). Maximal and minimal flow rates are considerably higher and lower, respectively, than the average flow rates. Maximum flows can reach 255 $m^3 s^{-1}$ in the springtime, or 200 $m^3 s^{-1}$ at other times of year. Minimum flow rates are only 14 $m^3 s^{-1}$ during much of the year and as low as 28 $m^3 s^{-1}$ in the spring.

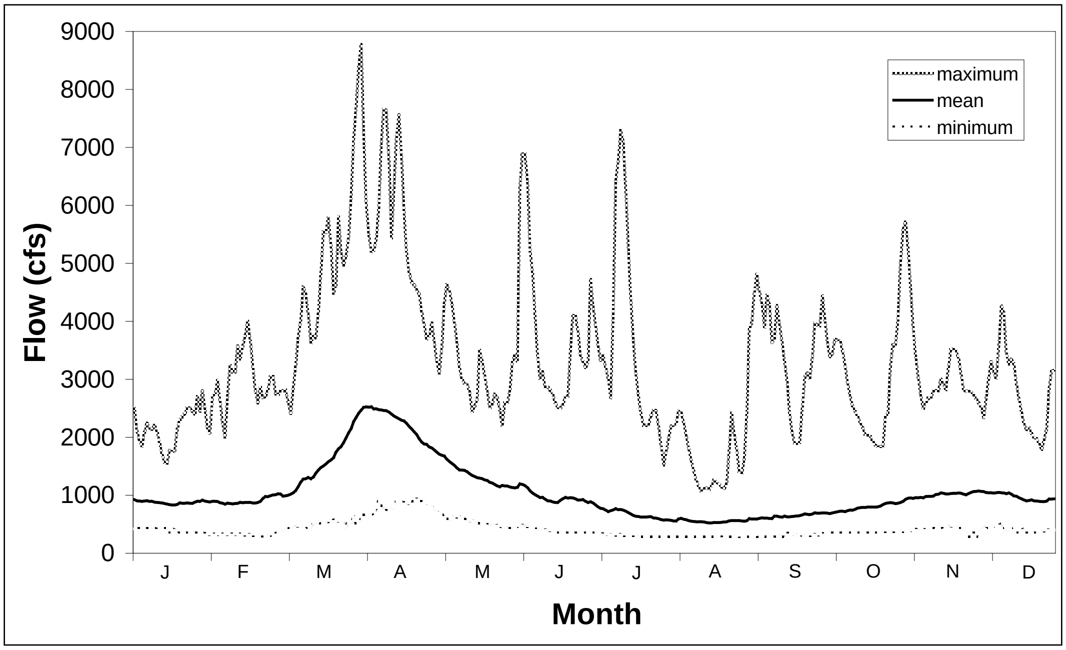


Figure 2. Flow of the Muskegon River at Evart, Michigan, approximately 50 miles downstream from the outlet of Houghton Lake, 1930 to 1999.

The hydraulic residence time of the lake is approximately 1.2 years (Pecor et al. 1973b). Extrapolating the seasonal variations in flow at Evart to Houghton Lake, on average the short-term hydraulic residence time of the lake will be reduced to approximately 5.8 months in an average spring. During a wet year, spring flows of nearly nine times the season average would reduce the short-term hydraulic residence time to approximately 1.6 months. Conversely, reduced flow during a dry year would lengthen the hydraulic residence time to approximately 16 months in the spring and more than 4 years during the summer.

The watershed of Houghton Lake includes the immediate drainage area around the lake and the watersheds of Higgins Lake and Denton Creek (Figure 3). The entire watershed (including the lake itself) has an area of 565 km^2. The immediate drainage, Higgins Lake and Denton Creek watersheds, and the lake itself are 140, 246, 98, and 81 km^2, respectively (Pecor et al. 1973b).

Nutrient loading

Nutrient loading to Houghton Lake was calculated by several studies conducted during the 1970s (Pecor et al. 1973b, USEPA 1975). Phosphorus and nitrogen loading to the lake were dominated by natural sources, rather than by runoff from developed areas (Table 1). Major tributaries were the

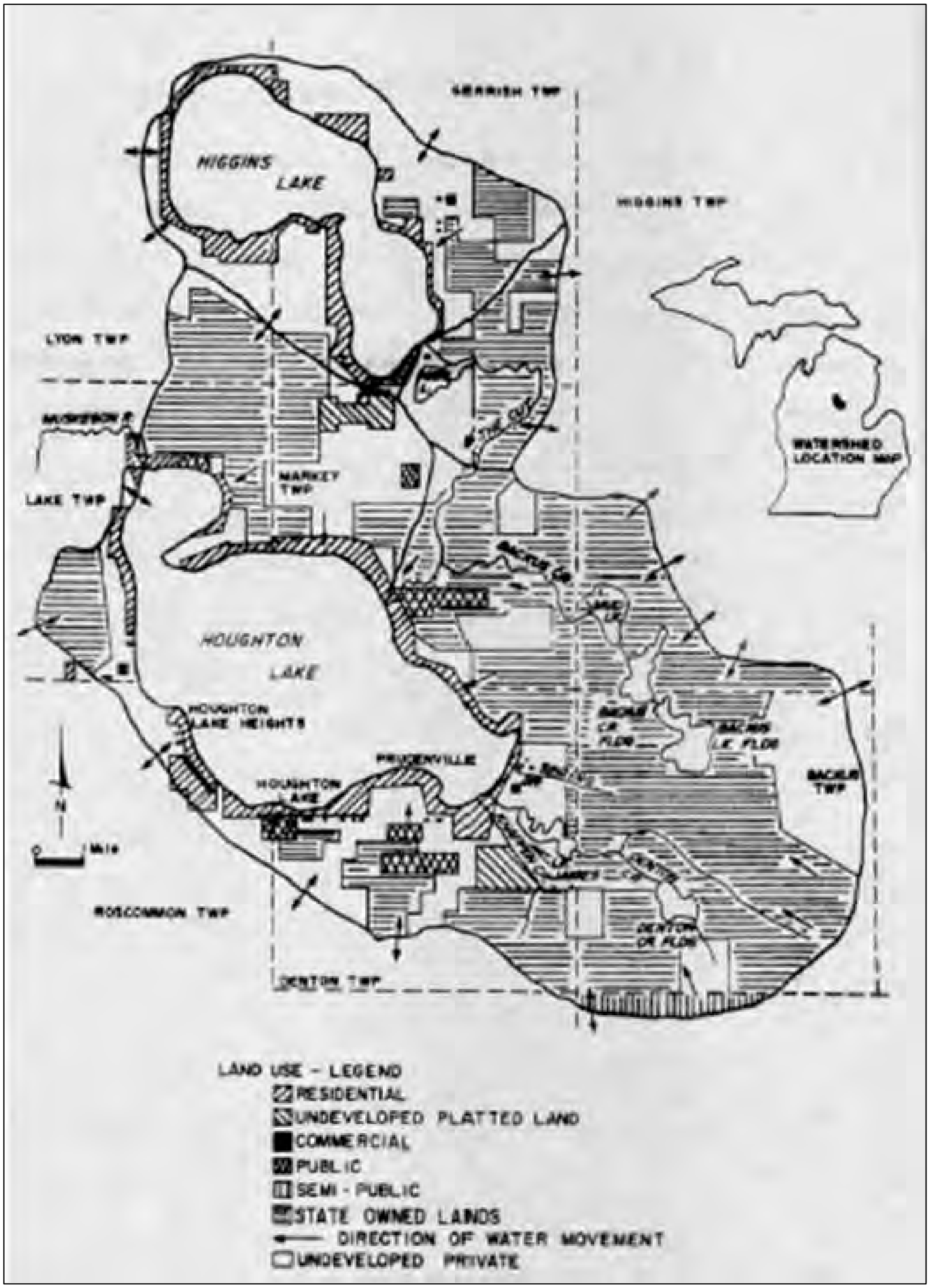


Figure 3. Watershed of Houghton Lake, Michigan.

most important source of phosphorus. Direct precipitation on the lake surface was the largest source of nitrogen loading and the second largest source of phosphorus loading. Drainage from residential areas and shallow groundwater (including septic inputs) were very minor sources of nutrient loading to the lake. Somewhat higher nutrient loads than those shown in Table 1 were calculated by the USEPA (1975), primarily due to much higher estimated inputs from septic systems and residential drainage.

Table 1. Sources of phosphorus and nitrogen loading to Houghton Lake, 1972 (Source: Pecor et al. 1973b).

Source	Phosphorus (lb/yr)	Nitrogen (lb/yr)
Residential drainage	352	4,220
Shallow groundwater	155	3,430
Forest & marsh drainage	849	19,100
Major tributaries	3,290	91,100
Precipitation	3,280	135,600
Deep groundwater	28	23,500
Total	**7,950**	**277,000**

Despite poor water quality in runoff entering the lake from developed areas, the volume of urban runoff and the amount of nutrient export from developed areas was lower than expected, presumably due to sandy soils which limit surface runoff (Pecor et al. 1973b). Only 6% of the annual phosphorus load and 3% of the annual nitrogen load were derived from cultural sources (Pecor et al. 1973b), due to the large fraction of the drainage basin that consisted of undeveloped state-owned land or lake surface.

Development around the shores of Houghton Lake since 1972 has probably had little impact on the nutrient budget of the lake. Land use changes in the watershed are constrained by the large amount of state-owned land and open water. In addition, since 1972, a local sewer initiative has replaced septic systems around the lake by municipal sewer systems that do not discharge nutrients into the lake. All of the residential shoreline areas around the lake are now served by sewer systems. Only properties more than 0.4 to 0.8 km (depending on location) from the lake remain on septic systems.

Water quality

Water quality studies from the mid 1970's have classified Houghton Lake as eutrophic or meso-eutrophic (Pecor et al. 1973a, USEPA 1975). The lake has fairly high nutrient concentrations and productivity, characteristic of a somewhat eutrophic lake, but as of 1972 it had not experienced the adverse conditions usually associated with eutrophication (Pecor et al. 1973a). No comprehensive water quality studies of the lake have been published since the mid 1970's.

Pecor et al. (1973b) conducted a detailed study of the water quality of Houghton Lake. They found an average pH of 8.2 and an alkalinity of approximately 92 mg $CaCO_3$ L^{-1}, both characteristic of a moderately alkaline lake. The average conductivity of 193 μmhos $(cm^2)^{-1}$ indicated moderate concentrations of total dissolved solids. The Secchi disk depth in the lake averaged 2 m. Total phosphorus concentrations averaged 21 μg P L^{-1}, whereas chlorophyll *a* concentrations in the lake ranged from 5.6 to 12.4 μg L^{-1}. Based on ranges described by Carlson (1977), these values are indicative of mesotrophic to eutrophic conditions. Dissolved oxygen concentrations remained above 6 mg L^{-1} at all locations throughout the entire ice-free season. In winter under the ice, near-surface dissolved oxygen concentrations remained above 6 mg L^{-1} but dissolved oxygen near the bottom dropped to 4.3 mg L^{-1} in one isolated deep (4.6 m) basin.

Plankton

In November of 1972, the phytoplankton (microscopic algae) community of the lake was dominated by the bluegreens *Polycystis* spp. and *Lyngbya* spp. in September and by the diatom *Fragilaria* spp. and unspecified flagellates (USEPA 1975). This phytoplankton community is characteristic of a shallow, moderately eutrophic lake. Pecor et al. (1973a) studied the diatom and chrysomonad components of the phytoplankton. They found 17 common species and concluded from the species composition that the Houghton Lake phytoplankton community was indicative of a shallow, alkaline, eutrophic lake with little organic enrichment and substantial wave action. No problematic algal blooms were noted by either study.

The zooplankton community of the lake was examined from 1971 through 1973 (Pecor et al. 1973a). Two rotifer genera, *Keratella* and *Polyarthra,* accounted for approximately 90% of the zooplankton. Seven percent of the zooplankton consisted of copepods, with nauplii of *Cyclops* and *Diaptomus* accounting for most of the organisms encountered. Cladocerans, including *Bosmina* and lesser numbers of *Daphnia* and *Chydorus*, made up only 3% of the zooplankton. The strong dominance of small zooplankton was considered indication of intense predation by fish (Pecor et al. 1973a). No comprehensive plankton studies of the lake have been published since the mid 1970's.

Benthos

The benthos of Houghton Lake was also examined by Pecor et al. (1973a), as part of their evaluation of water quality. They found that the benthos of Houghton Lake was dominated by organisms characteristic of littoral areas of large lakes. Both the productivity and diversity of the benthos were high. Scuds (*Hyalella azteca*), midges (Chironimidae), fingernail clams (*Pisidium* spp.), and worms (oligochaeta) made up approximately 87% of the benthos. Dense weedbeds supported the greatest density of benthic organisms. Many benthic organisms intolerant of low dissolved oxygen concentrations were present. No comprehensive benthos studies of the lake have been published since the mid 1970's.

Aquatic vegetation

Previous studies indicate that Houghton Lake has long supported an abundant and fairly diverse aquatic plant community. Plant species detected in the lake are listed in Table 2. Evaluation of the aquatic vegetation of the lake as part of a waterfowl study (Evenson et al. 1973) found a total plant standing crop of 1.01 metric tons (mt) per ha (901 pounds per acre [lb/ac]), averaged over the entire lake. Plant beds averaged 2.70 mt ha^{-1} (2,410 lb/ac^{-1}) and open-water areas averaged 0.67 mt ha^{-1} (600 lb/ac^{-1}). Evenson et al. (1973) delineated eight weedbeds: (1) the South Shore weedbed, (2) the Middle Ground weedbed, (3) the Muddy Bay weedbed, (4) the North Bay weedbed, (5) the North Bay weedbed A, (6) the North Shore weedbed, (7) the Sago [pondweed] bed, and (8) the little round weedbed (Figure 4). In all, these plant beds occupied approximately one-sixth (17%) of the total area of the lake.

Table 2. Aquatic plants found in Houghton Lake prior to 2001 (compiled from Evenson (1973) Pullman (2000)).

Common Name	Scientific Name
Submersed Plants	
Bladderwort	*Utricularia vulgaris*
Coontail	*Ceratophyllum demersum*
Elodea	*Elodea canadensis*
Alpine pondweed	*Potamogeton alpinus*
Richardson's pondweed	*P. Richardsonii*
Curlyleaf pondweed	*P. crispus*
Flat-stemmed pondweed	*P. zosteroformis*
Floating leaf pondweed	*P. natans*
Large leaf pondweed	*P. amplifolius*
Ribbon leaf pondweed	*P. epihydrus*
Robbins pondweed	*P. Robinsii*
Sago pondweed	*Stukenia pectinatus*
Small pondweed	*P. pusillus*
Variable pondweed	*P. gramineus*
Whitestem pondweed	*P. praelongus*
Muskgrass	*Chara sp.*
Naiad, water nymph	*Najas sp.*
White water crowfoot	*Ranunculus*
Eurasian watermilfoil	*Myriophyllum spicatum*
Northern watermilfoil	*M. sibiricum*
Water marigold	*Megalodonta (Bidens) beckii*
Water stargrass	*Zosterella (Heteranthera)*
Wild celery	*Vallisneria americana*
Emergent Plants	
Hard-stem bulrush	*Scirpus acutus*
Threesquare bulrush	*S. americanus*
Pickerel weed	*Pontedaria cordata*
Northern wild rice	*Zizania aquatica*
Spatterdock	*Nuphar variegatum*
White water lily	*Nymphaea tuberosa*

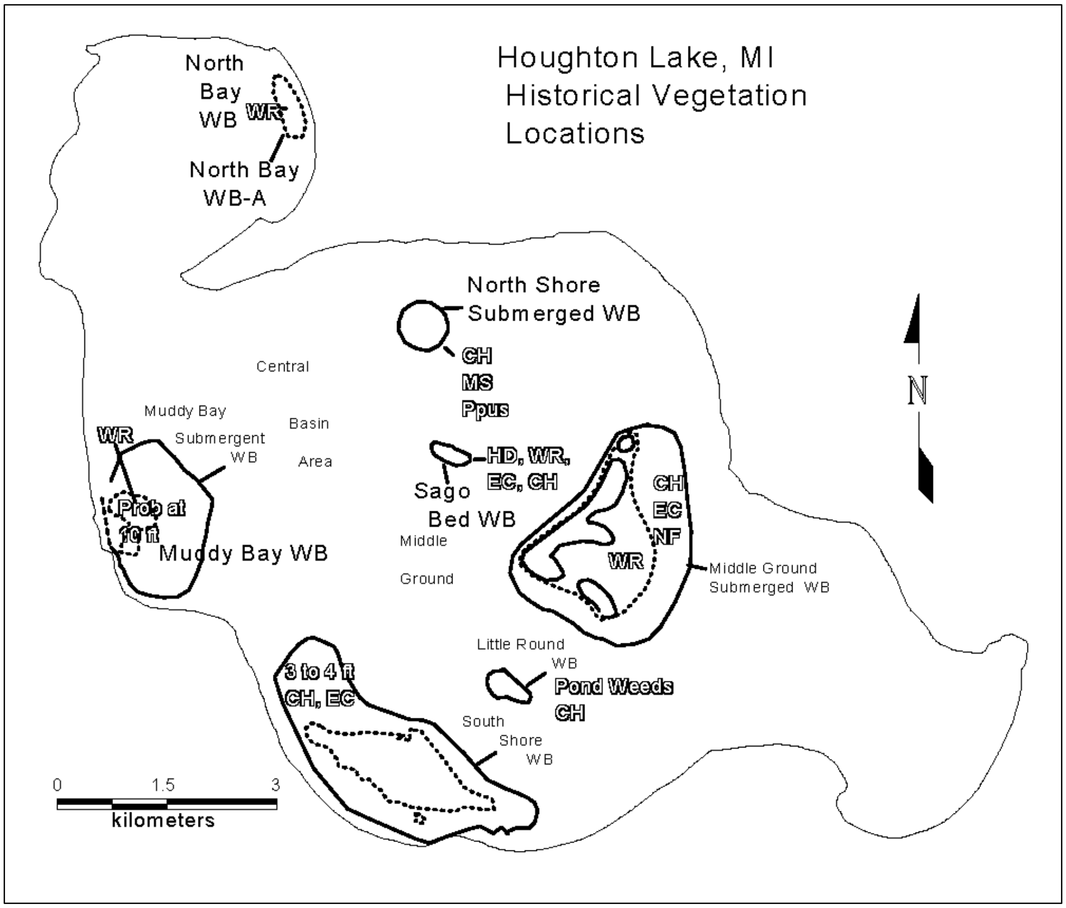


Figure 4. Historic plant bed locations in Houghton Lake (redrawn from Evenson et al. (1973)). WB = weedbed.

Many of the beds were dominated by the macroalga muskgrass (*Chara* spp.), and Elodea (*Elodea canadensis* L.) was the most dominant higher plant in the South Shore, Middle Ground, and Muddy Bay weedbeds. Watermilfoils (*Myriophyllum* spp.) were at most only moderately dominant, except in the North Shore weedbed.

Studies conducted during the last decade have expressed increasing concern about the expansion of watermilfoil species. Studies prior to 1999 did not differentiate between northern watermilfoil and Eurasian watermilfoil, so it is impossible to determine exactly when Eurasian watermilfoil was introduced to the lake, though no watermilfoil species was reported as particularly abundant prior to 1996. By 1996, watermilfoil had become the second-most-dominant submersed plant in the lake and was dense enough in several locations to be a cause for concern (Bonnette 1996). At this time, elodea was more abundant and more widespread than watermilfoil and several other native species were nearly as abundant as watermilfoil, although not as widespread. The distribution pattern described in 1996 (Bonnette 1996), with watermilfoil forming dense canopied beds at the lakeward and western edges of the south shore weedbed, suggests that Eurasian watermilfoil was probably well established in the lake and expanding. It is not clear whether it was present during the surveys conducted in the 1970s. Continuing concern about the expansion of Eurasian watermilfoil led to a study in 1999 (Pullman 2000), which mapped the distribution of that plant throughout the lake and determined that it could be found in nearly 4,000 ha of the lake. The 1999 study was followed in 2000 by a detailed point-intercept survey of the submersed vegetation of Houghton Lake (ReMetrix, LLC, unpublished data). This study developed the vegetation sampling grid used for pre- and post-management monitoring of the lake (see below), obtained an initial IKONOS satellite image (GeoEye, Dulles, VA) that has been used as a basemap for vegetation, treatment and depth maps of the lake, and initiated sampling of the grid. The 2000 vegetation survey was never completed due to a late season start and deteriorating weather conditions.

Fish

Houghton Lake is among the most important fishing resources in Michigan. The lake has been stocked with smallmouth bass (*Micropterus dolomieu*) northern pike (*Esox lucius*), walleye (*Stizostedion vitreum*), yellow perch (*Perca flavescens*) and bluegill (*Lepomis macrochirus*) (Schrouder 1993). Studies by the Michigan Department of Natural Resources (MIDNR) provide a fairly comprehensive picture of fish populations in the lake. A detailed study of fish populations in the lake during 1955 (Crowe and Latta 1956) estimated that the lake supported 3 to 4 million fish, or 333 to 489 legal-sized fish per ha (135 to 198 per acre). The catch in 1955 consisted of 63% panfish, 18% gamefish, and 19% roughfish. A less extensive study in 1972 (Pecor et al. 1973a) found similar results and compared growth rates of fish from Houghton Lake from 1922 until 1972 with the state average. Growth rates of bluegill, pumpkinseed (*Lepomis gibbosus*), rock bass (*Ambloplites rupestris*), and black crappie (*Pomoxis nigromaculatus*) were consistently higher than the state average, at least by the time fish reached their fourth year. Largemouth bass (*Micropterus salmoides*) and smallmouth bass also grew at rates greater than the state average. The length of these fish species at different age classes did not appear to have changed from 1939 until 1972. Walleye, yellow perch, and northern pike in Houghton Lake were all growing at rates below the state average. Growth rates of walleye and yellow perch had been poorest in the 1950s and improved since then, whereas the growth rates of northern pike were found to be stable over time. Another study in 1993 (Schrouder 1993) found that the composition of the fish community and growth rates were similar to those from previous studies.

As of 2001, Houghton Lake fish populations had not yet begun to show stunting or other impacts resulting from the expansion of Eurasian watermilfoil (Getsinger et al. 2002a). Since the large-scale Eurasian watermilfoil invasion was relatively recent at that time, pronounced impacts on the fisheries would not have been expected. If Eurasian watermilfoil was allowed to continue to dominate the vegetation of the lake, impacts on fish would likely manifest themselves over time.

Waterfowl

Houghton Lake is an important resource for waterfowl, particularly migrating ducks and coots. Based on studies by Evenson et al. (1973), aquatic plant materials were an important part of the diet for all of the waterfowl species examined except goldeneye (*Bucephala clangula*), at least seasonally. Plant materials were a major part of the diet in both spring and fall in greater scaup (*Aythya marila*), ringed-necked ducks (*Aythya collaris*), ruddy ducks (*Oxyura jamaicensis*), widgeons (*Mareca americana*), and coots (*Fulica americana*). Buffleheads (*Bucephala albeola*) and lesser scaup (*Aythya affinus*) also ate significant amounts of plant material in the fall. Plant species found in significant quantities in waterfowl diets included naiad (*Najas* spp.), elodea, Richardson's pondweed (*Potamogeton richardsonii* (A. Bennett) Rydb.), small pondweed (*P. pusillus* L), variable pondweed (*P. gramineus* L.), wild celery (*Vallisneria americana* L.), wild rice (*Zizania* spp.), and muskgrass. No comprehensive studies of waterfowl use on the lake have been published since the mid 1970's.

Recreational use of the lake

Houghton Lake is very heavily used for recreation and is a major resource, drawing users from the entire state of Michigan and beyond. The local year-around human population is approximately 11,000, but the population increases to approximately 30,000 during the summer vacation peak from Memorial Day through the Labor Day holiday periods. Selected winter activities, including the annual TIP-UP TOWN® U.S.A. winter festival, can attract 40,000 to 50,000 people.

The economies of communities around Houghton Lake are highly dependent on tourism associated with the lake. Over 80% of lake-related business owners feel they are dependent on the local tourism industry, with motel revenues between 1996–2001 grossing over $13 million (Deamud et al. 2004). Likewise, local property values are tied into the condition of the lake. The Houghton Lake townships contain commercial property valued in 2002 at $167 million dollars and residential property valued at $1.2 billion (Deamud et al. 2004).

Lake management history

The water level in Houghton Lake has been controlled by an outlet structure for many years. Prior to 1938, the lake level was controlled by a timber dam with flash boards. The present outlet structure was constructed in 1938. In 1982, the maximum legal lake levels were set at 346.9 m (1138.1 ft) above Mean Sea Level (MSL) in the summer and 346.7 m (1137.6 ft) above MSL in the winter. The court order that established these levels indicated that they were selected to best benefit the public and to protect natural resources and property values (Horn 1982). In practice, lake levels in this area are typically set sufficiently high to facilitate summer boating and lowered in the winter to reduce ice damage to shorelines and nearshore structures.

Fishery management began as early as 1921 and has included stocking of the lake with smallmouth bass, northern pike, yellow perch, bluegills, and walleye (see above). In addition to stocking Houghton Lake with various fish species, the MIDNR developed two large marsh areas on the northwestern side of the lake in 1965 and 1969 that were initially operated as northern pike spawning marshes (Schrouder 1993). These marshes are impounded by a dike system separating them from the lake and the water level in these impoundments is controlled by pumping. Due to a lack of natural access to these areas, fish were to be trapped and transferred in and out of them. Northern pike production in these marshes was not as good as expected and they were found to have little impact on pike populations in the lake (Schrouder 1993). Their operation as spawning marshes was discontinued in 1978 and they are presently maintained about 30 cm (1 ft) above the lake level and used for waterfowl management.

Swimmers' itch (a dermal rash on humans exposed to infected waters) treatments have been conducted in various parts of the lake since 1944 (Novy et al. 1973). These treatments apply relatively high doses of copper sulfate to kill snails, including those that serve as intermediate hosts for the swimmer's itch parasites. Table 3 lists the quantities of copper sulfate applied to the lake for swimmers' itch control between 1975 and 1999.[1] Copper from the treatments has accumulated in deep soft sediments of Houghton Lake, but not in most other locations or in most organisms living in the lake (Novy et al. 1973).

Table 3. Copper sulfate ($CuSO_4$) quantities applied to Houghton Lake for swimmers' itch control, 1975–1991.

Year	$CuSO_4$ (lb)
1975	42500
1976	9000
1977	17800
	31
	50800
1978	12000
	19000
1980	19500
	11000
1981	30000
	850
1982	35850
1983	11000
	26950
1984	38500
1986	27800
	9700
1991	9900

A number of herbicides have also been used to control nuisance levels of aquatic plants in Houghton Lake, such as diquat, endothall, and 2,4-D. Table 4 lists herbicide applications to the lake between 1975 and 1991, as permitted by the Michigan Department of Environmental Quality (MI-DEQ).[1] The target species for these herbicide applications were not recorded, so there is no record of plants controlled. All of the applications used relatively small quantities of herbicide, so it is likely that they were used to remove vegetation from relatively small sections of canal or waterfront (i.e., spot treatments).

Table 4. Herbicides applied to Houghton Lake, 1975–1991.

Year	Permit #	Herbicide	Amount
1976	76008	Diquat	0.4 gal
1978	78341	Dipotassium endothall	14 gal
1979	79019	Dipotassium endothall	54 lb
	79154	Dipotassium endothall	640 lb
1981	81230	Dipotassium endothall	300 lb
	81118	Diquat	3 gal
	81118	Dipotassium endothall	3 gal
1982	82388	Dipotassium endothall	100 lb
	82336	Amine endothall	120 lb
1984	84517	Diquat	0.25 gal
	84517	2,4-D	10 lb
	84517	Dipotassium endothall	0.33 gal
	84517	Amine endothall	0.125 gal

[1] Personal Communication. 2002. Eric Bacon, Michigan Department of Environmental Quality, Lansing, MI.

2 Impacts of Eurasian Watermilfoil

Concern about the proliferation of Eurasian watermilfoil in Houghton Lake was prompted by impacts of that plant reported from many other northern tier lakes. In many cases, invasion of a lake by Eurasian watermilfoil results in the replacement of native aquatic plants (Boylen et al. 1999; Lillie 1986; Madsen et al. 1991; Nichols and Mori 1971). Dominance by Eurasian watermilfoil often results in a substantial reduction in native plant species diversity. Boylen et al. (1999) provide a detailed, long-term documentation of the expansion of Eurasian watermilfoil in Lake George, New York, and the resulting progressive reduction in abundance of native plants and the diversity of the aquatic plant community.

Eurasian watermilfoil also often invades areas that previously supported little or no native plant growth. Initial establishment of Eurasian watermilfoil is often on the deep edge of existing aquatic plant beds. Once Eurasian watermilfoil has established a foothold in these areas, it spreads into existing plant beds, replacing the native species in them. This pattern was observed in Houghton Lake, where Eurasian watermilfoil was initially found along the edges of the southshore weedbed (Bonnette 1996), but then spread to dominate areas that had previously supported native vegetation.

The dense canopy formed by Eurasian watermilfoil can adversely impact water chemistry. For instance, matted Eurasian watermilfoil stems at the water surface inhibit water circulation and concentrate photosynthetic activity near the surface, increasing dissolved oxygen concentrations and pH in the canopy. Beneath the canopy, light, dissolved oxygen, and pH are reduced (Carpenter and Lodge 1986; Madsen 1997). The result is a steep vertical gradient of water chemistry.

Cycling of phosphorus and other important nutrients can also be affected by dense plant beds (Prentki et al. 1979). Increased resistance to flow causes water entering plant beds to slow down, thereby reducing its ability to carry suspended sediments. This leads to increased sedimentation and the accumulation of rich sediments in plant beds. Aquatic plants also release nutrients into the water when they die and begin to decay

(Carpenter 1980). Since rooted aquatic plants obtain most of their phosphorus and nitrogen from the sediments via root uptake (Barko and Smart 1981; Best and Mantai 1978), the cycle of growth and decay moves nutrients from the sediments into the water (Barko and Smart 1980; Landers 1982; Smith and Adams 1986). Plants can also promote the direct release of phosphorus from sediments by increasing pH through photosynthesis, which leads to increased rates of phosphorus release (James et al. 1995). Eurasian watermilfoil has an unusually high rate of shoot turnover during the growing season (Adams and McCracken 1974) and is capable of raising pH more than other plant species (Smith 1994); thus, relative to other plant species, Eurasian watermilfoil is likely to transfer greater quantities of nutrients than native plants (Nichols and Shaw 1986).

Invertebrate and fish communities in Eurasian watermilfoil beds differ from those associated with other submersed macrophytes. Dvorak and Best (1982) found that Eurasian watermilfoil had the poorest invertebrate fauna of eight morphologically distinct plant species. Eurasian watermilfoil beds in Lake Opinicon, Ontario, supported significantly fewer benthic and foliar invertebrates per square meter than did mixed beds of pondweeds (*Potamogeton* spp.) and wild celery (Keast 1984). In addition, fish abundance in the pondweed-wild celery community during daytime feeding periods was three to four times greater than in Eurasian watermilfoil beds. Fish and invertebrates are typically more abundant and diverse in aquatic plant beds than in adjacent open water regions (Wiley et al. 1984; Killgore et al. 1989). Populations of benthic invertebrates beneath submersed vegetation can be more than 100 times larger than those in nonvegetated openings within plant beds (Miller et al. 1989). Eurasian watermilfoil provides a habitat for invertebrates (Pardue and Webb 1985) that is better than the open water of the littoral zone, but not as good as a mixed community of native plant species.

Excessive growth of Eurasian watermilfoil can have a variety of undesirable impacts on fish populations, including obstruction of predation, alteration of feeding success and behavior, and coverage of spawning areas (Engel 1995). Production of forage fish and invertebrates increases directly with increasing macrophyte biomass, whereas production and condition of largemouth bass are maximal at intermediate levels of macrophyte biomass (Colle and Shireman 1980; Wiley et al. 1984). Small fish hide in vegetation, while adult fish remain along edges of vegetation or in open channels within plant beds (Engel 1988). Reduced predation success by largemouth bass in dense macrophyte beds can contribute to diminished bass production (Savino and Stein 1982; Engel 1987).

Replacing native plants with Eurasian watermilfoil can negatively impact waterfowl. Mallards, teal, and pintails prefer feeding on seeds and fruits from native submersed plants such as the pondweeds' overshoots and leaves of perennial submersed species such as the watermilfoils.

Replacing native plants with Eurasian watermilfoil dramatically increases the extent to which aquatic plants interfere with recreation. Compared with native plants, Eurasian watermilfoil biomass is concentrated at and near the water surface (Smith and Barko 1990). The dense mass of shoots at the surface makes it difficult or impossible to boat, swim, water ski, or fish in Eurasian watermilfoil-dominated areas. Interference with recreation can result in a reduction in income derived from the use of affected lakes for recreation. Failing to control Eurasian watermilfoil and other nuisance aquatic plants can also depress the value of lakefront properties (Driscoll et al. 1994).

3 Pre-Management Evaluation of the Lake: 2001

Conditions in the lake were evaluated in 2001 to provide information required to develop a plan for removing Eurasian watermilfoil and restoring the aquatic vegetation. Information collected included a survey of submersed vegetation in the lake, sampling to estimate the population size and distribution of the milfoil weevil (*Euhrychiopsis leconte*i (Dietz)), and an evaluation of water quality. Evaluation of the aquatic vegetation of Houghton Lake used three different approaches: (1) a point-intercept grid survey of plants observed in the field, (2) a hydroacoustic technique for quantifying bottom coverage and density of submersed vegetation, and (3) acquisition and analysis of high-resolution satellite imagery.

Point-intercept survey techniques are applicable to evaluating whole-lake changes in the frequency of occurrence of submersed plant species (Madsen 1999), and have been used in Michigan (Getsinger et al. 2001) and Vermont (Getsinger et al. 2002c) to quantitatively evaluate populations of Eurasian watermilfoil and native species before and after whole-lake herbicide treatments. Point-intercept sampling that records only presence or absence fails to provide a measure of species abundance at individual sampling points. To overcome this limitation, a scaled abundance metric was added (i.e., absent, rare (<3%), sparse (3–20%), common (20–60%), dense (>60%)) that was developed and recommended by the MI-DEQ (1999), and was recorded for individual species at each sampling point. Comparing this data set to post-treatment data sets will allow quantitative evaluation of plant community changes as management proceeds.

Hydroacoustic surveys have also been used to document changes in submersed plant communities following control measures. Early methods used strip-chart-based recording fathometers (Maceina and Shireman 1980) and relied on visual sightings of land-based features to estimate "on-lake positioning." More recently, digital hydroacoustic equipment has been used with differentially corrected global positioning systems (GPS). This evaluation used the Submersed Aquatic Vegetation Early Warning System (SAVEWS) developed by the ERDC (Sabol and Melton 1995; Sabol and Burczynski 1998). At intervals (usually 1 to 2 m) along a transect line, SAVEWS records: (1) geographical coordinates, (2) occurrences of "vegetated" and "nonvegetated" positions, (3) average water depth, and (4) average plant height.

Digital, georeferenced satellite imagery of sufficient resolution to allow delineation of aquatic vegetation growing at or near the water surface can now be ordered from commercial sources (e.g., GeoEye, Dulles, VA). After interpretation by commercially available software, the delineated imagery can serve as a source for mapping aquatic plant distributions at the time of imagery acquisition. These digital map products subsequently serve as an effective mechanism for evaluating spatial changes in plant distribution patterns. Unlike data sets derived from point-intercept and line-transect techniques, satellite imagery-based data sets provide complete spatial coverage for areas where plants are visible from the surface. The weakness of this technique is inability to penetrate cloud cover and to "see" submersed plants not visible from the surface.

Methods

Aquatic plant communities

Point-intercept survey

A grid of survey points on the lake was created in global information system (GIS) software using digital, georeferenced satellite imagery of Houghton Lake as base information. Grid point spacing was set at 300 m. Some additional points were added to provide better coverage of marginal areas. In all, 912 individual sites around the lake were surveyed (Figure 5). With a survey grid having 300-m spacing, each survey site represented approximately 9 ha of the lake (total lake area ~8,100 ha). Once grid points were established, their coordinates were input into GPS receivers used to navigate to these individual survey sites on the lake. Field maps were also created by overlay of survey point locations onto existing imagery. The 2001 point-grid field survey was conducted between July 23 and August 1. To sample the grid, a boat was navigated to each of the survey points using GPS. At each site, a double-sided collection rake was used to uproot plants and pull them to the surface for species identification. At a minimum, two rake throws were taken at each site with a goal of at least 2 m of bottom dragged in each throw. Relative abundance of each species collected was also recorded using the a-b-c-d ranking system adopted by

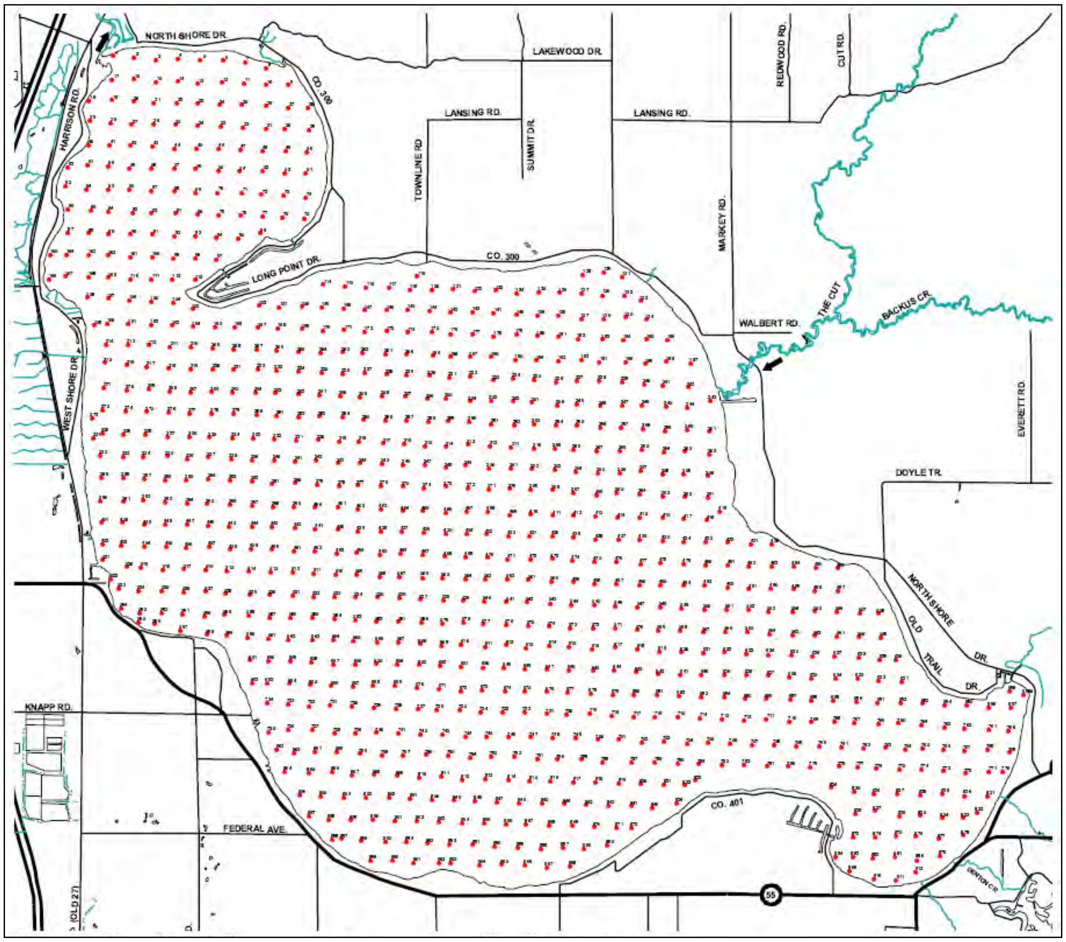


Figure 5. Location of point-grid vegetation sampling sites.

the MIDNR (a = rare [< 3% cover], b = sparse [3 to 20%], c = common [20–60%], and d = dense [>60%]). Plant architecture was also noted (bottom growing, in the water column, topped out). Samples of less common species that were difficult to identify in the field were collected in plastic bags, placed on ice, and returned to the laboratory for identification.

Plant information was recorded in the field using a differential GPS (DGPS) unit equipped with a datalogger and an extensive pre-loaded data dictionary. Vegetation data were returned to the laboratory upon completion of the survey, where they were compiled into GIS map layers for analysis. Distribution and abundance maps were developed for each species identified during the survey. Maps of overall vegetation density and architecture, species diversity, and projected post-treatment effects on plant density and architecture were also prepared.

Hydroacoustic vegetation assessment

The SAVEWS system, developed by the ERDC (Sabol and Melton 1995; Sabol and Burczynski 1998), was used to quantify aquatic plant coverage along selected transects. The hydroacoustic study of Houghton Lake was conducted using a scientific-grade 420-KHz digital echosounder directly linked to a DGPS receiver through a laptop computer running accompanying software. This system measures the hydroacoustic signatures of bottom and plants and ties this information to a constant flow of DGPS information. These raw data are saved and returned to the laboratory, where SAVEWS software uses custom algorithms to process echosounder data and calculate bottom coverage and geometry of submersed plant communities. The result is a collection of georeferenced datapoints at 2- to 3-m intervals along each survey transect. Each data point or report contains information on mean plant height, bottom coverage of vegetation, and water depth. Plant height and bottom coverage data are combined with water depth information to produce a new metric called plant biovolume, a representation of the fraction of the water column filled with submersed vegetation. For example, in 2 m of water with a mean plant height of 1 m and milfoil bottom coverage of 100%, milfoil biovolume would equal 50%. If plant height were reduced to 0.5 m in this example, biovolume would decrease to 25% despite no difference in bottom coverage by plants. Biovolume calculations allow quantification of how much of the water column is affected by aquatic plant growth. Hydroacoustic measurements and resulting calculations can be input directly into GIS for further analysis and map production.

The 2001 hydroacoustic survey of Houghton Lake was performed on July 24. The focus of the survey was collection of several whole-lake transects of hydroacoustic data to develop baseline information for the lake that could be compared with future hydroacoustic assessments to assist in evaluation of any management action. Six transects of data were collected during the survey: one on the north bay of the lake, four within the main central basin of the lake, and one in the east bay of the lake (Figure 6). During field data collection, rake samples of plants were collected to verify the presence of vegetation. Species delineation was not a focus of the analysis, but results of point grid measurements were used to roughly correlate hydroacoustic vegetation measurements with species present. Distinct changes in plant community architecture along transects were also recorded.

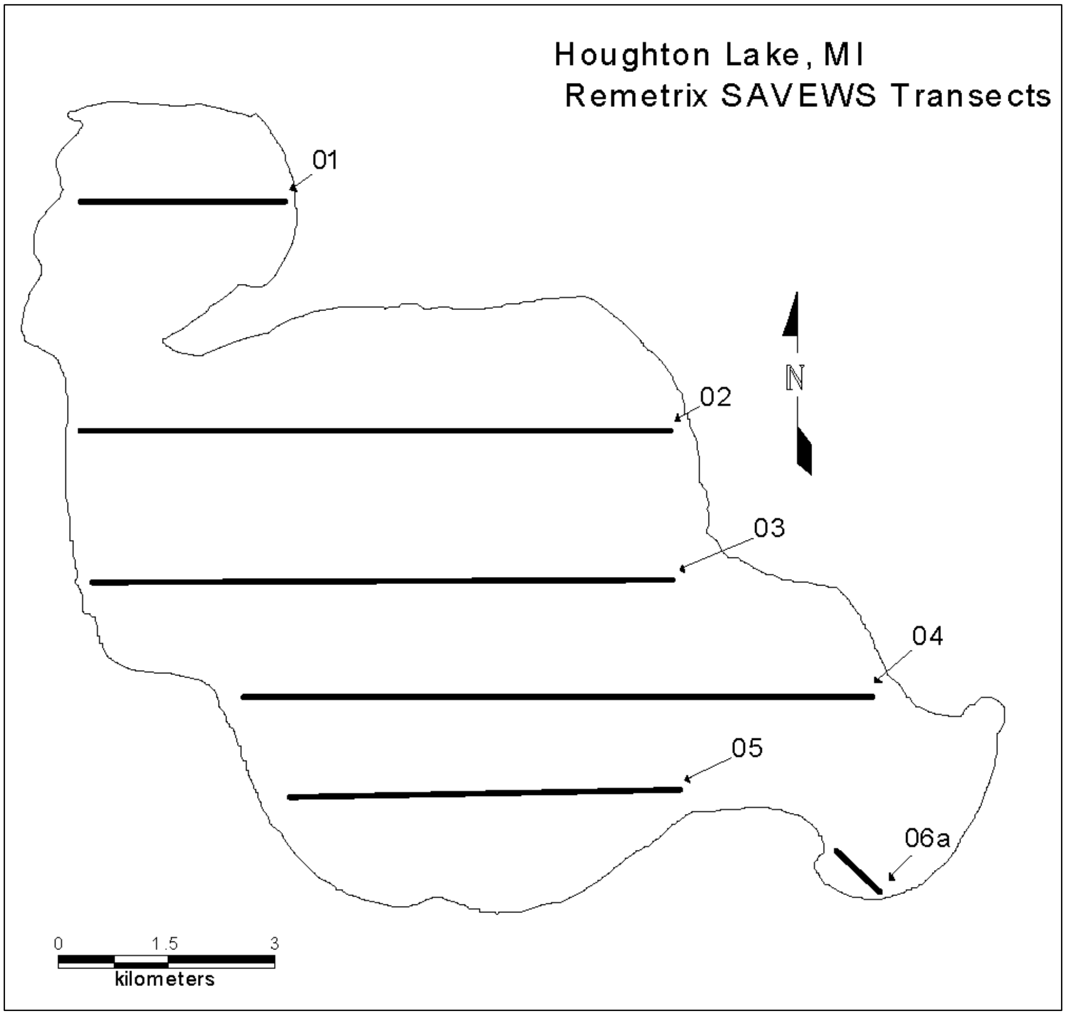


Figure 6. Locations of six permanent transects surveyed using the SAVEWS hydroacoustic system during July 2001 and July 2002.

Current SAVEWS processing software cannot accurately separate bottom and plant signatures from surface noise in areas where dense plant canopies approach the surface. These areas were noted during transect sampling, and the resulting field notes, supplementary GPS data, and visual interpretation of echosounder output were combined to assist in delineating these areas and calculating appropriate values for coverage and biovolume. Bottom coverage in areas with dense near-surface or topped-out vegetation was estimated at 100%. Average depth of near-surface plant canopies was set at 0.3 or 0.6 m, based upon field notes on canopy architecture.

Graphs were developed showing changes in plant height, water depth, bottom coverage of vegetation, and biovolume of vegetation along each hydroacoustic survey transect. Areas with near-surface growth were noted on each graph, along with calculations of average bottom coverage and biovolume for the specific transect (corrected to account for near-surface growth).

Transect data from each year were divided into 10-m increments. These subsets of the raw data included averages for water depth, plant height, biocover, and biovolume. The 10-m summaries were then combined into 300-m sections along each transect. A statistical analysis (Paired t-test) was performed on the 300-m sections to calculate the statistical probability of the changes that occurred in the hydroacoustic data.

Satellite image analysis

Coverage of aquatic plants in Houghton Lake was also assessed using 4-m ground resolution, multispectral imagery from the IKONOS satellite. The multispectral sensor on this satellite captures information in four spectral bands: visible red, visible green, visible blue, and near infrared. With careful contrast adjustment, these bands can be analyzed to detect emergent, floating, and topped-out submersed vegetation. In areas with good water quality, the canopy of submersed plants below the surface can also be detected.

The IKONOS imagery of Houghton Lake was initially acquired on August 6, 2001. Much of the image from this date was unacceptable for proper analysis of submersed vegetation due to a combination of cloud cover and surface water characteristics, so a second image was acquired on September 22 and 30, 2001. While these collection dates were removed from the time of field sampling by almost 2 months, late September is an excellent time to capture conditions of near-peak plant biomass since widespread submersed plant senescence usually does not occur until November. ReMetrix had previously obtained a similar image on October 18, 2000 with excellent results. Not all of the September 2001 collected imagery was of sufficient quality for analysis. Almost all of the September 22, 2001 data were affected by wind streaks on the lake. However, the vast majority of the September 30 scene, covering about 95% of the lake's surface area, was clean and served as the backbone of the analyzed image set. Most of the lake's east bay (~400 ha) was only in the September 22, 2001 scene. Therefore, ReMetrix used a clean section of the August 6, 2001 imagery of the east bay for its analysis.

Contrast-adjusted true (red, green, blue) and false color (near infrared, red, green) composites of IKONOS data were used to detect submersed vegetation in Houghton Lake. User-interactive feature mapping was used to select pixels known from 2001 field survey results to represent submersed vegetation. Two vegetation classes were created: topped-out and submersed. Once the classification was complete, the areas of classified pixels were calculated in GIS.

Milfoil weevil survey

The abundance and distribution of the milfoil weevil in Houghton Lake was evaluated by sampling plant stems at approximately half of the sampling grid locations used to evaluate aquatic plant populations. Weevil samples were collected from grid intersections along every other east-west grid line. At each sampling location, six 30-cm-long terminal stem segments were collected, provided that sufficient Eurasian watermilfoil was present. Stem segments were returned to the laboratory, and the number of weevil eggs, larvae, pupae, and adults on each 30-cm stem segment were counted under 10–30x magnification. Where Eurasian watermilfoil was sufficiently dense near the surface, the number of stems in a 0.1-m^2 quadrat was counted 30 cm below their terminal end (to provide an estimate of the number of 30-cm terminal stems per square meter).

Water quality

Thirteen stations were established in Houghton Lake for routine in situ measurements and water sampling. Stations were grouped according to habitat characteristics and proximity to embayments: stations 9 and 10 were located in the North Bay (historically sparsely vegetated with native species; Getsinger et al. 2002a); stations 14 and 15 were located in the South Bay (historically sparsely vegetated with native species; Getsinger et al. 2002a); stations 11, 12, 13, 16, and 21, located in the central area of the lake (designated as the Main Open area and historically sparsely vegetated with native species; Getsinger et al. 2002a); and stations 17, 18, 19, and 20, also located in the central area of the lake (designated as the Main Vegetated area and historically densely vegetated with native aquatic plants).

In 2001, water samples were collected from Houghton Lake and its tributaries on September 22–23. At each of the 13 sites described above, water was collected at the surface and just above the sediments using a Van Dorn bottle sampler. Water samples were also collected from seven tributary streams and one outlet stream (Muskegon River) by filling sample bottles just beneath the water surface. Water samples were kept on ice until they were returned to the Michigan Water Research Center (MWRC) laboratory in Mount Pleasant, MI, where they were logged in and processed.

Water temperature, DO, and conductivity profiles were measured at four open water and three plant bed sites using a Hydrolab Surveyor 3 instrument pack. The Hydrolab was also used to measure temperature, DO, and conductivity at all stream sites. The pH was measured using a hand-held meter; however, the meter was operable only for the first open-water site on September 22. Light profiles were measured at two open water and two plant bed sites using a Licor photometer to measure photosynthetically active radiation (PAR). Transparency was measured at open-water sites in the North Bay, Main Body, and SE Bay of the lake using a Secchi disk. Aquatic plant species, sediment composition, and weather conditions were noted at all sites (see field notes in Appendix A).

In the laboratory, water samples were filtered for total dissolved phosphorus (TDP) and nitrate/nitrite (NO_3 + NO_2). Alkalinity was measured with an acid titration and pH was recorded. Total phosphorus (TP), TDP, ammonium (NH_4), and nitrate were measured using standard colorimetric procedures. Turbidity was measured with a turbidometer (Model 2100P, Hach Company, Loveland, CO). Chlorophyll a was extracted from 500–1000 ml of water and measured on a spectrophotometer (Beckman, DU-640, Fullerton, CA).

The Carlson Trophic State Index (TSI, Carlson 1977), a comparative scale (0–100 units) normalized so that each increase in 10 units represents a doubling of algal biomass, was used to describe the relative productivity of the lake. The TSI was calculated from mean Secchi transparency, total P, and chlorophyll values over the sampling period. The light extinction coefficient was calculated to describe the transmission of light through the water. The light extinction coefficient (K_d) for PAR was calculated as

$$K_d = \frac{ln\, Ez_1 - ln\, Ez_2}{z_1 - z_2} \tag{1}$$

where:

E = PAR, μE m^{-2} s^{-1}
z = depth, m.

Results and discussion

Point-grid field survey

Table 5 presents the results of the 2001 point-grid vegetation survey. Cover estimates were summed using the midpoint of each cover class to yield cumulative species cover values (MI-DEQ 1999). Overall, submersed vegetation was found at 705 (or 77.3%) of the 912 survey sites. No vegetation was found at the remaining 207 sites. These results indicated that the total vegetated area of the lake (i.e., area with any amount of aquatic plant growth) was 6270 ha. Eurasian watermilfoil was found at 490 (53.7%) of the 912 sites (Figure 7). Thus, the total area of Houghton Lake with any level of Eurasian watermilfoil growth was approximately 4370 ha. Total cumulative vegetation cover was 30.6%. Native aquatic plants accounted for only 13.6% of this, and Eurasian watermilfoil accounted for the remaining 17%. Cover estimates indicate that 243 of the 490 sites with Eurasian watermilfoil (49.6% of Eurasian watermilfoil sites or 26.6% of 912 total sites) had common or dense coverage of the plant (i.e., > 20% bottom coverage), yielding approximately 2100 ha of the lake with common or dense Eurasian watermilfoil growth. Sites with the densest growth of Eurasian watermilfoil were primarily found in the main central basin of the lake, but various densities of Eurasian watermilfoil were also found scattered throughout areas of the lake's north and east bays.

In addition to Eurasian watermilfoil, 21 other submersed plant species were collected and identified (Table 5). After Eurasian watermilfoil, the plants most commonly encountered were elodea (32.6% of sites, 4.15% cover) and muskgrass (28.9% of sites, 4.4% cover), Richardson's pondweed (17.2%, 1.3% cover) and thin-leaved pondweeds (12.3%, 0.7% cover). All other species collected were found at less than 10% of survey sites. Distribution and abundance maps of all species collected are found in Appendix B along with maps showing cumulative vegetation density and plant community.

Table 5. Results of the 2001 point-grid vegetation survey.

Species Name	Number of AVAS in Cover Category				Total Cover	% of AVAS
	Rare	Sparse	Common	Dense		
Eurasian watermilfoil	143	104	130	113	16.9	53.7%
Curly leaf pondweed	2		1		0.05	0.3%
Elodea	143	106	33	15	4.1	32.6%
Muskgrass	102	105	41	15	4.4	28.8%
Richardson's pondweed	75	71	11		1.3	17.2%
Thinleaf pondweed	77	30	4	1	0.7	12.3%
Naiad	53	27	2	1	0.5	9.1%
Wild celery	35	19	2		0.3	6.1%
Whitestem pondweed	31	24	15		1.0	7.7%
Variable pondweed	28	8			0.1	3.9%
Coontail	20	11	2		0.2	3.6%
Water stargrass	18	3	5	1	0.4	3.0%
Nitella	8	6	1	3	0.4	2.0%
Water marigold	5	6			0.07	1.2%
Illinois pondweed	6	2			0.03	0.9%
Flatstem pondweed	4	1			0.02	0.5%
Largeleaf pondweed	4	1			0.02	0.5%
Robbins pondweed	2	1	1		0.06	0.4%
Northern watermilfoil	3	1			0.01	0.4%
White water crowfoot	8				0.01	0.9%
Floating leaf pondweed	2				0.00	0.2%
Bladderwort	1				0.00	0.1%
% Cover					**30.6**	
% Native Cover					**13.6**	

Hydroacoustic vegetation assessment

Table 6 and associated individual transect graphs (see Appendix A) show the results of hydroacoustic measurements of submersed vegetation along the six lake-wide transects of Houghton Lake on July 24, 2001. Transect 1 (running through the north bay of the lake) had the least amount of bottom coverage and plant biovolume (9.1% and 3.8% respectively).

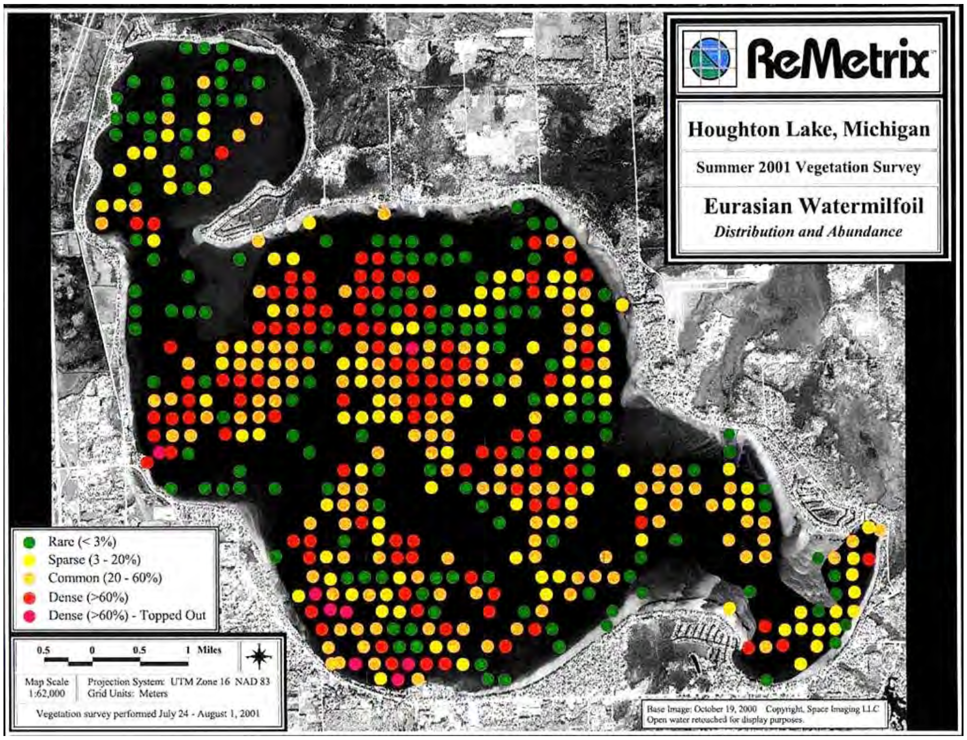


Figure 7. Abundance of Eurasian watermilfoil at point-grid sites, 2001.

Table 6. Transect averages for bottom coverage and biovolume (i.e., portion of water column occupied by plants) of vegetation determined from hydroacoustic assessment of Houghton Lake, Michigan, July 24, 2001.[1]

Transect ID	Bottom Coverage	BioVolume	Transect Length (m)
1	9.1%	3.8%	2,898
2	41.6%	21.9%	8,417
3	45.2%	21.4%	8,117
4	41.6%	13.6%	8,924
5	45.7%	23.1%	5,494
6	36.1%	14.0%	4,190

[1] Averages are corrected to reflect extrapolated data in dense near-surface or topped-out stands where hydroacoustic signal was disrupted. Transect length analyzed is also provided. Location of survey transects and graphical representation of results shown in separate map and associated graphs (Appendix B).

A comparison with point data showed that the most abundant species along transect 1 were Eurasian watermilfoil, Richardson's pondweed, and naiad. Bottom coverage of vegetation along transects 2–5 in the main basin of the lake was 41–45%, with biovolume ranging from 13.6 to 23.1%. As indicated by higher biovolumes, transects 2, 3, and 5 had the most near-surface or topped-out vegetation. If results of all four transects are taken as a representative average of the main basin of the lake, mean plant cover and percent biovolume was 43.5% and 20.0%, respectively. As indicated by point survey results, Eurasian watermilfoil represented the vast majority of this plant coverage and biovolume. Only along the western ends of transects 3 and 5 did elodea represent a significant fraction of the quantified vegetation. Transect 6 through the east bay of the lake also showed significant cover and biovolume. The western end of the transect showed a dense bed of primarily Eurasian watermilfoil. The remainder of vegetation detected in transect 6 was a mixture of Eurasian watermilfoil, pondweeds, and elodea. Bottom-growing vegetation, such as naiad along transect 1, was underquantified in this particular hydroacoustic analysis. Due to rough water on the day of the survey (up to 0.6-m waves), vertical oscillation of the hydroacoustic transducer required a lower sensitivity setting in interpretation software. Therefore, coverage by bottom-growing vegetation (less than 0.5 m ft in height) has been left undetected in this analysis.

Satellite image analysis

Maps with base composite images and associated classification are found in Appendix B. Analysis of true- and false-color IKONOS images of Houghton Lake detected 1,265 ha of submersed vegetation and 20 ha of topped-out submersed growth (total detected: 1,285 ha or 15.8% total lake coverage). This result represented the total area of plant growth detected in the western 95% of the lake from the September 30 scene. With data from the August 6 collection, the eastern 5% of the lake (East bay – 380 ha) had no detectable submersed vegetation due to limitations in water clarity and/or atmospheric conditions. Also, classification of approximately 810 ha near the western shore of the lake was limited due to haze and/or surface wave action on September 30. Both of these problems resulted in some level of underestimation of the detectable vegetation coverage for the whole lake.

Due to confusion with open water, classification of submersed vegetation is often limited to areas with common or dense growth of plants. In the classified section of the image (i.e., western 95%), 172 field survey sites showed common levels of submersed growth (20–60% cover) and 134 sites showed dense levels of submersed growth (>60% cover). Based on those levels and the mean of each cover class (common mean = 40% cover, dense mean = 80% cover) and assuming each site represents approximately 9 ha of the lake, 1,567 ha of the western 95% of the lake was covered by submersed plant growth in these classes.

By this calculation, 18% of the submersed vegetation (common or dense) in this area of the lake was not detected by satellite. This difference is likely due to a combination of limitations in water clarity, problems with haze in westernmost areas of the lake, and plant architecture. On this last point, 16 field sites showed dense levels of bottom-growing muskgrass or naiad, and 43 sites showed common levels of growth of these plants. Sites dominated by these plants are often not detected in satellite analysis due to depth of growth or confusion with sediment signatures. Using the mean levels from before, as much as 267 ha of submersed cover dominated by muskgrass or naiad may not have been detected in this analysis. This number is very close to the 281-ha difference between the total submersed coverage area for the western 95% of the lake (1,567 ha) and satellite-detected coverage (1,285 ha). Areas with detected submersed vegetation agreed well with an overlay of the distribution of 2001 field survey sites having common and dense levels of Eurasian watermilfoil (Figure 8). Using the mean cover values as before, the total bottom coverage of these Eurasian watermilfoil classes was 1,268 ha, a number very close to the classified submersed total of 1,285 ha.

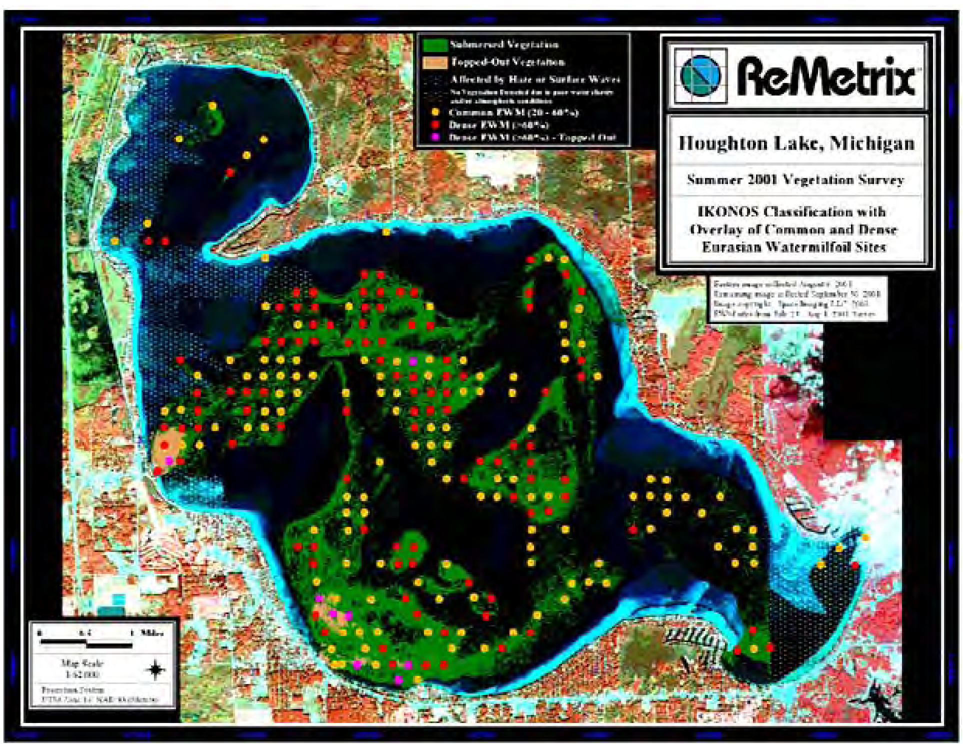


Figure 8. IKONOS image classification overlaid with areas where the point-grid survey recorded common or dense Eurasian watermilfoil, 2001.

Milfoil weevil abundance

Eurasian watermilfoil samples for weevil population measurements were collected from 109 grid locations. Weevils were found in 43 of 109 (39%) of the weevil sampling locations at densities from less than 0.25 to more than 1 weevil per stem (Figure 9). The remaining 61% were below the detection threshold of 0.17 weevils per stem. Most areas of the lake had few (<0.25 weevils per stem) or no weevils. Locations with higher weevil densities tended to occur in clusters. Weevil density was above 0.25 to 0.5 weevils per stem (the approximate threshold for impact on Eurasian watermilfoil) in several parts of the lake, mostly in parts of the south shore weedbed and along the northern shore of the lake. Weevils achieved a density in excess of one weevil per stem in only two areas of the lake, one in the south shore weedbed and one near the eastern shore of the lake. These locations are in the vicinity of the two locations where weevils were introduced to the lake during 2001 (EnviroScience, Inc.; unpublished data).

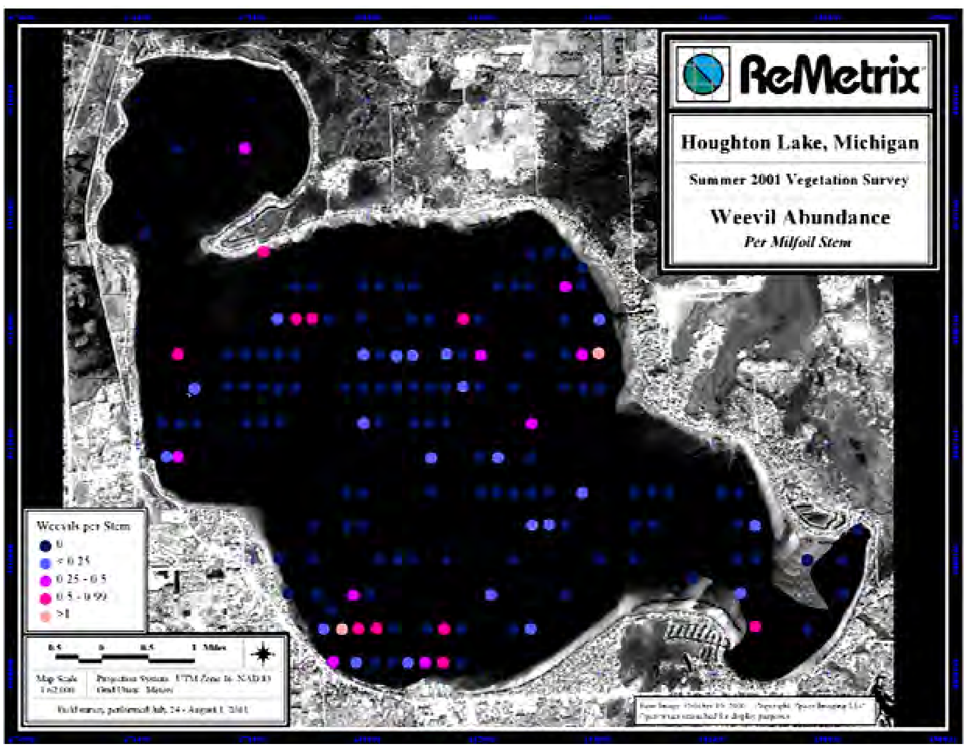


Figure 9. Distribution of milfoil weevil in Houghton Lake, 2001.

The approximate number of weevils per square meter was calculated for locations where a Eurasian watermilfoil stem count had been made (Figure 10). Scarcity of areas where stems could be collected from the surface resulted in sparse coverage for this measurement; nonetheless a pattern similar to the weevil-per-stem data emerges. Substantial weevil

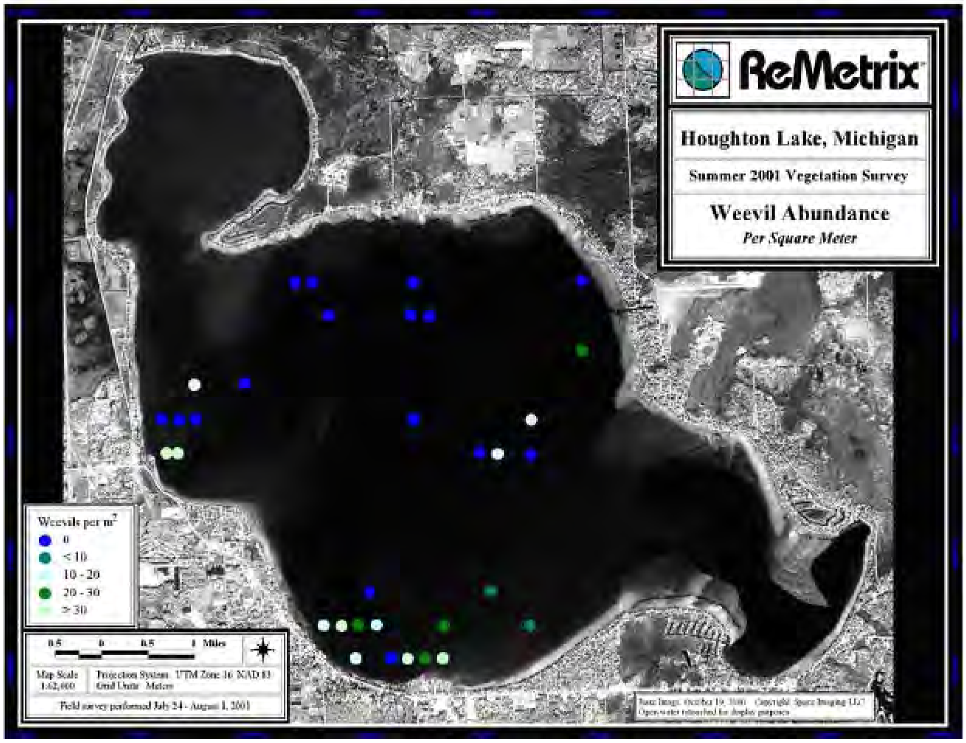


Figure 10. Density of milfoil weevils in Houghton Lake, 2001.

densities occurred primarily along the southern edge of the south shore weedbed, and in a few other isolated locations. In these cases, high weevil densities were produced where weevils were found in at least moderate abundance on dense Eurasian watermilfoil. The results presented here provide a relatively detailed picture of weevil distribution. The clumped distribution of weevils in Houghton Lake suggests that controlling Eurasian watermilfoil in the lake using weevils will require raising the weevil density throughout significant portions of the lake above the threshold for control, a value that is unknown, but may be in the range of one-quarter to several weevils per stem (see Newman and Biesboer (2000)). Determining which parts of the lake have exceeded the control threshold is probably more promising than attempting to calculate the total number of weevils required for control, since the location of weevils in the lake matters. At the time of sampling, only a few areas in the lake had achieved high enough numbers of weevils per stem to begin to impact Eurasian watermilfoil. Most areas of the lake were well below the threshold for weevil impact.

The results of this survey are not directly comparable to those obtained as part of commercial milfoil weevil introductions using the MiddFoil process (Enviroscience, Inc.). Samples from Houghton Lake were collected from a uniform sampling grid that covered the entire lake. In contrast, MiddFoil introduction sites are typically selected in areas deemed suitable for weevil establishment and an effort is made to intentionally select particular Eurasian watermilfoil stems showing varying degrees of weevil damage (i.e., stems are not collected randomly). Thus, the results presented here probably yielded weevil numbers that were more representative of weevil density in the entire lake, whereas MiddFoil surveys are more sensitive and more readily able to detect low numbers of weevils.

Water quality

Based on water quality measurements collected in 2001 (Tables 7 and 8), Houghton Lake may be classified as a well-buffered, well-mixed lake. Houghton Lake had circumneutral water (pH = 7.5–7.9) with a moderately high buffering capacity (alkalinity = 0.7–2.1 meq L^{-1}). Calcium carbonate was not present in the water. Ions dissolved in the water produced conductivity values (202–211 µohms cm^{-1}) typical of many Michigan lakes. The small difference in water temperature (<1°C) between surface and bottom indicates that Houghton Lake mixes frequently. Mixing was particularly complete in the shallow North Bay (Tables 7 and 9). Only the plant bed at site 17 showed thermal stratification – a quick drop in temperature with depth (Table 9). There was plenty of DO (7.4–10.9 mg L^{-1}) at all sample locations in the lake except the deep location at site 17. Here, the somewhat lower DO reading (5 mg L^{-1}) most likely results from decomposition of plant material and may be stressful to some fish species.

Nutrient concentrations were generally low throughout Houghton Lake. Total phosphorus (TP) concentrations were low (<10 µg L^{-1}) at all sites except at the bottom of sites 17 and 21 (Table 8). TP concentrations are usually <10 µg L^{-1} in oligotrophic lakes (Wetzel 1983). Low dissolved phosphorus measurements (0–2.3 µg L^{-1}) in all samples indicated that most of the phosphorus was bound up in suspended particles. This was particularly the case at site 17, where particles were visible in the water sample and turbidity values exceeded 10 NTU (Table 8). Based on its TP concentration, Houghton Lake would be considered oligotrophic. Inorganic nitrogen (nitrate and ammonium) is usually present in low concentrations (<1000 µg L^{-1}) in natural waters and rarely exceeds 10,000 µg L^{-1} (Lind 1985). On September 22, 2001, the concentration of nitrate and ammonium in Houghton Lake was low at all sampling locations, never exceeding 50 µg L^{-1} (Table 8). Nitrogen is an important nutrient for plant growth, and low levels may result from actively growing algae and aquatic plants.

Table 7. Average water chemistry measurements (surface and bottom) for inflowing streams and four locations in Houghton Lake, MI (September 2001).

Site	Location	Depth (m)	Temp. (°C)	Cond@25C (µohm/cm)	pH	Alkalinity (meq/L)	DO (mg/L)	Turbidity (NTU)	NO_3+NO_2 (µg/L)	NH_4 (µg/L)	TP (µg/L)	TDP (µg/L)	Chlorophyll (µg/L)
Inflow Streams	Surf. Avg	0.0	15.8	241	7.8	1.89	5.8	2.6	79.2	4.8	4.6	1.3	4.6
	stdev.		1.1	71	0.3	0.29	1.8	1.4	60.4	2.8	2.4	0.5	2.1
North Bay	Surf. Avg	0.0	16.1	205	7.8	1.78	8.9	2.0	39.7	2.4	1.5	0.0	3.4
	stdev.		0.2	6	0.1	0.03	0.2	0.2	10.4	0.0	1.0	0.0	1.2
	Bottom Avg.	1.5	16.1	204	7.8	1.76	8.7	1.3	35.9	3.8	2.1	0.0	3.8
	stdev.	0.0	0.2	5	0.1	0.06	0.3	0.2	2.6	2.3	0.4	0.0	0.0
Main, Open	Surf. Avg	0.0	17.4	209	7.5	1.69	8.7	1.7	32.3	6.6	3.8	0.8	5.2
	stdev.		0.4	2	0.2	0.18	0.3	0.5	5.8	8.0	4.1	0.6	1.6
	Bottom Avg.	3.8	16.6	210	7.8	1.92	7.9	2.7	31.6	6.8	5.5	1.2	6.7
	stdev.	1.0	0.1	2	0.1	0.06	0.4	1.3	8.3	7.0	6.9	1.0	2.8
Main, Plant	Surf. Avg	0.0	17.5	202	7.9	1.79	9.7	2.6	27.7	2.1	3.9	0.0	9.9
	stdev.		1.0	11	0.1	0.18	1.0	2.7	6.1	1.2	4.5	0.0	11.3
	Bottom Avg.	2.0	16.3	210	7.8	1.80	7.5	10.1	29.8	3.1	12.2	0.8	19.6
	stdev.	0.9	0.2	14	0.1	0.09	1.8	17.3	7.4	2.3	19.3	0.7	32.5
SE Bay	Surf. Avg	0.0	17.2	211	7.9	2.10	8.8	1.5	26.1	2.8	2.2	0.3	5.1
	stdev.		0.1	0	0.1	0.37	0.2	0.4	1.3	0.1	1.2	0.2	0.1
	Bottom Avg.	4.5	16.3	210	7.8	1.86	8.0	2.3	24.2	3.9	6.2	0.3	6.1
	stdev.	2.1	0.1	4	0.0	0.03	0.3	0.9	1.7	0.3	6.4	0.2	2.8

Table 8. Physical and chemical measurements at open water and stream sites in Houghton Lake, MI (September 2001).

Location	Depth (m)	Temp. (°C)	Cond@25C (µohm/cm)	pH	Alkalinity (meq/L)	DO (mg/L)	Turbidity (NTU)	NO_3+NO_2 (µg/L)	NH_4 (µg/L)	TP (µg/L)	TDP (µg/L)	Chloro-phyll (µg/L)	Sediments
Stream Sites													
Site 1	0.0	15.38	234	7.89	1.80	3.23	4.10	59.08	7.07	6.78	1.64	5.89	grass
Site 3	0.0	15.90	240	7.74	2.00	6.73	1.40	44.65	2.62	1.70	<0.30	2.65	sand/organic
Site 4	0.0	16.30	223	7.42	1.52	4.10	1.30	83.5	8.88	4.70	1.48	7.17	organic
Site 5	0.0	13.88	378	8.21	2.40	5.82	2.40	197.9	2.65	5.61	0.66	1.67	sand/detritus
Site 6	0.0	17.04	194	8.01	1.80	7.36	2.10	35.04	5.58	1.89	<0.30	6.14	sand
Site 7	0.0	16.18	177	7.53	1.84	7.41	4.50	55	2.14	7.10	<0.30	4.3	sand/detritus
Site 8	0.0	16.91	223	7.60	2.04	7.59	2.00	13.77	4.27	2.18	0.38	7.3	fine organics
North Bay Sites													
Site 9	0.0	15.98	209	7.85	1.80	9.04	2.10	47.01	2.35	2.27	<0.30	4.24	organic/sand
Site 9	1.5	15.90	207	7.71	1.80	8.91	1.45	37.73	2.16	1.76	<0.30	3.77	
Site 10	0.0	16.22	201	7.65	1.76	8.75	1.80	32.31	2.41	0.80	<0.30	2.55	clay
Site 10	1.5	16.22	200	7.84	1.72	8.50	1.20	34.12	5.45	2.34	<0.30	3.82	
Main Body, Open Water													
Site 11	0.0	16.64	208	7.11	1.56	8.48	1.30	31.69	2.42	<0.30	0.54	2.64	
Site 11	3.0	16.42	208	7.74	1.92	7.98	1.50	28.86	2.37	0.37	0.38	3.57	
Site 12	0.0	17.67	210	7.54	1.48	8.98	1.40	37.09	3.18	1.47	<0.30	6.6	organic muck
Site 12	2.5	16.66	211	7.96	1.96	7.41	3.70	44.55	4.8	3.51	2.34	10.87	
Site 13	0.0	17.63	211	7.61	1.88	8.65	1.60	28.15	2.39	1.18	0.29	4.89	clay
Site 13	4.5	16.71	212	7.75	1.96	8.38	1.20	22.15	2.76	2.13	<0.30	4.76	
Site 16	0.0	17.37	210	7.49	1.68	8.33	2.50	25.43	20.93	2.76	<0.30	5.42	clay/organics

Location	Depth (m)	Temp. (°C)	Cond@25C (µohm/cm)	pH	Alkalinity (meq/L)	DO (mg/L)	Turbidity (NTU)	NO_3+NO_2 (µg/L)	NH_4 (µg/L)	TP (µg/L)	TDP (µg/L)	Chloro-phyll (µg/L)	Sediments
Main Body, Open Water (cont.)													
Site 16	4.5	16.63	211	7.74	1.96	7.89	3.10	28.74	19.22	3.85	0.49	6.95	
Site 21	0.0	17.55	207	7.56	1.86	8.82	1.85	39.02	4.2	9.88	1.50	6.24	clay/organics
Site 21	4.5	16.67	208	7.82	1.82	7.68	3.90	33.88	4.92	17.56	1.76	7.25	
Main Body, Plant Beds													
Site 17	0.0	19.00	200	7.90	2.00	10.94	6.60	36.61	3.89	10.61	<0.30	26.57	rich organic
Site 17	1.0	16.04	227	7.58	1.80	5.09	36.00	39.54	6.4	41.04	1.27	68.34	
Site 18	0.0	17.10	187	7.89	1.76	9.94	1.20	22.95	1.28	1.65	<0.30	6.53	organic
Site 18	1.5	16.31	192	7.90	1.68	9.44	1.75	21.7	1.37	2.32	<0.30	2.82	
Site 19	0.0	17.21	209	7.70	1.56	9.33	1.50	25.93	1.82	1.49	<0.30	4.23	
Site 19	3.0	16.53	209	7.75	1.88	7.82	1.20	28.51	1.68	3.55	<0.30	4.59	
Site 20	0.0	16.71	210	7.98	1.84	8.46	0.95	25.41	1.43	1.96	<0.30	2.18	
Site 20	2.5	16.45	212	7.79	1.84	7.55	1.50	29.45	2.78	1.71	0.26	2.46	
Southeast Bay													
Site 14	0.0	17.11	211	7.80	1.84	8.95	1.20	25.12	2.89	1.38	<0.30	5.01	organic
Site 14	3.0	16.31	207	7.85	1.88	7.82	1.60	23.02	4.09	1.65	0.28	4.12	
Site 15	0.0	17.28	211	7.99	2.36	8.68	1.75	26.98	2.74	3.02	0.26	5.2	organic
Site 15	6.0	16.23	212	7.79	1.84	8.21	2.90	25.43	3.68	10.68	<0.30	8.05	

Table 9. Light, temperature, and chemistry profiles at open water and plant bed sites in Houghton Lake, MI (September 2001).

Depth (m)	Temp. °C	pH	DO (mg/L)	Light (µe/m²/s)	Conductivity (µmhos/cm)
Open Water					
Site 10					
0.0	16.22	8.60	8.75	153.70	201
0.5	16.22		8.62	93.56	201
1.0	16.22		8.59	86.78	200
1.5	16.22	8.40	8.50	57.74	200
			extinction coefficient =	0.643	
Site15					
0.0	17.28		8.68		211
0.5	17.26		8.82		210
1.0	17.26		8.78		208
2.0	17.14		8.75		212
3.0	16.97		8.72		213
4.0	16.55		8.64		208
5.0	16.37		8.38		218
6.1	16.23		8.21		212
Site 16					
0.0	17.37		8.33		210
0.5	17.34		8.23		210
1.0	17.36		8.20		210
2.0	17.16		8.32		211
3.0	16.73		8.14		211
4.0	16.63		8.07		211
4.5	16.63		7.89		211
Site 21					
0.0	17.55		8.82	406.90	207
0.5	17.55		8.77	257.30	212
1.0	17.45		8.11	195.50	208
2.0	17.22		8.52	90.02	210
3.0	16.9		8.43	23.08	211
4.0	16.68		7.77	14.39	214
4.5	16.67		7.68	3.56	208
			extinction coefficient =	1.013	

Depth (m)	Temp. °C	pH	DO (mg/L)	Light (μe/m²/s)	Conductivity (μmhos/cm)
Plant Beds					
Site 17					
0.0	19.00		10.94		200
0.5	16.94		9.09		210
1.0	16.04		5.09		227
Site 18					
0.0	17.10		9.94	243.2	187
0.5	16.87		9.71	167.4	189
1.0	16.45		9.42	142.5	192
1.5	16.31		9.44	51.8	192
			extinction coefficient =	1.092	
Site 19					
0.0	17.21		9.33	1010	209
0.5	17.15		8.95	624.2	212
1.0	16.94		8.84	212.7	211
2.0	16.55		8.23	44.47	208
3.0	16.53		7.82	5.303	209
			extinction coefficient =	1.783	

The chlorophyll *a* concentration was measured as a surrogate for algal abundance. Chlorophyll *a* was moderate (2–10 μg L^{-1}) at most sample sites (Table 8). Exceptionally high chlorophyll values at site 17 suggest that the particles collected in the water sample were living algal cells. In Houghton Lake moderate algal abundance is sufficient to cloud the water and reduce transparency to 1.8 m in North Bay and 2.8–3.0 m in the rest of the lake. These are typical Secchi disk values for a moderate to highly productive lake. Light diminishes quickly in the lake water and has an extinction coefficient of 0.64–1.0 in the open water and 1.1–1.8 in the plant beds (Table 9, Figure 11). Based on chlorophyll *a* concentrations and Secchi depths, Houghton Lake would be considered mesotrophic.

The dense beds of rooted aquatic plants (particularly Eurasian watermilfoil) are spots of high productivity. Within these beds, surface water is calm and warm. Algae grow profusely on the surface of the plants and eventually fall off into the water, providing food for small invertebrates. Fish species are prevalent in and around the plant beds (see Appendix A). However, if oxygen levels decrease within the plant bed, fish may move toward the perimeter or leave the weed bed altogether.

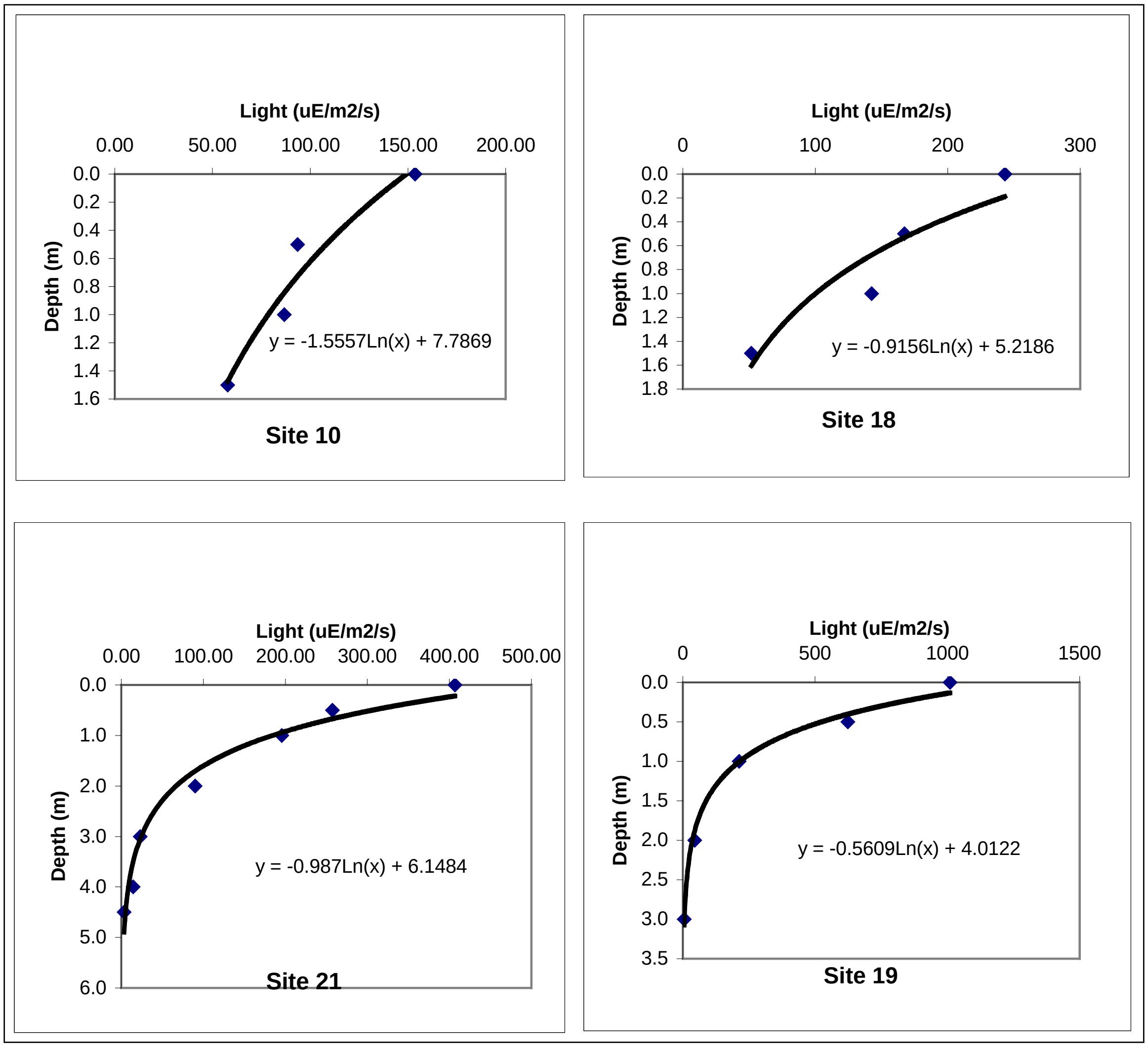


Figure 11. Light profiles for open water (Sites 10, 21) and plant beds (Sites 18, 19) in Houghton Lake, September 2001. Light extinction.

The seven inflowing steams/canals contribute nutrients, dissolved ions, and sediments to Houghton Lake. Average stream nitrate concentration (particularly site 5) was higher than that of Houghton Lake (Table 7).

Average stream conductivity was 241 µohms cm^{-1}, 24% higher than sites in Houghton Lake. Three of the streams contributed cool water to the lake, and four had sandy sediment at their mouths (Table 8). This sediment may eventually end up in Houghton Lake. Site 5 (Spring Brook Creek) was particularly interesting. It had cold water (14°C) with high ion concentrations (cond. = 378 µohms cm^{-1}), lots of nitrate (197 µg L^{-1}), and moderately low dissolved oxygen (5.8 mg L^{-1}). This stream may be a good brook trout habitat, but the high nitrate concentrations indicate human impact upstream.

4 The Houghton Lake Management Strategy

Goals of the management strategy

Mitigation of Eurasian watermilfoil impacts

Aquatic plant problems in Houghton Lake have resulted from the proliferation of the nonindigenous aquatic plant Eurasian watermilfoil. Given the potential of this exotic plant to aggressively expand and replace native vegetation and the problems associated with its dominance, the aim of management should be to reduce Eurasian watermilfoil to a relatively low abundance throughout the lake. Strategies used to manage this species should therefore be capable of significantly reducing Eurasian watermilfoil abundance lakewide. One goal of Houghton Lake management is to maintain the Eurasian watermilfoil population at a sufficiently low abundance that large monospecific beds of that plant are not present and native plants dominate the vegetation of the lake.

Preservation of Houghton Lake critical resources

Houghton Lake has a very high natural resource value; thus techniques used to reduce the impacts of Eurasian watermilfoil in Houghton Lake must preserve these critical resources. Critical resources most likely to be influenced by lake management include: a healthy native plant community, good water quality, and a productive sport fishery. By preserving these natural resources, the economic value of the lake will also be maintained, including property values, recreational activities, and tourism.

Maintaining native plant diversity and abundance

Native aquatic plants are a valuable and important component of the Houghton Lake ecosystem. The strategy for managing Eurasian watermilfoil should, in the long term, enhance the native plant community. Since Eurasian watermilfoil itself has the potential to dramatically reduce native plant abundance, short-term reductions in native plant populations may be tolerated as control techniques reduce Eurasian watermilfoil abundance to maintenance (low) levels. Once Eurasian watermilfoil has been reduced to an acceptably low abundance in the lake, every effort should be made to restore native plant populations. There is no evidence that native plant populations were causing problems for the Houghton Lake ecosystem or for users of the lake prior to the invasion of Eurasian watermilfoil; therefore aggressive and widespread control of native plants is not recommended as a plant management goal at this time.

Both the abundance and diversity of the native plant community are important. Prior to management, native plants covered approximately 77% of the lake, and had a cumulative cover of approximately 14% (see above). Michigan Department of Natural Resources (MIDNR) Fisheries guidelines suggest that eutrophic lakes should have native aquatic plants in 20 to 40% of the littoral in order to preserve aquatic vegetation as fish habitat (MIDNR 1993). The Houghton Lake Management Feasibility Study (Smith et al. 2002) recommended that management should seek to maintain vegetation in approximately 70% of the lake and to restore native cumulative cover to approximately 20%. These goals account for the ability of Eurasian watermilfoil to invade areas that were not previously vegetated (increasing the vegetated area) and to displace native plant species (reducing cumulative cover of native plants).

Protecting the water quality of the lake

Although several studies have found that Houghton Lake is eutrophic or nearly so (Pecor et al. 1973a; USEPA 1975), these studies have noted the lack of negative impacts often associated with eutrophication. The lake is productive enough to support an important fishery, but has good water clarity most of the time and remains free from nuisance algal blooms. Preservation of existing water quality should be a goal of lake management.

Control of dense, nuisance stands of Eurasian watermilfoil can result in negative water quality impacts. Harvesting typically results in a temporary increase in turbidity (Carpenter and Gasith 1978; David and Greenfield 2003), presumably due to resuspension of sediments, as well as epiphytic periphyton and associated materials. Rapid senescence following contact-type herbicide treatments can lead to mobilization of nutrients via leaching from plant tissue, which can stimulate algal growth. Rapid decomposition of herbicide-killed plant tissue when water temperatures are elevated can also exacerbate dissolved oxygen demands, leading to reduced oxygen concentrations or anoxia. Rapid removal of large expanses of canopy-forming macrophytes such as Eurasian watermilfoil may also result in an increase in wave-induced sediment resuspension if no plant cover remains to protect the sediment from shear stresses.

Maintaining the fishery

As described above, Houghton Lake is an extremely important fishing resource; thus, maintaining the sport fishery is a crucial goal of lake management. Monitoring of fish populations was not included in the pre-management evaluation of the lake but would have been desirable. Whole-lake fluridone treatments have been strongly opposed by the Michigan DNR Fisheries Section on the grounds that they might harm fish populations, even though their analysis of the impacts of early whole-lake treatments in Michigan (Schneider 2000) found that most detectable impacts on fish populations were positive. In contrast with the view promoted by the MIDNR, most published studies describe an optimal plant density for the production of larger game fish (Colle and Shireman 1980; Wiley et al. 1984), with diminished production at the high densities characteristic of lakes dominated by monospecific Eurasian watermilfoil beds (Savino and Stein 1982; Engel 1987). Based on results from the published literature, reduction in the Eurasian watermilfoil and management of lower, more natural plant densities would be expected to improve the condition of the fishery in the lake.

The Houghton Lake management strategy: 2002–2006

Table 10. Comparison of Eurasian watermilfoil management options.

Option	Extent of Control	Risk of Failure	Rapidity	Non-Target Impact
Fluridone	Nearly Complete	Low	Rapid	Moderate
Weevil	Moderate	Moderate?	Slow	None
Simultaneous Integrated	Variable	Low	Moderate	Low
Sequential Integrated	Variable	Low to Moderate	Rapid	Moderate

After reviewing results of 2001 pre-management evaluation and considering four possible options for management (Table 10), the HLIB selected a sequential integrated management strategy for controlling Eurasian watermilfoil. This strategy used a whole-lake fluridone herbicide application to provide selective, lake-wide Eurasian watermilfoil control. This fluridone treatment was then followed by a maintenance control strategy that included stocking of milfoil weevils and/or targeted applications of selective, systemic herbicides to areas of recovering Eurasian watermilfoil. This integrated strategy was implemented to provide selective long-term control of Eurasian watermilfoil while preserving Houghton Lake critical resources.

Fluridone is a systemic bleaching herbicide that compromises the photosynthetic capacity of susceptible aquatic plants like Eurasian watermilfoil (Weed Science Society of America (WSSA) 2007). At concentrations above 5 $\mu g\ L^{-1}$, whole lake application of Sonar® A.S. (0.48 $kg\ L^{-1}$ liquid formulation of fluridone herbicide) effectively controls Eurasian watermilfoil, and impacts on non-target vegetation are moderate below 10 $\mu g\ L^{-1}$ (Smith and Pullman 1997). Most fluridone treatments conducted according to the "6 bump 6" Michigan protocol eliminate more than 80% of the Eurasian watermilfoil. Although low-rate fluridone treatments are quite selective, populations of elodea, naiad, water marigold, and northern watermilfoil were expected to be greatly reduced in the year of treatment using fluridone.

The significance of impacts on non-target vegetation depends on the abundance of the plant species involved and the extent/longevity of the impact. Based on 2001 pre-treatment assessment, the perennial species, elodea, was very abundant in Houghton Lake, growing densely under Eurasian watermilfoil in many locations. Elodea is quite susceptible to fluridone, and can be greatly reduced by even low rate fluridone treatments (Smith and Pullman 1997). Anticipating that a whole-lake fluridone treatment might dramatically reduce the amount of elodea in the lake, the Houghton Lake Management Feasibility Study (Smith et al. 2002) stated that reintroduction of this species in the year following treatment might be necessary. The same study also suggested that naiad might also be greatly reduced during the year of treatment, but recovery of this annual plant from seed was likely in subsequent years. Water marigold has been eliminated from some Michigan lakes by whole-lake fluridone treatments (Smith and Pullman 1997). Since 2001 assessment showed water marigold present at only 1.2% of 912 survey locations, elimination of this species was predicted to have little impact on habitat quality but would reduce the diversity of the plant community on the lake.

A study of the effects of whole-lake fluridone treatments on fish (Schneider 2000) found that most detectable impacts on fish populations were positive. It should be noted that many of the lakes studied by Schneider were treated with higher doses of fluridone (>10 $\mu g\ L^{-1}$) than currently allowed by the MI-DEQ. Similarly, a study of food web impacts of fluridone treatments conducted on several Michigan lakes found that food web impacts of whole lake fluridone treatments did not appear to be particularly harmful (Valley and Bremigan 2002).

The integrated strategy initiated in 2002 with fluridone treatment described use of milfoil weevils and spot treatment with selective systemic herbicides to any recovering populations of Eurasian watermilfoil. The milfoil weevil is a native North American insect that feeds upon Eurasian watermilfoil. Weevil larvae burrow in the stem, consuming the vascular tissue and interrupting the flow of sugars and other materials between the upper and lower parts of the plant (Creed and Sheldon 1994). Holes where the larvae burrow into and out of the stem allow disease organisms a foothold in the plants and allow gases to escape from the stem, causing the plants to lose buoyancy and sink (Creed et al. 1992). Reduction in the buoyancy of plants also makes residual Eurasian watermilfoil less visible and problematic than a similar amount of unaffected vegetation growing at water surface. The weevil prefers Eurasian watermilfoil and spends most of its life on that plant, but does feed on the closely related, native northern watermilfoil (Sheldon and Creed 1995). Therefore, based on aquatic plant community composition of Houghton Lake observed in pre-treatment evaluations, milfoil weevil stocking was not anticipated to impact other non-target aquatic vegetation in the lake.

The milfoil weevil is commercially available for use in suppressing Eurasian watermilfoil under the tradename Middfoil™ (Enviroscience, Inc.). The strategy for using the weevil to suppress Eurasian watermilfoil involves introducing large numbers of insects to augment the natural population. The exact density of insects needed to suppress Eurasian watermilfoil is not known, but reported monitoring of various weevil stocking programs describes achieving 0.5 to 4 weevils per stem for detectable declines (Creed and Sheldon 1995; Newman and Biesboer 2000). The 2001 weevil survey (see Chapter 3) found milfoil weevils at 39% of 109 grid locations in Houghton Lake. Weevils achieved a density in excess of 1 weevil per stem in two areas of the lake that were near locations where they had been stocked in 2001. It was projected that a whole-lake fluridone treatment would reduce Eurasian watermilfoil to densities insufficient to support a large population of weevils in Houghton Lake. Therefore, the final integrated management strategy of the lake called for targeted stocking of weevils to selected recovering populations of milfoil.

Following the initial whole-lake fluridone phase in 2002, the long-term management plan for the lake also called for targeted use of selective, systemic herbicides (i.e., 2,4-D and triclopyr) to control recovering populations of Eurasian watermilfoil. Starting in 2005, applications to approximately 150 ha of the main lake annually included the use of Renovate 3 and Renovate OTF (a liquid and granular triclopyr formulation, respectively) and Navigate (a granular 2,4-D formulation). These products are auxin-type herbicides with selective activity on dicot species such as Eurasian watermilfoil at low to moderate application rates (WSSA 2007; Getsinger et al. 2004). Targeted applications of these products as part of the integrated management strategy were designed to sustain long-term control of Eurasian watermilfoil. This maintenance control philosophy would minimize overall chemical use while maintaining healthy, diverse populations of native vegetation.

5 Phase 1: Whole-Lake Fluridone Treatment and Assessment: 2002–2004

Fluridone treatment and residue monitoring: 2002

The first phase of the Houghton Lake management strategy was a whole-lake application of Sonar® A.S. aquatic herbicide (active ingredient: fluridone) to the lake. The most critical aspect for selectively controlling Eurasian watermilfoil using fluridone is to maintain an adequate herbicide concentration/exposure time (CET) relationship (Netherland et al. 1993, 1997; Netherland and Getsinger 1995a, 1995b). Results of these and other evaluations have consistently shown that achieving aqueous doses of fluridone between 5 and 6 μg L^{-1} for 14 to 21 days of initial exposure, and maintaining levels $\geq$ 2 μg L^{-1} for an additional 60 to 90 days, will provide 85 to 95% control of Eurasian watermilfoil. This CET treatment regime will also eliminate and/or minimize injury to most nontarget vegetation. To achieve > 95% control of Eurasian watermilfoil, higher fluridone concentrations (10 to 15 μg L^{-1}) are required; however, these slightly higher rates are likely to increase nontarget plant injury to sensitive species in the year of treatment.

Concentration/exposure time relationships are determined in the field by monitoring the aqueous levels of fluridone throughout the lake for up to 90 days post-treatment (Getsinger et al. 2001, 2002b). By monitoring aqueous residues over time, sequential or "booster" treatments can be planned and conducted to ensure that the initial concentrations are achieved and that the appropriate fluridone concentrations are maintained. By maintaining adequate fluridone CET relationships, selective control of Eurasian watermilfoil has been achieved in other northern tier lakes (Getsinger et al. 2002a, 2002b; Madsen et al. 2002). In addition, adequate monitoring of aqueous residues can provide data to match fluridone levels with target and nontarget plant injury assessments to predict the progress and outcome of a treatment (see Chapter 3).

Fluridone impacts on aquatic plants can also be monitored using a physiological assay that indicates symptoms related to a mode of action. A physicological assay has the advantage of revealing the onset herbicide effects before visual symptoms occur (Sprecher and Netherland 1995).

Fluridone interrupts carotene pigment biosynthesis in newly emerging tissue by blocking phytoene desaturase, an enzyme necessary for production of the intermediate, phytofluene (Bartels and Watson 1978; Sandmann and Böger 1983). Because phytofluene is not produced, phytoene, another intermediate pigment, accumulates, and the carotenoids, α-carotene and β-carotene, are not synthesized (Figure 12). Carotenoids are yellow pigments that help plants photosynthesize, and protect the chlorophyll pigments from photoxidation under stressful photosynthetic conditions. Damaged chlorophyll limits the photosynthetic process, and plants eventually die.

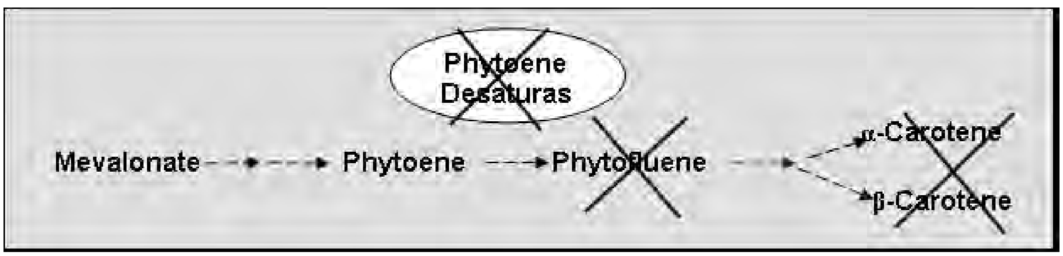


Figure 12. Fluridone mode of action in the carotenoid biosynthetic pathway of newly emerging tissue.

Visual symptoms of fluridone exposure are bleaching of plant apices as chlorophyll is destroyed via photooxidation (Bartels and Watson 1978). Plant apices may also appear light pink or purple when the duration or dose of fluridone increases as the anthocyanin pigments are unmasked after chlorophyll photooxidation (Doong et al. 1993). Previous mature stems (i.e., older tissues) remain green and continue to photosynthesize.

In the past, monitoring chlorophyll has been a physiological assay used in small-scale fluridone research studies to track and predict control of hydrilla and Eurasian watermilfoil (Netherland et al. 1993; Netherland and Getsinger 1995a, 1995b). Because the degree of chlorosis produced by fluridone in emerging tissues has been shown to be dose proportional in several species, chlorophyll data documented plant injury and, in conjunction with shoot biomass weight, determined efficacy. In a greenhouse study, measurement of β-carotene levels was correlated to fluridone efficacy against hydrilla (Doong et al. 1993). Sprecher et al. (1998) demonstrated how elevated concentrations of the colorless pigment phytoene in aquatic plant tissues were unique to fluridone exposure.

Although all plants have trace amounts of phytoene, when exposed to fluridone most plants rapidly accumulate significant amounts of phytoene, which can be easily measured using tissue extracts in an ultraviolet spectrophotometer. Phytoene concentrations alone do not predict a decrease in biomass of an aquatic plant species (Sprecher et al. 1998); phytoene in combination with β-carotene and chlorophyll, however, may correspond with biomass reduction.

In addition to using the physiological assay to evaluate the impact of fluridone in the field, the assay can be used to evaluate plants exposed to varying concentrations of fluridone in the laboratory prior to application. Results of pre-application testing can be used to estimate the concentration of fluridone that will be required to effectively control Eurasian watermilfoil in the field. Prior to selecting a dose rate for the application, physiological assays were used to determine whether a treatment conducted according to standard Michigan protocols would adequately control the Eurasian watermilfoil growing in Houghton Lake.

Methods and materials

Pre-treatment susceptibility testing

Prior to selecting a dose rate for the whole-lake application, plant susceptibility to fluridone was evaluated using the commercially available physiological assay, PlanTEST (SePRO Corporation). Eurasian watermilfoil was collected from 25 of 36 total sample sites on Houghton Lake in April 2002. Plants were placed in labeled zip-lock storage bags, stored in coolers, and returned to the SePRO laboratory in Carmel, Indiana. The plants arrived in excellent condition and were cleaned and processed immediately. Although the initial intent was to collect enough tissue at each site to run an independent test, weather conditions at Houghton on collection day precluded the collection of adequate tissue at several sites. Sites 3, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 21, 22, 24, 27, and 36 were assayed independently, as ample tissue was collected. Sites 1 2, 4, 5, 19, and 20 were assayed in combination due to inadequate tissue. No Eurasian watermilfoil tissue was collected at sites 6, 8, 18, 23, 25, 30, 31, 32, 33, 34, and 35; therefore Eurasian watermilfoil from these sites was not assayed.

Eurasian watermilfoil for each site was placed in culture medium and was exposed to nine fluridone concentrations, including exposures to 1, 2, 3, 4, 5, and 6 µg L^{-1}. Exposures were conducted for an 18-day period to determine upper threshold limits and response data below the threshold rate. During the 18-day incubation period, Eurasian watermilfoil growth was excellent in untreated controls for all sites with the exception of sites 13, 14, 19, and 20. Untreated Eurasian watermilfoil from all other sites either doubled in biomass or tripled in total stem length during the course of the assay.

In addition to exposure of Eurasian watermilfoil in culture medium, Houghton Lake water (80 L) was collected and brought to the SePRO research laboratory in Westfield, Indiana. The water was filtered to remove particulates, and Eurasian watermilfoil from sites 3, 7, 10, 11, 17, 21, and 27 was assayed in Houghton Lake water. Low concentrations of potassium nitrate and potassium phosphate were added to help promote Eurasian watermilfoil growth. Use of Houghton Lake water resulted in growth characteristics similar to those in the culture medium.

Herbicide application

Based on the results of plant susceptibility testing and MI-DEQ regulations, fluridone was initially applied at a calculated whole-lake dose of 6 $\mu g\ L^{-1}$. At 14 days post-application the concentration of fluridone was measured, and then a booster application of fluridone, calculated to raise the herbicide concentration back to 6 $\mu g\ L^{-1}$, was applied. Fluridone dose rates were calculated based on the volume of the upper 3 m (10 ft) of the lake (i.e., excluding the volume of any areas deeper than 3 m), as required by MI-DEQ regulations. The initial application was conducted on May 14 and 15, and the booster application occurred on June 12, 2002.

Six outboard-powered skiffs (5 to 6 m in length) were used in deeper parts of the lake and an airboat was used in the shallows to apply fluridone herbicide. Variable rate application (VRA) technology, developed for precision agriculture, was used to ensure precise and even application of herbicide at rates appropriate to the depth of water in different areas. A VRA digital prescription for Houghton Lake was calculated using GIS to combine the distance between application swaths with 30-cm (1-ft) resolution bathymetric data. Swaths were 100 m apart for the initial application and 200 m for the second application. The prescription adjusted application rates for each 0.3-m change in water depth along a treatment swath.

Each application boat was equipped with a Raven injection controller linked to a field computer running Farm Site Mate VRA software coupled with a Wide Area Augmentation System (WAAS)-enabled Garmin GPS 17N antenna (average horizontal accuracy < 3 m). Based on the application prescription and boat speed, the integrated GPS/computer/controller delivered precise amounts of fluridone into trailing hoses hung in the propeller wash of the application boats. Navigation along designated swath lines was performed using a second WAAS-corrected GPS receiver preloaded with the locations of swath endpoints. The VRA software also displayed actual boat paths overlain on an October 2000 false-color satellite image of Houghton Lake. The Farm Site Mate VRA software recorded the total volume of fluridone applied as well as real-time geo-referenced application rates for each application vessel, based on information provided back to it from the injection controller. This information was used to produce an “as-applied” map for each of the fluridone treatments (Figure 13).

The initial application took slightly more than one day to complete. By the end of the first day, the entire lake had been treated, with the exception of a few shallow areas at one end of the lake. Treatment of these areas extended into a second day. The wider swath separation used for the second treatment allowed it to be completed in a single day.

Post-treatment herbicide concentrations

Water and plant samples used to monitor fluridone concentrations and impacts were collected from 36 sampling stations distributed around the lake (Figure 14). Near-surface water samples were collected from these locations 2, 7, 14, 25, 30, 43, 56, and 86 days following the initial treatment. Fluridone concentrations were determined using a commercially available procedure (FasTEST: SePRO Corporation, Carmel, IN), which uses an enzyme-linked immunosorbent assay (ELISA) technique.

High performance liquid chromatography (HPLC) measurement of fluridone concentrations was used as a check on the accuracy of the commercial ELISA. Samples for HPLC analysis of fluridone concentration were collected from a subset of 19 of the 36 permanent sampling stations described above, and were established in selected areas to represent balanced coverage of the entire water body (Figure 15). Two stations were located in the North and East Bays, and 16 stations were located in the central basin area of the lake (eight in the West Central Basin and eight

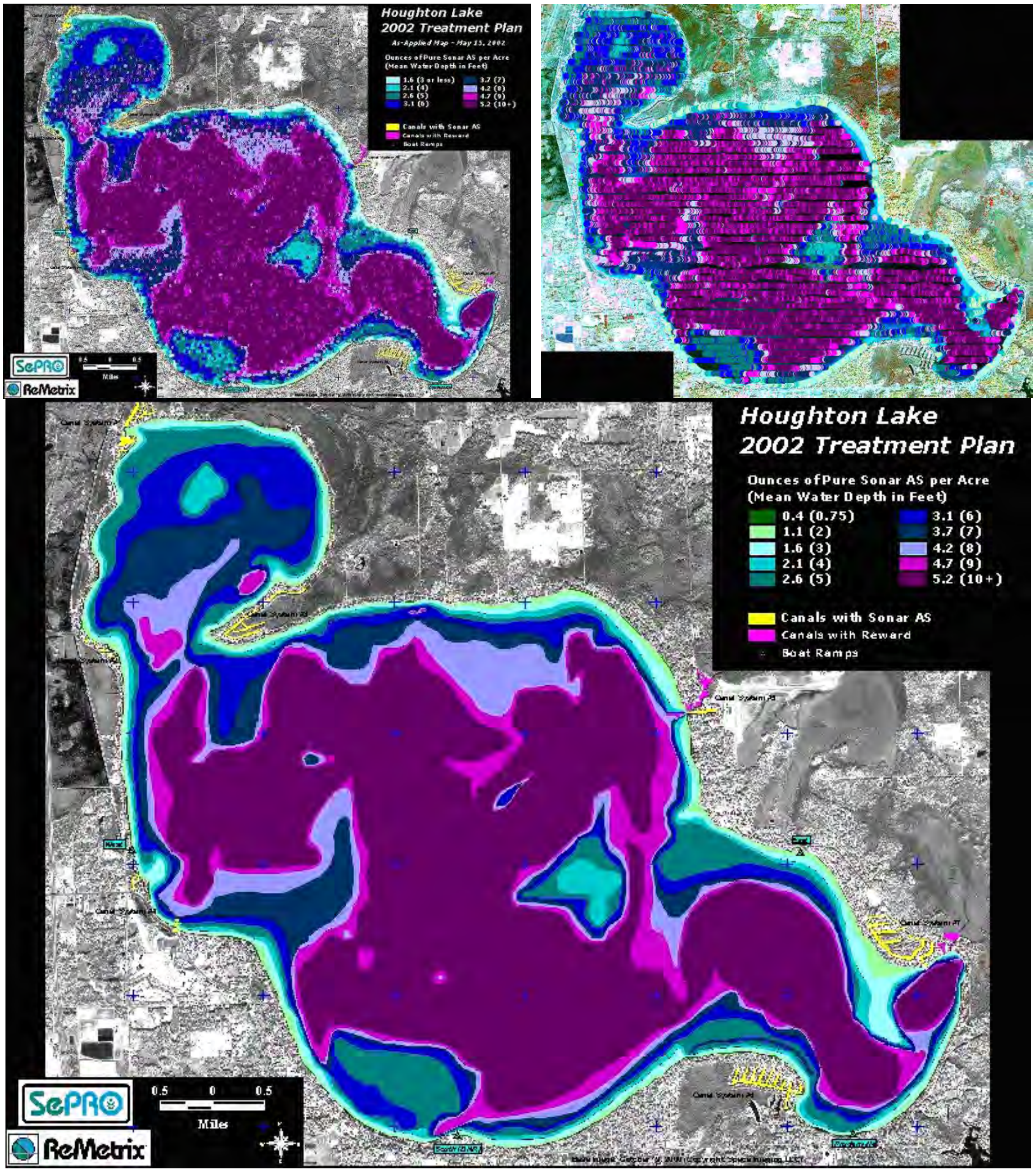


Figure 13. As-applied maps for the May 14–15 (top left) and June 12, 2002 (top right) applications of fluridone to Houghton Lake along with original digital representation of georeferenced prescription for computer control of application equipment (bottom).

in the East Central Basin). Three additional stations were located downstream of Houghton Lake in the Muskegon River. Heights Marina (station 36) was located 1 km downstream of the spillway. Two stations were located in Dead Stream Flooding; one at the Michelson boat ramp (station 37) 8.8 km downstream from station 36 (9.8 km below the spillway), and one at the MIDNR boat ramp (station 38) located 2.5 km downstream from station 37 (12.3 km below the spillway).

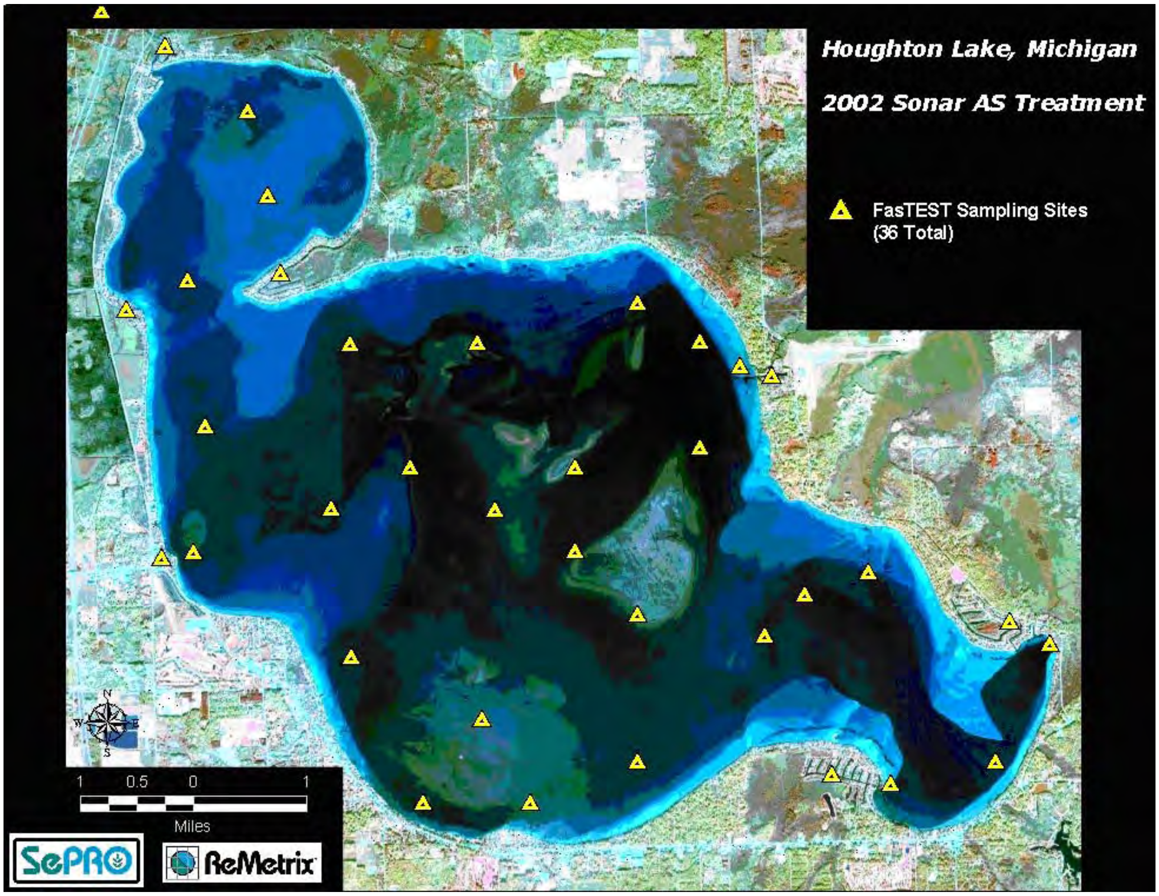


Figure 14. Collection locations of water and plant samples used to monitor fluridone concentrations and impacts.

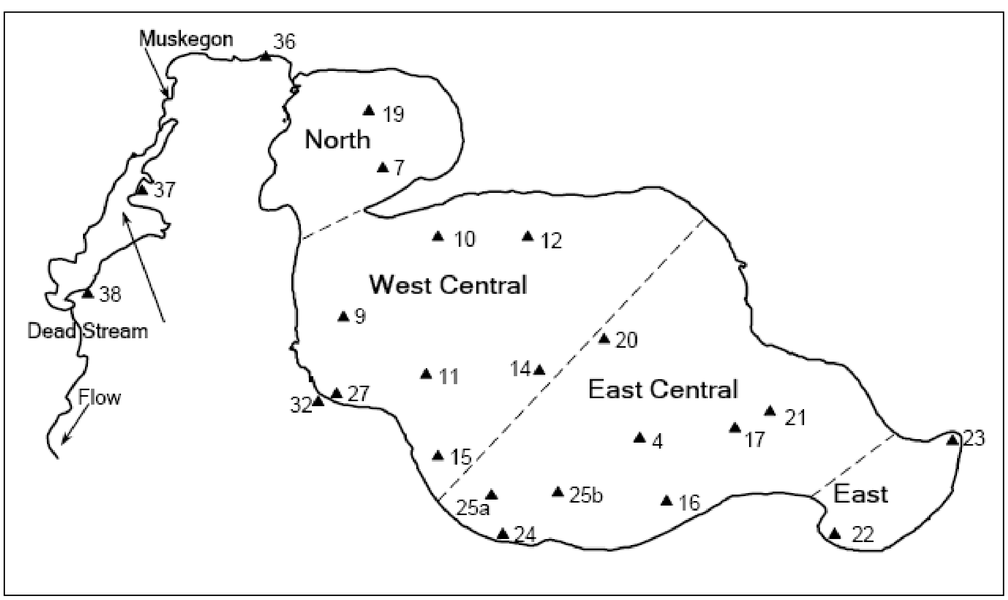


Figure 15. Sample sites in the East Bay, East Central Basin, West Central Basin, and North Bay on Houghton Lake. Additional sample sites are on the Muskegon River at Heights Marina (36), at the Michelson boat ramp (37), and the MIDNR boat ramp (38).

At each of these locations, duplicate water samples were collected in 500-mL amber high-density polyethylene bottles at 30, 43, 56, and 86 days after treatment (DAT). Immediately after collection, samples were placed in ice chests to keep them chilled and in the dark. They were shipped overnight to the ERDC laboratory and, upon receipt, immediately frozen until analysis. When all samples were collected through 86 DAT, they were analyzed by HPLC.

The HPLC analysis was conducted using a Waters HPLC system, made up of the following components: Waters 510 delivery pump, Waters 486 UV detector, Waters 746 data integrator, and Waters μ Bondapak C18, 3.9′ × 300-mm HPLC column. The method employed has been described in Getsinger et al. (2001) and Netherland et al. (2002). Solid phase extraction (SPE) cartridges were used as a pretreatment for cleaning the water samples as well as concentrating fluridone. The SPE cartridges were Waters SPE-Pak vac 6 cc (500 mg) C18 cartridges, which were placed on a 12-place SPE-Pak vacuum manifold (JT Baker PN 7018-00). After column conditioning procedures, an aliquot of 100-mL water sample was filtered through the SPE cartridges to a final elution of 2-mL with methanol. Samples were collected and stored in 4-mL amber glass vials and held until analysis. Fluridone concentrations in water were determined by comparing the detector response by peak area for the samples against the peak area response obtained from known standard concentrations of fluridone. Standards were prepared from analytical grade fluridone (99.1% purity) obtained from SePRO Corporation. The HPLC conditions were set as follows: eluent for mobile phase was 65:35 methanol:water; chart speed was set at 0.25 cm min^{-1}; flow rate was 1.2 mL min^{-1}; wavelength was 313 nm, attenuation was 8 as the standard value was set at 0.2 mg L^{-1}; and the sample injection volume was 100 μL. Run time for this compound was approximately 10 minutes, with the fluridone peak registered at 7 minutes. The reporting limit for this method is 1.0 μg L^{-1}. For quality control, five samples of distilled water were spiked with analytical grade fluridone at 0.2 mg L^{-1}; average recovery for spiked samples averaged 106%, with a range of 100 to 115%. Average recovery from five spiked field samples was 100%, with a range of 98 to 101%.

Data were statistically analyzed using SigmaPlot 8.0 (SPSS Corporation, Chicago, IL). All fluridone concentration data were regressed against time using the exponential decay model:

$$y = a * exp(-b * x) \quad (2)$$

where:

y = chemical concentration
a = intercept of regression line
b = slope of regression line
x = sampling time.

Dissipation half-lives ($t_{1/2}$) of fluridone were then calculated using the slope (b) of each significant regression ($p < 0.05$) in the equation:

$$t_{1/2} = ln(0.05) / b \quad (3)$$

Monitoring herbicide impacts on plants

Table 11 lists aquatic plant species sampled for pigment (chlorophyll, phytoene, and carotene) analysis in Houghton Lake during this study. Table 12 specifies plant samples collected at each water residue sampling station (Figure 15) at 30, 43, 56, and 86 days after treatment (DAT).

Table 11. Plant species sampled for pigment analysis in Houghton Lake, Michigan.

Scientific Name and Authority	Common Name	Growth Form	Native or Exotic
Ceratophyllum demersum L.	Coontail	Submersed	Native
Elodea canadensis Michx.	Elodea	Submersed	Native
Megalodonta beckii (Torr. Ex Spreng.) Greene	Water marigold	Submersed	Native
Myriophyllum spicatum L.	Eurasian watermilfoil	Submersed	Exotic
Potamogeton amplifolius Tuckerman	American pondweed	Submersed	Native
Potamogeton crispus L.	Curlyleaf pondweed	Submersed	Exotic
Potamogeton gramineus L.	Variable pondweed	Submersed	Native
Potamogeton praelongis Wolfen	Whitestem pondweed	Submersed	Native
Potamogeton robbinsii Oakes	Fern pondweed	Submersed	Native
Potamogeton zosteriformis Fern	Flatstem pondweed	Submersed	Native
Stukenia pectinata (L.) Borner	Sago pondweed	Submersed	Native
Utricularia gibba L.	Creeping bladderwort	Submersed	Native
Vallisneria americana L.	Wild celery	Submersed	Native
Zosterella dubia (Jacq.) MacM.	Water stargrass	Submersed	Native

Table 12. Plant species found at sampling stations after fluridone treatment in Houghton Lake, Michigan.

Basin	Station	Days After Treatment			
		30	43	56	86
North	7			*M. spicatum*	
	19	*M. spicatum*	*E. Canadensis* *M. spicatum* *P. praelongus*		*M. spicatum* *S. pectinata* *V. Americana* *Z. dubia*
West Central	10		*M. spicatum*	*M. spicatum*	
	11	*M. spicatum*		*M. spicatum*	
	12	*E. Canadensis* *M. spicatum*	*E. Canadensis* *M. spicatum* *P. praelongus*		*M. spicatum* *S. pectinata*
	14	*M. spicatum*	*E. Canadensis* *M. spicatum*		
	15	*M. spicatum*		*M. spicatum*	
	27	*M. spicatum*	*M. spicatum*		*M. spicatum*
	32	*E. Canadensis* *M. beckii*			
East	22	*C. demersum* *M. spicatum* *P. crispus*	*M. spicatum* *P. praelongus*		*C. demersum* *P. amplifolius* *U. gibba*
	23		*E. Canadensis* *P. robbinsii*		*C. demersum* *P. gramineus* *P. robbinsii*
East Central	4	*M. spicatum*		*M. spicatum* *Z. dubia*	
	16			*M. spicatum*	
	17	*M. spicatum*			
	20		*M. beckii* *M. spicatum* *Z. dubia*	*E. Canadensis* *M. spicatum* *Z. dubia*	*Z. dubia*
	21			*M. spicatum* *Z. dubia*	
	24	*M. spicatum*		*M. spicatum*	
	25a		*E. Canadensis* *M. spicatum* *Z. dubia*		
	25b		*E. Canadensis* *M. spicatum*		*P. zosteriformis*
Heights Marina	36		*V. americana*		
Michelson	37	*C. demersum* *E. Canadensis* *M. spicatum* *P. crispus*			
MIDNR Ramp	38	*E. Canadensis* *M. spicatum* *V. americana*			

Apical stems of plants were collected using a rake at each station at each sampling event. Immediately after collection, samples were put in plastic bags, and then placed in ice chests. Samples were kept chilled in the dark until shipped overnight to the ERDC laboratory and, upon receipt, were immediately analyzed for the pigments phytoene, β-carotene, and total chlorophyll.

Sprecher et al. (1998) describe analytical procedures for characterizing phytoene and β-carotene concentrations. Approximately 5 cm of fresh apical shoot tissue from collected plant samples was weighed (0.25 to 0.5 g), and then mechanically homogenized in 5 mL of a freshly made solution of 6% (w/v) KOH in MeOH. Tubes were capped and centrifuged for 5 minutes at 3000 rpm. The supernatant was decanted into a fresh tube containing 2 mL of light petrol (petroleum benzin, #85100, b.p. 80-110 C, Fluka, Ronkonkoma, NY), and shaken vigorously. After separation of the epiphase (1 minute), an aliquot was transferred to a 1.5 mL disposable UV semimicro cuvette (methacrylate, Dynalon, Rochester, NY) using a glass transfer pipette. Samples were then covered to avoid light. After the solution completely cleared (30 minutes), samples were read using a spectrophotometer (Beckman, DU-640, Fullerton, CA).

Sample absorbance was read at 287 nm for phytoene and at 445 nm for β-carotene. Pigment concentrations were calculated using the following equation:

$$\text{Pigment concentration } (\mu g\ g^{-1}) = ([(A/E) * 2\ mL/100\ mL]\ g\ FW^{-1}) * 10^{6} \quad (4)$$

where:

A = absorbance (287 nm for phytoene or 445 nm for β-carotene)
E = extinction coefficient (1108 for phytoene or 2500 for β-carotene)
g FW = grams fresh weight of each sample.

Analysis for total chlorophyll concentration is after Hiscox and Israelstam (1979). Approximately 3 cm fresh apical shoot tissue from collected plant samples was weighed (0.1 to 0.3 g) and placed in 10 mL of dimethyl sulfoxide (DMSO). To extract chlorophyll into the DMSO, test tubes were placed in a water bath for 6 hr at 65 °C. After removing tubes from the water bath, a 3-mL aliquot was transferred to a disposable standard cuvette. Using a spectrophotometer (Beckman, DU-640, city, state) sample absorbance was read at 645 nm and 663 nm. Samples with absorbance values greater than 1.2 were diluted with 1:1 with DMSO to obtain a readable value. Pigment concentrations were calculated using the following equations (Arnon 1949):

$$\text{chlorophyll } a \left(\text{mg g}^{-1}\right) = \left(\begin{bmatrix}\left(0.0127 * A_{663}\right) \\ -\left(0.00269 * A_{645}\right)\end{bmatrix} * 10\,\text{mL}\right) \text{g FW}^{-1} \quad (5)$$

$$\text{chlorophyll } b \left(\text{mg g}^{-1}\right) = \left(\begin{bmatrix}\left(0.0229 * A_{645}\right) \\ -\left(0.00468 * A_{663}\right)\end{bmatrix} * 10\,\text{mL}\right) \text{g FW}^{-1} \quad (6)$$

where:

A_{645} = absorbance at 645 nm
A_{663} = absorbance at 663 nm
g FW = grams fresh weight of each sample.

Total chlorophyll concentration equals the sum of chlorophyll *a* and chlorophyll *b* concentrations.

Results and discussion

Pre-treatment susceptibility testing

Eurasian watermilfoil collected at the 25 sites on Houghton Lake showed a homogenous response to fluridone treatment. A t-test ($p < 0.05$) indicated there were no significant differences in the assay response between Eurasian watermilfoil from the various sample sites. Given the broad pretreatment sampling conducted on Houghton Lake, it is expected that the Eurasian watermilfoil population throughout the 8,100-ha water body would show a similar level of injury to the fluridone application. Moreover, assay data collected in August 2001 were compared to data collected in May 2002, and the results were the same with no significant differences noted. Finally, comparison of the biochemical response of Eurasian watermilfoil in culture medium versus that grown in Houghton Lake water indicated that the response to fluridone application did not differ significantly between growth media.

Eurasian watermilfoil response data from Houghton Lake suggest that upper limit thresholds (>80-% reduction in biochemical parameters compared to untreated controls) were reached at concentrations greater than 4 µg L^{-1}. Fluridone concentrations above this range (up to 25 µg L^{-1}) did not result in any further reduction in plant biochemical parameters. Concentrations of 2 and 3 µg L^{-1} resulted in a 61- to 74-% reduction in plant biochemical parameters. Under field conditions, previous experience suggests that this level of reduction would result in a slow but ultimately phytotoxic response by Eurasian watermilfoil. Concentrations of 0.5 and 1 µg L^{-1} resulted in a 19- to 33-% reduction in biochemical parameters. These data demonstrate that a significant difference in Eurasian watermilfoil response exists between 1 and 2 µg L^{-1}. While concentrations above 2 µg L^{-1} would likely result in the maintenance of a phytotoxic dose, the reduction below 2 µg L^{-1} would likely allow biochemical recovery of the remaining Eurasian watermilfoil biomass.

It is also interesting to note that statistical differences ($p = 0.05$) in the biochemical response of Houghton Lake Eurasian watermilfoil were noted between 0.5 and 1 µg L^{-1}, 1 and 2 µg L^{-1}, 2 and 3 µg L^{-1}, and 3 and 4 µg L^{-1}. There were no differences noted between 4 µg L^{-1} and the higher concentrations that were assayed. These data demonstrate the high level of sensitivity of Eurasian watermilfoil to fluridone, and show that once below the threshold, the reduction in response was often linear in nature. In essence, the difference between exposure to 1 and 2 µg L^{-1} was likely significant on Houghton Lake.

In comparing Eurasian watermilfoil from Houghton Lake to Eurasian watermilfoil collected from Wolverine Lake, MI (data not presented), the biochemical response of Wolverine Lake Eurasian watermilfoil at 2, 3, and 4 µg L^{-1} (25-, 38-, and 59-% reduction in biochemical parameters) is significantly different compared to Houghton Lake (61-, 74-, and 85-% reductions). While Eurasian watermilfoil from Wolverine Lake does show a similar response in assay to 6 µg L^{-1} (78-% reduction), it is likely that biochemical recovery of Eurasian watermilfoil from a fluridone treatment could occur between 2 and 4 µg L^{-1} on Wolverine Lake (data not presented). By contrast, this range of concentrations would remain quite lethal to the Eurasian watermilfoil in Houghton Lake. The assay data demonstrated that the difference between Eurasian watermilfoil control and growth regulation can be site-specific, and can be impacted by very small differences in fluridone concentrations.

Based on the assay results described above, maintenance of residues between 2 and 6 µg L^{-1} for greater than 90 days after treatment was expected to result in excellent control of Eurasian watermilfoil. It is important to keep in mind that while the initial fluridone concentration is an important factor, experience suggests that the long-term maintenance of phytotoxic residues is of greater importance when treating Eurasian watermilfoil. PlanTEST data clearly documented that Houghton Lake Eurasian watermilfoil was highly susceptible to fluridone. The high level of susceptibility to rates above 2 µg L^{-1} suggested that maintaining concentrations somewhat above this threshold for as long a period as possible would provide the key to long-term control. Rapid Eurasian watermilfoil recovery will generally come from established root crowns (full of stored carbohydrates) that have not received an adequate fluridone exposure period to provide complete control.

Post-treatment herbicide residues

Fluridone concentrations measured by ELISA showed that the target concentration of 6 µg L^{-1} fluridone was exceeded by about 17% (Figure 16). While somewhat higher than anticipated, this initial value (7.02 µg L^{-1}) was well within the range of levels typically obtained in large whole-lake applications. By 14 days after treatment (DAT), residue levels had decreased to 3.0 µg L^{-1}, which triggered a booster application on 5 June. The booster dose resulted in re-setting the whole-lake aqueous concentration to 6.2 µg L^{-1} fluridone. Fluridone levels slowly declined through August to reach a mean concentration of 2.5 µg L^{-1}.

Whole-lake mean water residues showed that mean aqueous concentrations of fluridone declined from 7.9 µg L^{-1} at 30 DAT to 3.8 µg L^{-1} at 86 DAT (Table 13). Furthermore, water residues showed that aqueous fluridone concentrations ranged from 7.0 µg L^{-1} in the East Central Basin to 8.6 µg L^{-1} in the North Bay 30 DAT. These residues reflect the impact of the booster treatment on 5 June, which added an additional 2.8 µg L^{-1} to the system, as the booster was designed to re-set the whole lake fluridone level to 6 µg L^{-1}. Downstream from Houghton Lake, in the Muskegon River, fluridone concentrations were 6.3 µg L^{-1}, 4.3 µg L^{-1}, and 2.9 µg L^{-1} at Heights Marina, Michelson, and MIDNR ramp, respectively, at 30 DAT. These levels depict an expected steady decline of fluridone in waters downstream from the lake, with concentrations decreasing with respect to increasing distance downstream.

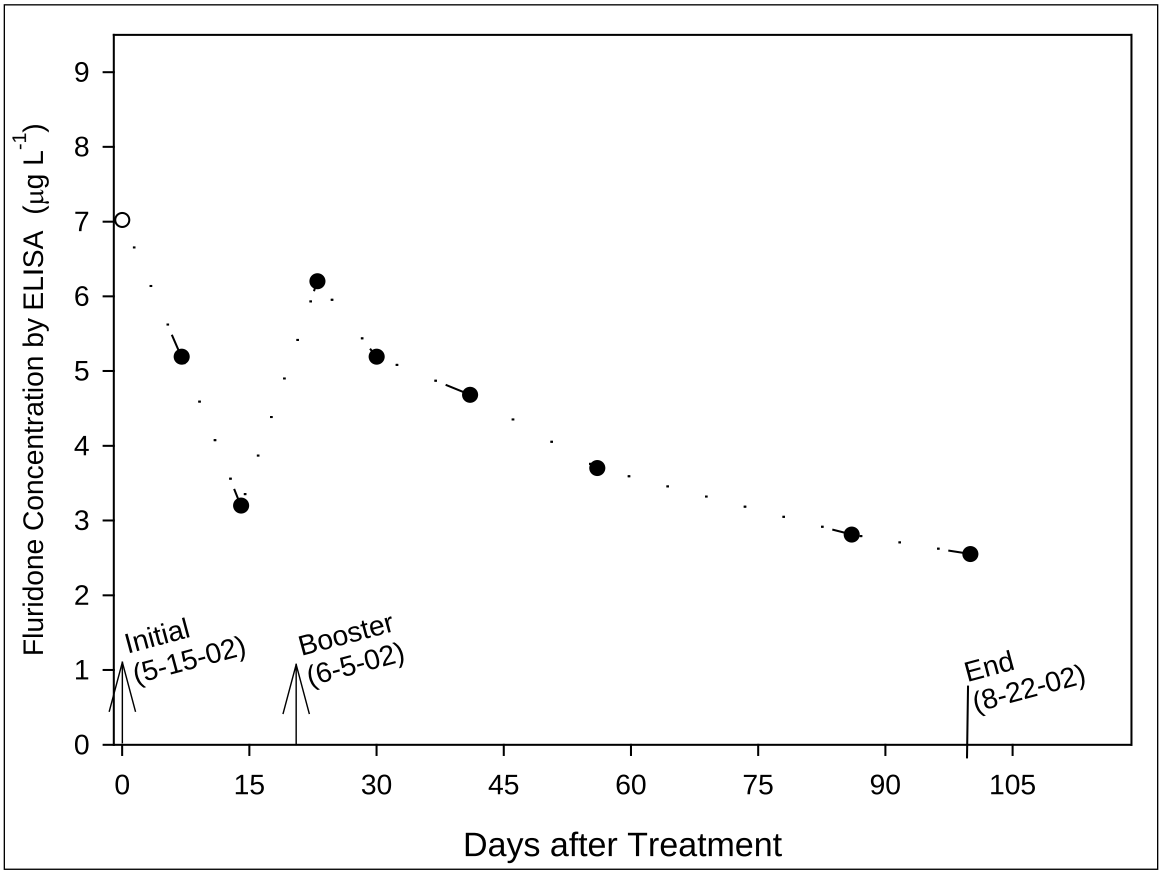


Figure 16. Water residues from Houghton Lake, Michigan analyzed by SePRO Corporation using ELISA.

As expected, fluridone gradually dissipated from the lake water column as evident in residues collected 43, 56, and 86 DAT (Table 13). At 43 DAT, aqueous concentrations ranged from 5.8 to 7.2 µg L^{-1} (mean = 6.7 µg L^{-1}) and at 56 DAT, aqueous concentrations were between 4.5 and 5.7 µg L^{-1} throughout the lake (mean = 5.2 µg L^{-1}). Downstream, concentrations tapered to 4.1 µg L^{-1}, 3.6 µg L^{-1}, and 2.8 µg L^{-1} at Heights Marina, Michelson, and MIDNR ramp, respectively, at 56 DAT. Measured fluridone levels would not be expected to cause serious injury to nontarget vegetation in the downstream reaches. By 86 DAT, aqueous concentrations ranged from 3.7 µg L^{-1} in the East Central Basin to 3.8 µg L^{-1} in the North Bay (mean = 3.8 µg L^{-1}).

Table 13. Fluridone concentrations (µg·L^{-1}) in Houghton Lake after treatment (as measured by HPLC).

Location	Station	Days After Treatment			
		30[1]	43	56	86
North Bay	7			5.2 ± 0.04	
	19	8.6 ± 0.3	6.6 ± 0.04	4.5 ± 0.2	3.8 ± 0.4
West Central Basin	9			5.5 ± 0.2	
	10		6.9 ± 0.4	5.7[2]	
	11	7.9 ± 0.01		5.5 ± 0.01	
	12	8.1 ± 0.1	7.6 ± 0.3		3.8 ± 0.1
	14	7.7 ± 0.2	6.8 ± 0.1		3.7 ± 0.1
	15	7.8 ± 0.1		5.4 ± 0.01	
	27	8.5 ± 0.3	7.2 ± 0.1	5.3 ± 0.4	4.1 ± 0.7
	32	7.8 ± 0.04		4.6 ± 0.1	
East Bay	22	8.0 ± 0.2	6.2 ± 0.04		3.7 ± 0.06
	23		5.8 ± 0.1	5.0 ± 0.2	3.5 ± 0.05
East Central Basin	4	7.1 ± 0.1		5.3 ± 0.2	
	16	7.8 ± 0.04		5.6 ± 0.3	
	17	7.8 ± 0.04			
	20		6.5 ± 0.01	5.2 ± 0.03	3.7 ± 0.1
	21			5.2 ± 0.1	
	24	7.9 ± 0.05		4.8 ± 0.2	
	25a		6.9 ± 0.2		3.8 ± 0.01
	25b		6.8 ± 0.1		3.7 ± 0.1
Whole-lake mean ± 1 SE		**7.9 ± 0.3**	**6.7 ± 0.4**	**5.2 ± 0.3**	**3.8 ± 0.2**
Heights Marina	36	6.3 ± 0.04		4.1 ± 0.04	
Michelson	37	4.3 ± 0.8		3.6 ± 0.3	
MIDNR Ramp	38	3.0 ± 0.1		2.8 ± 0.1	

[1] Residues analyzed by HPLC. Data represent mean (± 1 SE) of water samples collected at each site (n = 2).

[2] n = 1.

The calculated half-life of aqueous fluridone concentrations ($t_{1/2}$) for Houghton Lake was 53.31 days (Figure 17). This value matches well with the measured dissipation of fluridone residues shown in Figure 16. Fluridone residues dissipated at similar rates in the East Bay, West Central Basin, and East Central Basin, where calculated half-lives were between 53 and 56 days, whereas the shorter half-life of 43 days in the North Bay indicated that fluridone dissipated more rapidly in that area (Figure 18).

Comparison of water residues measured by ELISA and HPLC

Aqueous fluridone levels measured by SePRO Corporation via ELISA at locations and times corresponding to samples collected and measured by the ERDC (Table 14) were compared with the corresponding HPLC results. A least square regression line fitted to the data demonstrates that there is a highly significant ($R^2 = 0.87$, $P < 0.001$), nearly 1:1 relation between fluridone concentrations measured by the two methods (Figure 19). This comparison falls within the range of correlations ($R^2 = 0.84$ to 0.97) reported in other field studies that compared the two analytical techniques (Netherland et al. 2002).

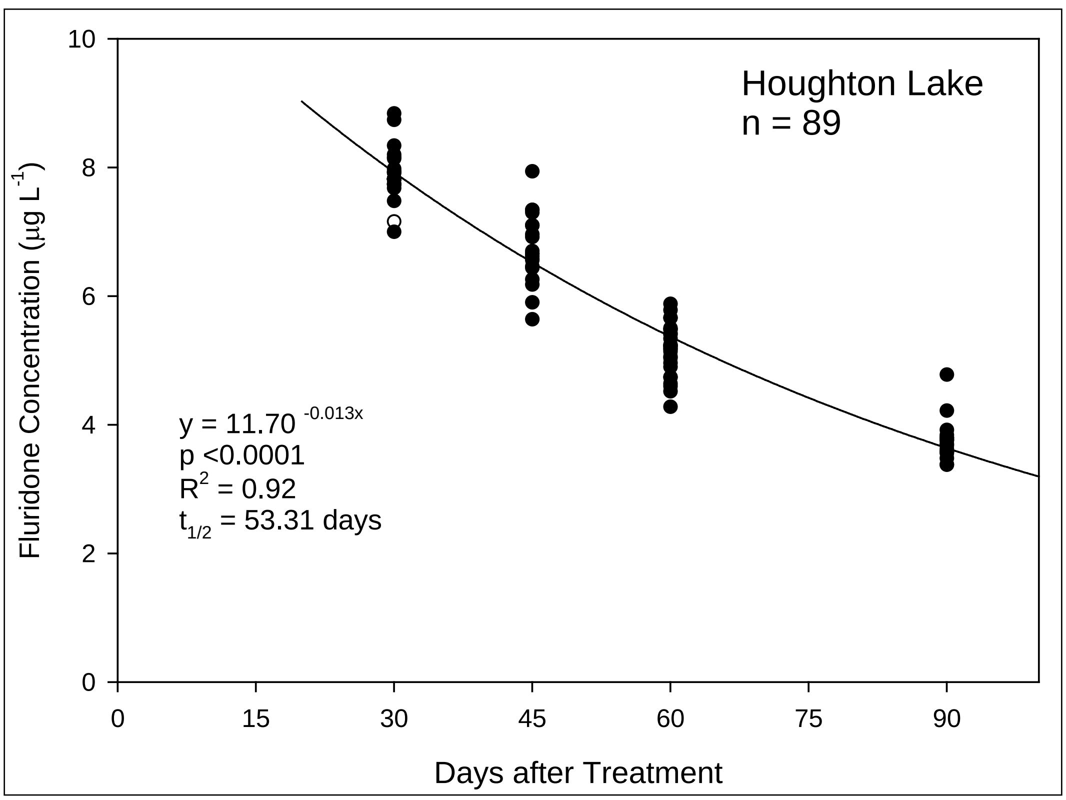


Figure 17. Dissipation of fluridone throughout Houghton Lake, Michigan following application.

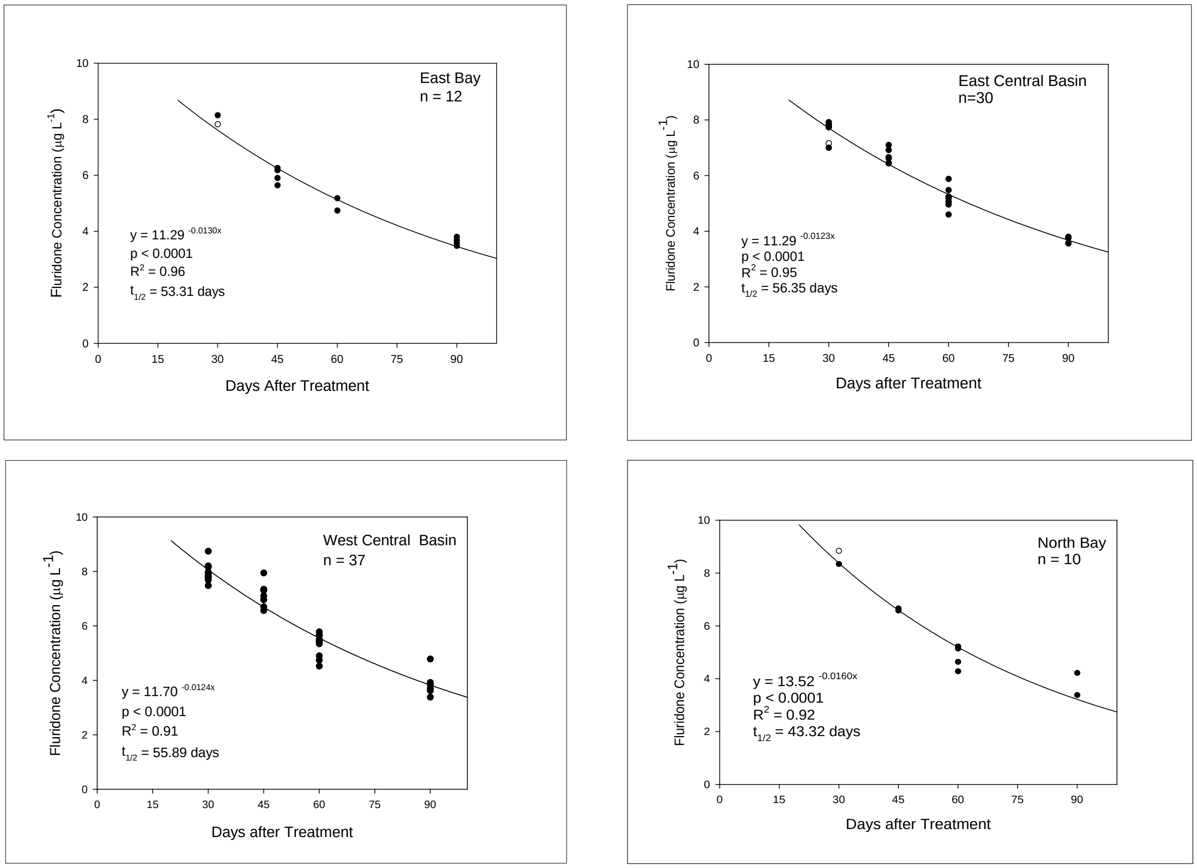


Figure 18. Dissipation of fluridone following application in four basins of Houghton Lake, Michigan.

Table 14. Water residues analyzed by ELISA depicting fluridone concentrations (µg L^{-1}) in Houghton Lake, Michigan.

Location	Station	Days After Treatment		
		30	43	56
North Bay	7			4.1
	19	5.8		
North Central Basin	10		5.1	3.8
	11	5.5		4.1
	12	5.4	5.2	
	14	5.6	5.1	
	15	5.4		4.2
	27	5.7	5.3	3.9
East Bay	22	5.1	5.0	
East Central Basin	4	4.9		3.9
	16			3.6
	20			4.2
	21			4.3

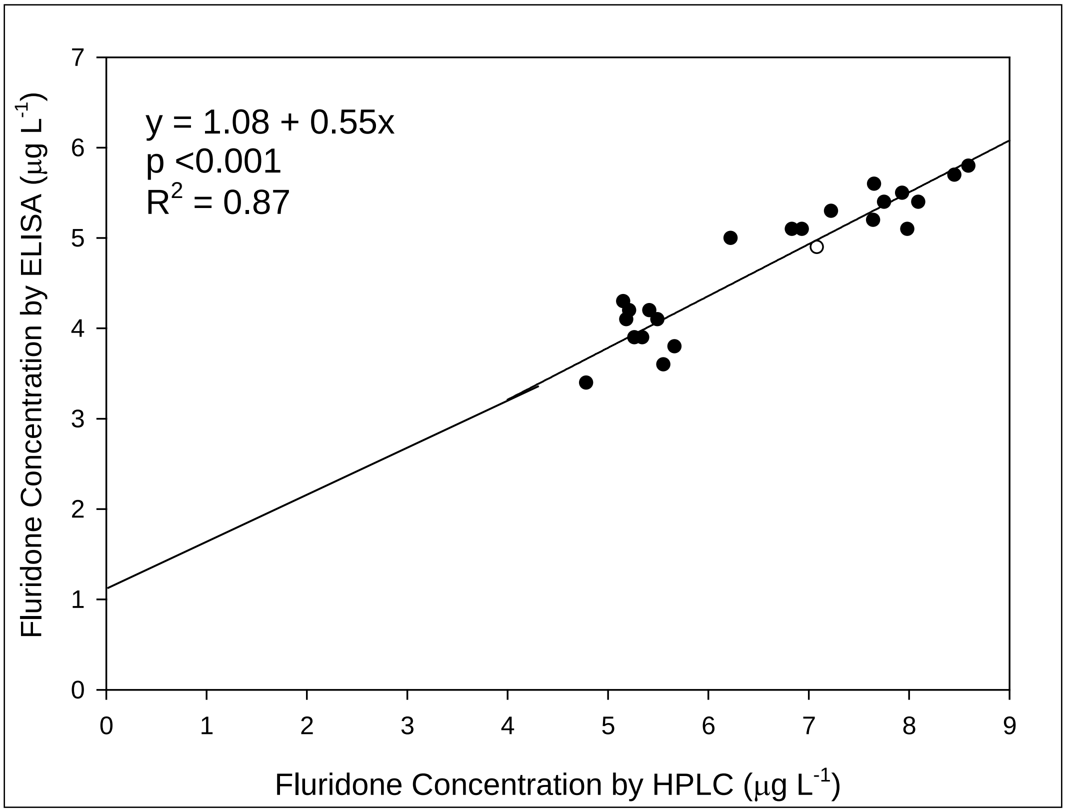


Figure 19. Relation between fluridone concentration measured by HPLC and ELISA techniques.

Plant injury assessment following fluridone treatment

Eurasian watermilfoil analyzed by the ERDC

Elevated phytoene concentrations in Eurasian watermilfoil plant tissue indicated fluridone exposure (Table 15). As aqueous herbicide residues averaged 7.9 µg L^{-1} throughout Houghton Lake (Table 13), plant tissue phytoene ranged from 55.5 to 91.9 µg g FW^{-1} at 30 DAT. Untreated Eurasian watermilfoil exhibit phytoene levels between 10 and 20 µg g FW^{-1} (Sprecher et al. 1998). Fluridone exposure also was evident in Eurasian watermilfoil collected downstream of Houghton Lake. At Michelson (station 37) and MIDNR boat ramp (station 38), plant phytoene levels were 131 and 85 µg g FW^{-1}, respectively (Table 15). Throughout the lake, plant tissue phytoene concentrations ranged from 90.9 to 134.4 µg g FW^{-1} at 43 DAT. By 56 DAT, concentrations ranged from 51.8 to 92.9 µg g FW^{-1}. Although aqueous fluridone residues dropped to 3.76 µg L^{-1} by 86 DAT (Table 13), tissue phytoene levels persisted above 100 µg g FW^{-1} (Table 15). Sample numbers dwindled from 9 or 10 samples to 3 at 86 DAT due to insufficient sample material as Eurasian watermilfoil biomass decayed.

Table 15. Phytoene concentrations (µg·FW^{-1}) of Eurasian watermilfoil at sample sites after fluridone treatment in Houghton Lake.

Basin	Station	Days After Treatment			
		30[1]	43	56	86
North	7			80.2 ± 10.1	
	19	91.9 ± 1.3	101.0 ±20.5		110.1 ± 18.7
West Central	10		105.3 ± 10.4	86.2 ± 4.7	
	11	55.5 ± 11.6		77.7 ± 6.0	
	12	63.6 ± 2.7	99.9 ± 7.1		108.0 ± 9.9
	14	91.3 ± 14.6	97.9 ± 6.0		
	15	91.0 ± 8.3		74.8 ± 4.1	
	27	85.7 ± 10.0	134.4 ± 11.9	92.9 ± 5.1	101.4 ± 22.2
East	22	76.5 ± 13.5	90.9 ± 11.9		
East Central	4	78.2 ± 13.0		84.9 ± 0	
	16			87.62± 9.0	
	17	58.4 ± 4.7			
	20		105.0 ± 5.9	78.7 ± 0	
	21			89.1 ± 7.3	
	24	68.2 ± 3.4		51.8 ± 6.8	
	25a		97.3 ± 11.2		
	25b		105.8 ± 16.7		
Heights Marina	36				
DCF Michelson	37	130.8 ± 7.9			
MIDNR Ramp	38	84.7 ± 7.2			

[1] Data represent mean (± 1 SE) of plant samples (n = 3).

Depressed β-carotene levels (Table 16) concomitant with decreasing chlorophyll concentrations (Table 17) signified the onset of decay in Eurasian watermilfoil plants throughout Houghton Lake by 56 DAT. By 30 DAT, levels of β-carotene were below the normal range of 20 to 40 µg g FW^{-1} found in untreated Eurasian watermilfoil (Sprecher et al. 1998). Plants found at Michelson (station 37) and the MINDR ramp (station 38) downstream of Houghton Lake exhibited β-carotene concentrations of 20.8±2.0 and 13.5±0.8 µg g FW^{-1}, respectively (Table 16); however, chlorophyll concentrations were above 1.0 mg g FW^{-1} (Table 17), which suggests that these plants were still healthy and photosynthesizing. At 43 DAT, β-carotene levels were below 13 µg g FW^{-1} in East Bay and East Central Basin, while levels ranged from 14 to 21 µg g FW^{-1} in the West Central Basin and 15 µg g FW^{-1} in the North Bay (Table 16). Accordingly, chlorophyll concentrations were lower in the East and East Central Basin (0.4 to 0.7 mg g FW^{-1}) than in the northern part of the lake (0.6 to 0.9 mg g FW^{-1}; Table 7). Chlorophyll concentrations further declined in the North Bay and West Central Basin at 56 and 86 DAT (Table 17).

Table 16. β-carotene concentrations (µg·g FW⁻¹) of Eurasian watermilfoil at sample sites after fluridone treatment in Houghton Lake.

Basin	Station	Days After Treatment			
		30[1]	43	56	86
North	7			11.7 ± 1.5	
	19	12.5 ± 0.8	15.8 ± 1.7		5.5 ± 1.1
West Central	10		16.2 ± 1.7	10.5 ± 2.1	
	11	16.5 ± 0.3		10.9 ± 1.7	
	12	16.8 ± 1.2	21.4 ± 1.2		18.1 ±1.2
	14	13.9 ± 1.1	14.2 ± 2.6		
	15	18.8 ± 1.7		9.3 ± 1.6	
	27	22.1 ± 9.6	19.0 ± 2.3	11.4 ± 0.4	11.2 ± 3.4
East	22	11.6 ± 2.6	12.4 ± 0.7		
East Central	4	10.3 ± 1.2		5.9 ± 0	
	16			8.7 ± 0.5	
	17	18.9 ± 3.1			
	20		13.6 ± 1.7	9.3 ± 0	
	21			8.4 ± 1.6	
	24	12.3 ± 0.5		9.9 ± 1.3	
	25a		10.7 ± 1.2		
	25b		12.8 ± 3.1		
Heights Marina	36				
DCF Michelson	37	20.8 ± 2.0			
MIDNR Ramp	38	13.5 ± 0.8			

[1] Data represent mean (± 1 SE) of plant samples (n = 3).

Table 17. Chlorophyll concentrations (mg·g FW⁻¹) of Eurasian watermilfoil at sample sites after fluridone treatment in Houghton Lake.

Basin	Station	Days After Treatment			
		30[1]	43	56	86
North	7			0.77 ± 0.10	
	19	0.91 ± 0.05	0.62 ± 0.02		0.40 ± 0.09
West Central	10		0.90 ± 0.02	0.86 ± 0.10	
	11	0.91 ± 0.01		0.85 ± 0	
	12	1.02 ± 0.01	0.90 ± 0.09		0.58 ± 0.09
	14	1.23 ± 0.06	0.73 ± 0.11		
	15	1.01 ± 0.21		0.76 ± 0	
	27	0.95 ± 0.08	0.92 ± 0.07	0.71 ± 0.10	0.34 ± 0.03
East	22	1.05 ± 0.09	0.66 ± 0.10		
East Central	4	0.84 ± 0.05			
	16			0.74 ± 0.10	
	17	1.30 ± 0.11			
	20		0.66 ± 0.03		
	21				
	24	0.74 ± 0.23			
	25a		0.57 ± 0.08		
	25b		0.35 ± 0.23		
Heights Marina	36				
DCF Michelson	37	1.07 ± 0.12			
MIDNR Ramp	38	1.12 ± 0.03			

[1] Data represent mean (± 1 SE) of plant samples (n = 3).

Pigment concentrations of Eurasian watermilfoil collected in Houghton Lake during herbicide exposure reflect fluridone efficacy against this target plant. Field observations indicated approximately 90-% reduction in plant biomass by August 22, 100 DAT (data not presented). Continuous exposure to fluridone caused plant injury, and eventually death. A steady increase in phytoene levels indicated plants were taking up fluridone while a gradual decline in β-carotene and chlorophyll concentrations indicated plants were damaged by the herbicide.

Eurasian watermilfoil analyzed by SePRO Corporation

Phytoene levels in Eurasian watermilfoil samples analyzed by SePRO Corporation ranged from 13.2 μg g FW^{-1} in the North Bay to 37.6 μg g FW^{-1} in the West Central Basin at 30 DAT (Table 18). Although phytoene levels rose somewhat at 43 DAT, phytoene concentrations reported here (Table 8) were 60% less than those reported by ERDC for both 30 and 43 DAT (Table 15). There were significant increases in phytoene levels by 56 DAT (Table 18), which corresponded to phytoene levels shown in Table 15.

Concentrations of β-carotene varied during fluridone exposure throughout Houghton Lake (Table 18). Concentrations ranged from 2.6 to 9.9 μg g FW^{-1} at 30 DAT and 7.3 to 11.9 μg g FW^{-1} at 43 DAT. Although concentrations of β-carotene reported by ERDC were two-fold higher for both 30 and 43 DAT (Table 16), by 56 DAT, β-carotene analyzed by SePRO matched those analyzed by ERDC.

Chlorophyll concentrations were similar for Eurasian watermilfoil collected 30, 43 and 56 DAT (Table 18). Concentrations ranged from 0.4 to 0.6 mg g FW^{-1} in all parts of Houghton Lake. Chlorophyll concentrations reported by ERDC were 50%, 44%, and 31% higher at 30 DAT, 43 and 56 DAT, respectively (Table 17).

Phytoene levels in Eurasian watermilfoil analyzed by SePRO indicated uptake of adequate fluridone by plants in Houghton Lake. Concentrations of β-carotene and chlorophyll depicted plant injury due to herbicide exposure. Differences between samples analyzed by SePRO and ERDC probably reflect the range of injury and decay of Eurasian watermilfoil throughout Houghton Lake following fluridone treatment.

Table 18. Pigment concentrations of Eurasian watermilfoil collected and analyzed by SePRO Corporation 30, 43, and 56 days after fluridone treatment (DAT) in Houghton Lake, Michigan.

		Phytoene (μg·g FW^{-1})			β-carotene (μg·g FW^{-1})			Chlorophyll (mg·g FW^{-1})		
Basin	Station	30 DAT[1]	43 DAT	56 DAT	30 DAT	43 DAT	56 DAT	30 DAT	43 DAT	56 DAT
North	7			62 ± 15.1			8.1 ± 0.1			0.6 ± 0
	19	13.2 ± 4.2			6.5 ± 1.1			0.6 ± 0		
West Central	10		55.2 ± 13.3	64.1 ± 13.3		11.1 ± 1.3	8.3 ± 0.2		0.6 ± 0	0.6 ± 0
	11	17.5 ± 8.4		53.3 ± 19	6.9 ± 0.1		9.2 ± 1.1	0.6 ± 0		0.6 ± 0
	12	28.3 ± 14.1	13.1 ± 1.9		6.1 ± 0.2	11.4 ± 1.5		0.6 ± 0	0.52 ± 0.1	
	14	37.6 ± 18.8	57.1 ± 14.8		9.1 ± 1.7	11.9 ± 4.1		0.6 ± 0	0.62 ± 0	
	15	19.3 ± 4.6		90.3 ± 2.9	7.8 ± 2.1		8.9 ± 0.5	0.5 ± 0		0.6 ± 0.1
	27	18.5 ± 13.2		98.4 ± 4.6	2.6 ± 0.7		10.4 ± 1.3	0.4 ± 0.1		0.6 ± 0
East	22	29 ± 11.9	41.1 ± 16		9.9 ± 0.8	7.3 ± 0.8		0.4 ± 0.1	0.6 ± 0	
East Central	4	18.3 ± 7.6			8.7 ± 0.4			0.5 ± 0		0.4 ± 0
	16			81.3 ± 5.2			9.1 ± 0.2			0.5 ± 0
	20									0.4 ± 0
	21			84.1 ± 11.1			10.1 ± 0.1			0.5 ± 0
	24			79.3 ± 18.8			11.1 ± 2.1			0.5 ± 0

[1] Data represent mean (±1 SD) of plant samples (n = 4).

Nontarget plants

All pigment concentrations, including phytoene, β-carotene, and chlorophyll, for nontarget plants in Houghton Lake are shown in Table 19. Coontail samples were collected in the East Bay (station 22) at 30 and 86 DAT. Phytoene concentrations initially were high, 132.4 μg g FW^{-1}, then decreased to 45 μg g FW^{-1} by 86 DAT. Downstream at Michelson (station 37), tissue phytoene levels were 24.3 μg g FW^{-1}. In the laboratory, untreated coontail apices had phytoene levels of 12 to 15 μg g FW^{-1} (ERDC unpublished data). Tissue β-carotene concentrations ranged from 2.6 to 3.3 μg g FW^{-1} in plants in the East Bay and were 7.5 μg g FW^{-1} at Michelson. Untreated coontail apices typically have β-carotene concentrations of 20 μg g FW^{-1} (ERDC unpublished data). Chlorophyll concentrations were also low (0.1 to 0.4 mg g FW^{-1}). High phytoene levels indicate fluridone uptake by the plants, while low β-carotene and chlorophyll concentrations indicate plant injury. Although these pigment concentrations reflect the susceptibility of coontail to fluridone, Smith and Pullman (1997) reported less than 10% of all fluridone field applications of 5 to 10 μg L^{-1} in Michigan eliminated coontail.

Table 19. Pigment concentrations of nontarget plants at sample sites 30, 43, 56, and 86 days after fluridone treatment (DAT) in Houghton Lake, Michigan.

Station	Phytoene (µg·g FW^{-1})				β-Carotene (µg·g FW^{-1})				Chlorophyll (mg·g FW^{-1})			
	30 DAT[1]	43 DAT	56 DAT	86 DAT	30 DAT	43 DAT	56 DAT	86 DAT	30 DAT	43 DAT	56 DAT	86 DAT
Ceratophyllum demersum												
22	132.4 ± 0			45.0 ± 0	2.6 ± 0			3.3 ± 0				0.1 ± 0
25a												0.2 ± 0
DCF Michelson	24.3 ± 1.4				7.5 ± 1.8				0.4 ± 0.1			
Elodea canadensis												
4											0.4 ± 0	
12	63.3 ± 0	84.5 ± 10.4			4.0 ± 0	4.2 ± 0.2			0.7 ± 0	0.3 ± 0.03		
19		86.3 ± 5.5				3.4 ± 0.3				0.5 ± 0.1		
20			67.4 ± 7.3				11.2 ± 1.4					
23		88.1 ± 11.7				5.8 ± 0.4				0.4 ± 0.1		
25a		77.8 ± 3.3				3.7 ± 0.3				0.5 ± 0.03		
25b		89.1 ± 19.8				5.8 ± 0.4				0.5 ± 0.1		
32	65.5 ± 10.3				5.8 ± 0.8				0.5 ± 0.1			
DCF Michelson	68.3 ± 0				5.8 ± 0				0.6 ± 0			
MIDNR Ramp	60.8 ± 10.9				8.1 ± 2.8				0.5 ± 0.1			
Megalodonta beckii												
20		115.5 ± 8.4				0.9 ± 0.2				0.1 ± 0.01		
Potamogeton amplifolius												
22				243.7 ± 8.7				36.5 ± 1.5				0.9 ± 0.2
Potamogeton crispus												
22	239.0 ± 31.2				16.2 ± 0.6				0.7 ± 0.3			
DCF Michelson	204.4 ± 43.0				15.7 ± 1.4				0.7 ± 0.1			

Station	Phytoene (μgg FW^{-1})				β-Carotene (μgg FW^{-1})				Chlorophyll (mgg FW^{-1})			
	30 DAT[1]	43 DAT	56 DAT	86 DAT	30 DAT	43 DAT	56 DAT	86 DAT	30 DAT	43 DAT	56 DAT	86 DAT
Potamogeton gramineus												
23				515.7 ± 17.7				17.6 ± 1.0				0.6 ± 0.1
Potamogeton praelongis												
12		545.1 ± 70.3				8.1 ± 1.4				0.4 ± 0.02		
19		700.0 ± 60.1				9.4 ± 0.6				0.3 ± 0.04		
22		173.2 ± 14.8				10.7 ± 2.3				0.9 ± 0.06		
Potamogeton robbinsii												
23		111.0 ± 25.2		99.4 ± 13.8		21.0 ± 6.3		49.9 ± 4.6		1.0 ± 0.2		1.6 ± 0.1
Potamogeton zosteriformis												
25b				356.5 ± 0				68.4 ± 0				0.8 ± 0
Stukenia pectinata												
12				228.9 ± 0				29.4 ± 0				0.9 ± 0
19				74.5 ± 8.6				23.3 ± 0.7				0.6 ± 0.1
Vallisneria americana												
19				131.4 ± 4.5				10.2 ± 0.7				0.3 ± 0.06
Heights Marina		41.5 ± 4.6				1.8 ± 0.2				0.2 ± 0.03		
MIDNR Ramp	30.5 ± 2.3				14.8 ± 9.5				0.5 ± 0.01			
Zosterella dubia												
4			79.0 ± 1.1				12.7 ± 1.3				0.5 ± 0.02	
19				48.5 ± 16.8				15.0 ± 4.1				0.6 ± 0.1
20		67.7 ± 7.7	69.9 ± 6.0	84.9 ± 10.2		14.8 ± 1.0	15.6 ± 0.4	17.6 ± 2.3			0.6 ± 0.04	0.6 ± 0.1
21			155.4 ± 16.4				18.5 ± 2.6					
25a		69.8 ± 24.6		88.3 ± 6.1		13.6 ± 2.6		17.3 ± 2.2		0.5 ± 0.04	0.3 ± 0.04	0.5 ± 0.04

[1] Data represent mean (±1 SE) of plant samples (n = 3).

Elodea phytoene levels ranged from 60.8±10.9 µg g FW^{-1} at MIDNR ramp (station 38) to 63.3 µg g FW^{-1} in the East Central Basin of Houghton Lake (station 20) at 30 DAT. These levels increased slightly 43 DAT in the East Central Basin. Tissue β-carotene concentrations varied from 3.4±0.3 to 5.8±0.8 µg g FW^{-1} in different lake locations at 30 and 43 DAT. Field collected untreated elodea typically has β-carotene concentrations above 20 µg g FW^{-1} and phytoene levels below 10 µg g FW^{-1} (ERDC unpublished data). Although elodea is considered highly susceptible to fluridone (Westerdahl and Getsinger 1988; Smith and Pullman 1997), it has been shown to recover even after a 90-day exposure to 20 µg L^{-1} in an outdoor mesocosm study (Netherland et al. 1997).

Phytoene levels for water marigold were 115.5±8.4 µg g FW^{-1} at station 20 by 43 DAT; however, these high levels appear to be normal for this species (Sprecher et al. 1998; Nelson et al. 2002). Concentrations of β-carotene and chlorophyll found in water marigold from Houghton Lake, 0.9±0.2 µg g FW^{-1} and 0.1±0.01 mg g FW^{-1}, respectively, correspond with concentrations found in plants subjected to 7.5 µg L^{-1} fluridone for 45 days in a small-scale chamber study (Nelson et al. 2002). Although there was a significant decrease in water marigold shoot biomass after exposure to 7.5 µg L^{-1} fluridone for 84 days compared to the untreated reference in that study, there was not a significant shoot biomass reduction in plants exposed to 5.0 µg L^{-1} fluridone for 84 days. These results led the authors to conclude that water marigold was minimally impacted by low rates of fluridone (≤5 µg L^{-1}.).

The pondweed species (e.g., Potamogetons) sampled from Houghton Lake all exhibited high phytoene levels that ranged from 200 to 700 µg g FW^{-1} throughout the fluridone treatment. Relatively high phytoene levels were also observed in *P. nodus* after a 30-day exposure to fluridone in a small-scale experiment (Sprecher et al. 1998). During the Houghton Lake treatment, most pondweed species maintained β-carotene concentrations between 15 and 68 µg g FW^{-1} and chlorophyll concentrations between 0.6 and 1.6 mg g FW^{-1}. One exception was whitestem pondweed, which exhibited β-carotene concentrations between 8.1 and 10.7 µg g FW^{-1} and chlorophyll concentrations between 0.3 and 0.9 µg g FW^{-1}. Although *Potamogeton* species usually survived field applications using fluridone rates of less than 10 µg L^{-1} (Smith and Pullman 1997), the sensitivity of many species, including whitestem pondweed, is unknown.

Phytoene levels of sago pondweed (*Stukenia pectinatus*) were 228.9 µg g FW^{-1} in the West Central Basin and 74.5 µg g FW^{-1} in the North Bay at 86 DAT. Phytoene levels in untreated sago pondweed have been reported to range from 14.5 to 20 µg g FW^{-1} (Sprecher et al. 1998). Concentrations of β-carotene and chlorophyll observed in plant tissue in both the West Central Basin and the North Bay were similar to concentrations reported for untreated plants (Sprecher et al. 1998). Sago pondweed has been reported to have intermediate susceptibility to fluridone (Smith and Pullman 1997). In an outdoor mesocosm study, fluridone doses of 10 and 20 µg L^{-1} significantly reduced sago pondweed shoot biomass while 5µg L^{-1} did not affect shoot biomass 90 DAT (Netherland et al. 1997).

Wild celery exhibited elevated phytoene levels in samples collected at MIDNR ramp at 30 DAT as well as in samples collected in the North Bay at 86 DAT. Concentrations of β-carotene and chlorophyll for plants at the MIDNR ramp were similar to those observed in an outdoor mesocosm study in which wild celery was not adversely affected when subjected to a 30-day exposure of 5 µg L^{-1} fluridone (data not presented). In another outdoor mesocosm study, wild celery shoot biomass was not affected during a 90-day exposure of 5 µg L^{-1} fluridone, but decreased with doses of 10 and 20 µg L^{-1} fluridone (Netherland et al. 1997). These results are supported with phytoene, β-carotene and chlorophyll concentrations reported in Sprecher et al. (1998), where doses of 10 or 20 µg L^{-1} fluridone produced β-carotene concentrations below 8 µg g FW^{-1} and chlorophyll concentrations below 0.4 mg g FW^{-1}.

Phytoene levels for water stargrass varied in Houghton Lake throughout the fluridone treatment. Plant tissue phytoene ranged from 48.5 µg g FW^{-1} in the North Bay at 86 DAT to 155.4 µg g FW^{-1} in the East Central Basin at 56 DAT. In contrast, β-carotene concentrations were between 12.7 and 18.5 µg g FW^{-1}, while chlorophyll concentrations were between 0.5 and 0.6 µg g FW^{-1}. Water stargrass is reportedly tolerant to fluridone; this species survived more than 85% of all fluridone field applications in Michigan, including those with treatment rates above 15 µg L^{-1} (Smith and Pullman 1997). In a field study, water stargrass increased in frequency in all treatment lakes in Michigan when Eurasian watermilfoil was controlled after a fluridone application (Getsinger et al. 2001).

Elevated phytoene levels in all nontarget plants except water marigold indicated fluridone uptake during the Houghton Lake treatment. Continuous exposure to fluridone may have caused plant injury as evident by low β-carotene and chlorophyll concentrations in species such as coontail, elodea, and whitestem pondweed. Other species, including large leaf pondweed, curlyleaf pondweed, variable pondweed, Robbins pondweed, ribbon leaf pondweed, sago pondweed, and water stargrass, maintained relatively normal β-carotene and chlorophyll concentrations, and may not have been injured.

Overall assessment of the fluridone application

Aqueous fluridone levels measured in Houghton Lake reflected values typically associated with a low-dose, whole-lake applications targeted at a fluridone concentration of 6 μg L^{-1} with a follow-up booster application. Streamflow at the Evart station downstream from the lake (Figure 20) were near the long-term average during May–July, 2002 and then declined to near minimum flows during September through December. Under these conditions the residence time of fluridone in the lake was 53.3 days; sufficient for a highly successful fluridone treatment. In a wetter year, maintaining effective fluridone concentrations would have been much more difficult.

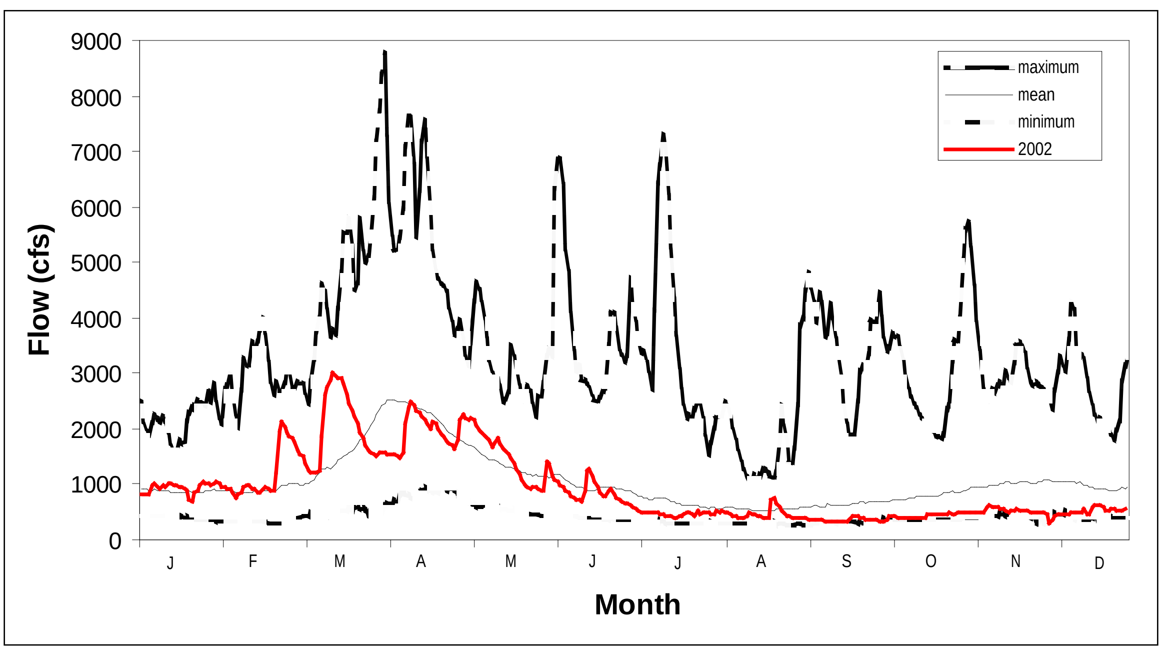


Figure 20. Flow of the Muskegon River during 2002, compared with the long-term maximum, mean, and minimum flows.

Post-treatment fluridone concentrations measured throughout the lake were relatively uniform, presumably due to the even application of herbicide produced by the computerized application system. Although fluridone is very slow acting relative to other herbicides, some early whole-lake applications in Michigan were sufficiently uneven that uniform control of Eurasian watermilfoil was not achieved (data not presented). Uneven applications are also likely to produce increased damage to non-target plants, at least in the areas where high concentrations of fluridone occur. Downstream fluridone levels dissipated in a manner that would be expected to provide minimal nontarget impacts.

Based on assessment of pigment concentrations, the target plant, Eurasian watermilfoil, was severely injured by the fluridone treatment, leading to widespread death of the plant in Houghton Lake. This outcome agrees well with predictions from pre-treatment testing, which indicated that the Eurasian watermilfoil in Houghton Lake was susceptible to low concentrations of fluridone. Nontarget plants in the lake typically susceptible to fluridone, including coontail and elodea, exhibited physiological responses to the treatment that indicate likely injury. Other nontarget species such as pondweeds and water stargrass exhibited responses typically associated with limited or no injury.

There was a high correlation between water residues analyzed by HPLC and ELISA methods. This comparison verifies that the ELISA technique is an accurate, real-time tool for measuring aqueous fluridone concentrations (Netherland et al. 2002). Comparison of the plant pigment data showed a wide range of Eurasian watermilfoil injury throughout Houghton Lake; however, trends in pigment concentrations were similar between ERDC and SePRO samples.

Post-fluridone treatment vegetation and water quality assessment: 2002–2004

Post-treatment monitoring evaluated the impact of the 2002 fluridone treatment on target and non-target vegetation, and on water quality in the lake. Vegetation evaluations were conducted in 2002, 2003, and 2004, and included point-intercept surveys, hydroacoustic transect surveys, satellite image analysis, line-intercept transects, and biomass sampling. Water quality sampling was conducted from May through September 2002, and included measurements of temperature, dissolved oxygen, pH, conductivity, photosynthetically active radiation (PAR), water column transparency, total nitrogen (TN), total phosphorus (TP), turbidity, total suspended solids (TSS), and chlorophyll.

Methods

Aquatic plant communities

Post-treatment evaluation of the Houghton Lake plant community used the same techniques used to collect pre-treatment data: (1) point-intercept surveys, (2) SAVEWS transects, and (3) satellite image analysis techniques. In addition, 10 "special interest" areas were selected for additional evaluation during the year of treatment (2002) and two years post-treatment (2004). SAVEWS surveys and line-intercept sampling were conducted along transects through these areas. In 2002, biomass samples were collected from three of these areas.

2002, 2003, and 2004 point-intercept grid surveys

The 2002 point-intercept vegetation survey was conducted on August 19 and 20, 2002, using the same sampling techniques and locations that had been used in 2001. This survey provided documentation of the lakewide impact of the 2002 treatment, and fulfilled one of the regulatory requirements specified by the MI-DEQ as a condition of the herbicide application permit. The survey was repeated at one year post-treatment, when it was conducted between August 4 and August 6, 2003, and two years post-treatment, conducted August 23 to 26, 2004.

SAVEWS permanent transect survey

SAVEWS surveys were conducted for six permanent transects in July 2001 and again on July 25, 2002; July 25, 2003; and August 25, 2004. The 2004 survey was delayed until August, to better coincide with the point-intercept survey of the lake. Detailed methods for conducting these surveys are provided above. Acoustic sampling of these areas was designed to document changes in plant height, biovolume, and cover along the transect lines. Means of these three parameters were compared ($p = 0.05$) using Analysis of Variance (ANOVA) techniques for ranked data, based on Kruskal-Wallis techniques included in the Statistix software package.

Diver surveys

Diver surveys were conducted along eight areas of special interest, located along the acoustic transects described above. Special interest areas were selected by inspecting the 2001 pretreatment survey data and choosing 10 areas where healthy plant growth had been detected. Locations of the eight transects surveyed by divers are illustrated in Figure 21 (geographical coordinates for their beginning and ending points are provided in Appendix C). Seven of the eight transects (2, 4, 5, 6, 8, 9, and 10) were sampled again in August 2004. Transects were sampled by having a diver record plant species occurrences in each 1-m interval along the 100-m transect.

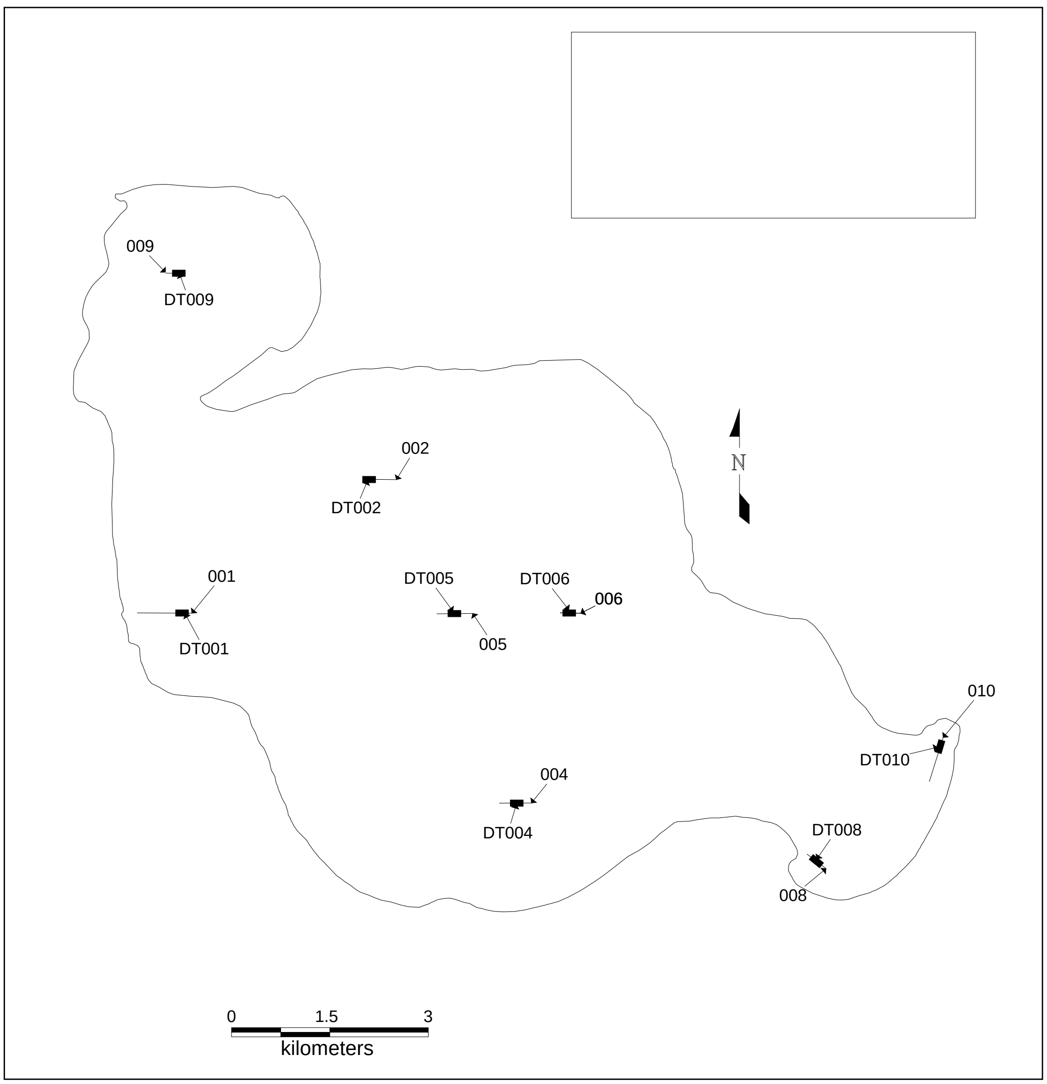


Figure 21. Locations of eight special areas where diver transects were surveyed during June and August 2002 to assess changes in frequency of occurrence of individual plant species resulting from the whole-lake fluridone treatment.

Resulting data sets were analyzed to evaluate changes in occurrences of individual plant species and changes in occurrences of different abundance classes for individual plant species. Statistical comparisons were based on Chi-square techniques for 2×2 tables included in the Statistix software package (Analytical Software, Tallahassee, Florida).

Plant biomass samples

Plant biomass samples were collected at three areas of special interest (Figure 22) during May, July, and August 2002. Site 1 was located in an intermediate depth area where elodea and other native species were abundant and mixed with sparse Eurasian watermilfoil. Site 2 was located in a shallow-water area and was dominated by Eurasian watermilfoil, with a sparse understory of elodea. Site 3 was located in a relatively deep area and was almost monotypic Eurasian watermilfoil during the May sampling. At each site and sampling trip, 14 plant biomass samples were collected by a diver by removing all shoot material and Eurasian watermilfoil roots originating from within a 0.1-m^2 sampling area outlined by a 2.5-cm PVC frame. Collected plant material was brought to the surface, rinsed, placed in a labeled plastic bag, stored on ice, and air-freighted overnight to the ERDC. At ERDC, samples were sorted for Eurasian watermilfoil shoots and roots, and elodea shoots. Shoots of other native species were grouped as a composite sample. All plant material was oven-dried at 70 °C to constant weight and weighed. Dried samples were weighed to the nearest 0.01 g.

Resulting data sets were analyzed to evaluate changes in dried weights for Eurasian watermilfoil shoots and roots, elodea shoots, combined native species shoots, and total vegetation. Means of these biomass parameters were compared ($p=0.05$) using ANOVA techniques of ranked data based on Kruskal-Wallis techniques included in the Statistix software package.

Analysis of satellite imagery

A satellite image was collected on September 30, 2002, in order to compare plant coverage with that determined from pre-treatment images. Although the image collection date did not overlap with the field sampling dates, the image collection date coincides with those from 2001 and 2002. The image was analyzed as described for the pre-treatment evaluation of satellite imagery.

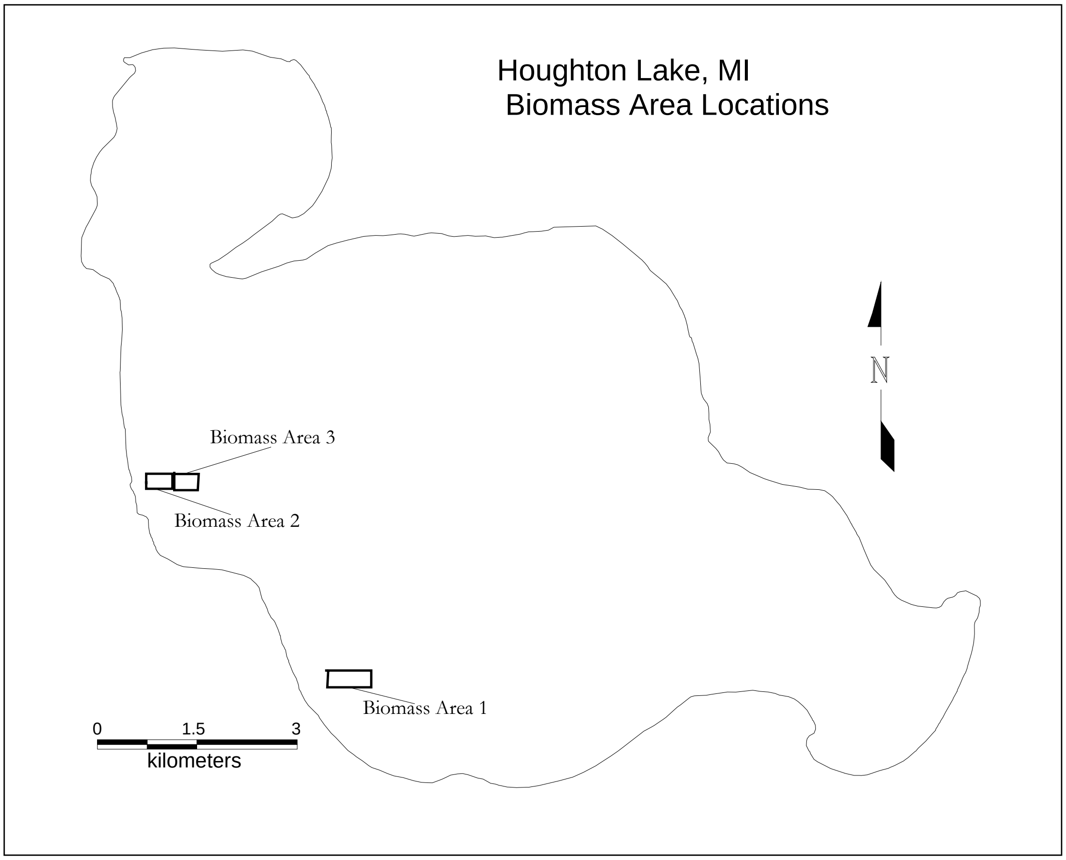


Figure 22. Locations of three special areas where plant biomass samples were collected by divers from Houghton Lake during May, July, and August, 2002 to assess changes resulting from the whole-lake fluridone treatment.

Water quality

Year of treatment water quality sampling began in early May, shortly before the whole-lake fluridone treatment, and continued at biweekly intervals during fluridone-induced plant dieback between June and September by field crews from the Michigan Water Research Center (MWRC), Central Michigan University (CMU), Mt. Pleasant, Michigan. Vertical profiles of temperature, dissolved oxygen, pH, and conductivity were measured using a Hydrolab Surveyor 3 calibrated against known buffer solutions and dissolved oxygen concentrations. Measurements of PAR were taken at 0.5-m intervals using a Licor PAR photometer. Water column transparency was measured using a 10-cm-diam, alternating black and white Secchi disk.

Water samples were collected at all stations near the lake surface and its bottom on each sampling date using a Van Dorn water sampler. All samples were placed in amber polypropylene bottles and kept on ice in a cooler during transit for analyses. With the exception of the sampling period in May, samples were sent to the ERDC Eau Galle Aquatic Ecology Laboratory, Spring Valley, Wisconsin, for analyses. Samples collected in May were analyzed by CMU Staff at the MWRC (described above). Total nitrogen and TP were analyzed after digestion with potassium persulfate on a Lachat QuikChem automated system (Lachat Methods 10-107-04-1-A and 10-115-01-0-A; Lachat Division, Milwaukee, Wisconsin). Turbidity was determined as nephalometric units (NTU). Bottom samples only were analyzed for TSS. Samples were filtered onto pre-weighed glass fiber filters (Gelman Metricel A/E), dried at 105 °C, and weighed to the nearest 0.1 mg (American Public Health Association (APHA) 1998). Linear relationships between turbidity and TSS were used to estimate TSS for surface samples. Samples for chlorophyll (a measure of algal biomass), corrected for phaeopigments, were filtered onto 0.45-µm mixed cellulose ester filters (Millipore MF membrane filter, 47 mm diam) and dissolved in 90-% acetone prior to spectrophotometric analysis. The Carlson Trophic State Index (Carlson 1977) and light extinction coefficient were calculated as described above.

Results and discussion

Impacts on the aquatic plant community

2002 point-intercept grid survey (year-of-treatment)

Results of the 2002 point-grid survey are shown in Table 20. In August 2002, muskgrass and water stargrass were the most abundant submersed plant species, occurring at 40.1 and 7.7% of the sample locations, respectively. All other species collected, including Eurasian watermilfoil, were found at less than 5% of survey sites. Two previously collected species were not found in 2002 (water marigold and curly-leaved pondweed). In both cases, the species were present at low abundance before treatment, and post-treatment surveys could easily have missed them.

Eurasian watermilfoil coverage was dramatically reduced in 2002 following treatment. Figure 23 shows the 2002 Eurasian watermilfoil survey results. Eurasian watermilfoil occurrences declined by 91% from 2001 to 2002 (490 occurrences in 2001 versus 45 occurrences in 2002). All but one of the 2002 occurrences were rated as rare (less than 3-% cover). From 2001 to 2002, the cumulative cover of Eurasian watermilfoil declined by more than 99%, from 16.9% in 2001 to 0.06% in 2002 (Table 20).

Table 20. Submersed aquatic plants found during point-grid survey of Houghton Lake, Michigan conducted August 20–21, 2002. For each species, the number of sites where the plant was found at particular densities is noted: D = dense (>60% cover), C = common (20–60%), B = sparse (3–20%), and A = rare (<3% cover).

Name	Rare (A)	Sparse (B)	Common (C)	Dense (D)	Total	% of Survey Sites	Cumulative Cover %
Muskgrass	127	152	62	25	366	40.1	6.72
Water stargrass	29	14	23	4	70	7.7	1.54
Eurasian watermilfoil	44	1			45	4.9	0.06
Variable pondweed	27	16	1		44	4.8	0.25
Wild celery	22	10	3		35	3.8	0.27
Coontail	19	12	1		32	3.5	0.20
Nitella	9	11	4		24	2.6	0.31
Largeleaf pondweed	13	4	1		18	2.0	0.10
Elodea	15	2			17	1.9	0.04
Whitestem pondweed	13	3			16	1.8	0.05
Thinleaf pondweed	11	3	1		15	1.6	0.09
Naiad	8	2			10	1.1	0.03
Richardson's pondweed	5	4			9	1.0	0.05
Flatstem pondweed	7				7	0.8	0.01
Robbins pondweed	3	1	1	1	6	0.7	0.15
White water crowfoot	1	1	1		3	0.3	0.06
Bladderwort	1	1			2	0.2	0.01
Floating leaf pondweed	1	1			2	0.2	0.01
Illinois pondweed	1	1			2	0.2	0.01
Northern watermilfoil	1	1			2	0.2	0.01
Water marigold					0	0	
% Cover							**9.6**
% Native Cover							**9.6**

Overall, submersed vegetation was found at 680 (or 74.6%) of the 912 survey sites, compared with 705 (77.3%) vegetated points in 2001. This indicates only a 3.6-% reduction in vegetated points from 2001, despite the dramatic reduction of Eurasian watermilfoil in the lake.

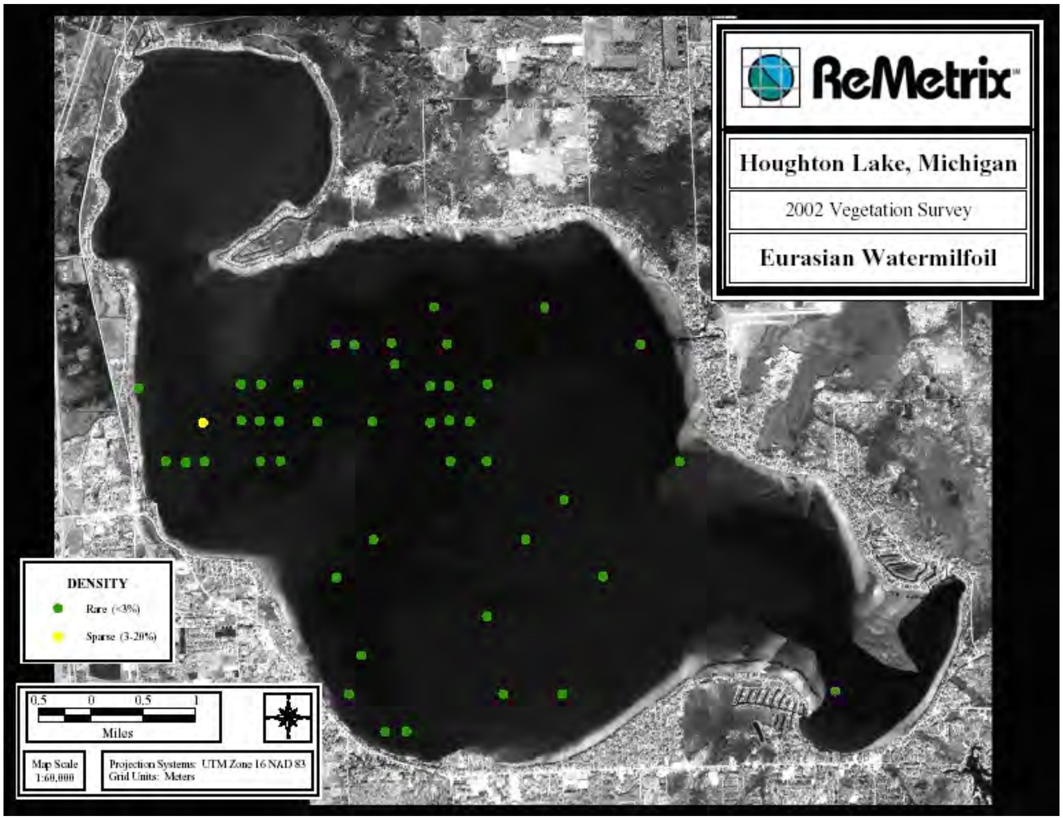


Figure 23. Locations of Eurasian watermilfoil, from the 2002 point-grid survey.

It also meets the critical resource preservation goal of maintaining vegetation covering at least 70% of the lake. Each sample point represents roughly 9 ha of the lake (at the 300-m grid spacing). Thus, the above results suggest that the total vegetated area of the lake in August of 2002 (i.e., area with any amount of aquatic plant growth) was 6,050 ha as compared with 6,273 ha in 2001. Appendix B includes distribution maps for all species encountered, as well as maps of the overall vegetation presence and a species diversity map that notes the number of different species collected and identified at each survey site.

Although there was little change in the overall vegetated area, cumulative plant cover declined from 30.6% to 10.0% (Table 20). Much of this decline resulted from the removal of Eurasian watermilfoil, which accounted for almost 17% of the cumulative cover in 2001. Much of the remaining decrease in cover resulted from reductions in elodea, naiad, whitestem pondweed, Richardson's pondweed, and thin-leaved pondweed. Declines in these species were offset somewhat by increases in muskgrass, variable pondweed, water stargrass, bladderwort and white water crowfoot.

2003 point-intercept grid survey (1-year post-treatment)

Muskgrass was the most frequently encountered plant in 2003, present at 38.3% of sample sites (Table 21). The next five most abundant species were pondweeds (*Potamogeton* spp.). Flat-stemmed pondweed, curlyleaf pondweed, largeleaf pondweed, and thinleaf pondweed increased in frequency from 2002 to 2003. Variable pondweed remained fairly consistent (6.0%) compared to past years. All other species were present at less than 2% of the total points sampled. In 2003, 513 points (56%) out of 912 total points sampled had submersed vegetation. By comparison, submersed vegetation was found at 680 points (74.6%) in 2002, and 705 points (77.3%) in 2001. This indicates a 24.6% reduction in vegetated points from 2002 and a 27.2 % decline from 2001.

Although there was a decline in the overall vegetated area, cumulative plant cover increased to 11.1% in 2003 (Table 21) from 10.0% in 2002. This increase resulted from the expansion of curlyleaf pondweed, which was not detected in 2002 but increased to a cumulative cover of 1.7% in 2003, as well as increases in the cover of flatstem, variable, largeleaf, and thinleaf pondweeds. Curlyleaf pondweed forms herbicide-resistant turions, which apparently survived the fluridone treatment and germinated in 2003. Rapid growth of this species in 2003 led to cumulative cover 5.7 times that present prior to the whole-lake fluridone treatment. Samples with curlyleaf pondweed rated dense were primarily concentrated in the south shore plant bed, with a few smaller populations along the eastern shore of the central basin (Figure 24). Cumulative cover of native species in 2003 was 9.4%, which is slightly less than the 10.0% measured in 2002 and well below pre-treatment native cover of 13.6% in 2001. Continued reductions in elodea, naiad, whitestem pondweed, and Richardson's pondweed kept native cover below that of 2001.

Eurasian watermilfoil was not detected at any of the sampling points in 2003. The 2003 survey also failed to detect elodea, coontail, water marigold, northern watermilfoil, white water crowfoot, and Illinois pondweed: six native plant species that had formerly been found in the lake. Wild rice, which was once abundant in the lake (Bonnette 1996) but had not been detected by the 2001 plant survey, reappeared in the lake during 2003 (Figure 25).

Table 21. Species of submersed plants found during 2003 GPS-point survey conducted August 4–6, 2003. For each species, the number of sites where the plant was found at particular densities is noted: D = dense (>60% cover), C = common (20–60%), B = sparse (3–20%), and A = rare (<3% cover).

Name	Rare (A)	Sparse (B)	Common (C)	Dense (D)	Total	% of Survey Sites	Cumulative Cover %
Muskgrass	122	133	61	33	349	38.3	7.16
Flatstem pondweed	71	46	2		119	13.0	0.67
Curlyleaf pondweed	31	16	14	10	71	12.2	6.84
Variable pondweed	20	22	11		53	5.8	0.75
Thinleaf pondweed	33	6	2		41	4.5	0.19
Largeleaf pondweed	12	8	2		22	2.4	0.19
Water stargrass	1	6	3		10	1.1	0.20
Wild celery	6	2			8	0.9	0.03
Robbins pondweed	4	2			6	0.7	0.03
Arrowhead	4	1			5	0.5	0.02
Naiad	2	1			3	0.3	0.01
Richardson's pondweed	3				3	0.3	0.00
Wild rice	1	1			2	0.3	0.18
Bladderwort	1				1	0.1	0.09
Bladderwort (mini)	1				1	0.1	0.09
Floating leaf pondweed	1				1	0.1	0.09
Nitella	1				1	0.1	0.09
Whitestem pondweed	1				1	0.1	0.09
White water crowfoot					0	0	
Coontail					0	0	
Elodea					0	0	
Eurasian watermilfoil					0	0	
Illinois pondweed					0	0	
Northern watermilfoil					0	0	
Water marigold					0	0	
% Cover							**16.3**
% Native Cover							**8.5**

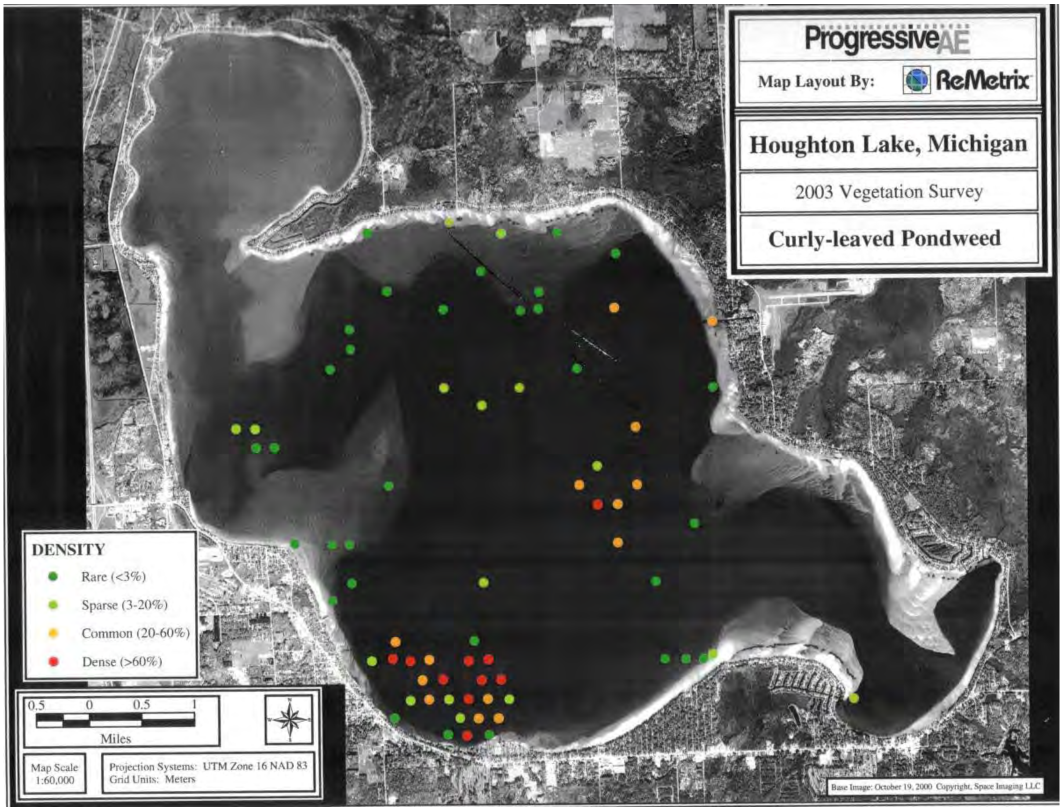


Figure 24. Locations of curlyleaf pondweed, from the 2003 point-grid survey.

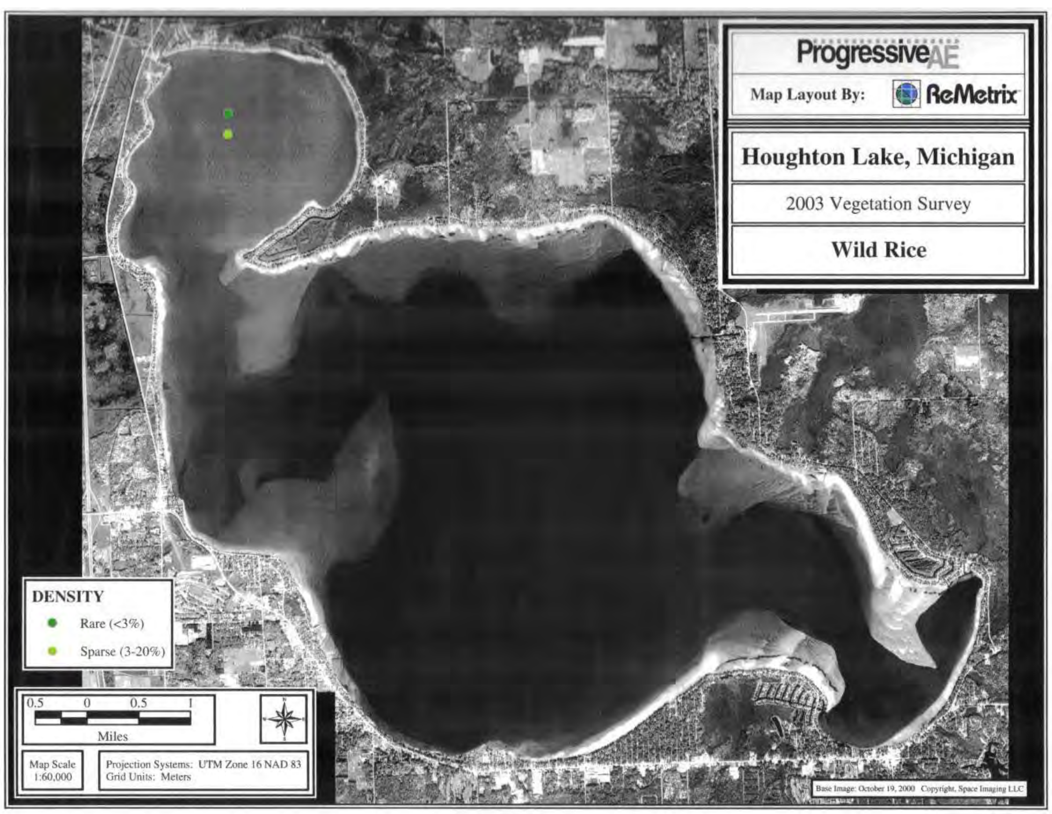


Figure 25. Locations where wild rice was found by the 2003 point-grid survey.

2004 point-intercept grid survey (2-years post-treatment)

In 2004, muskgrass remained the most frequently encountered plant, present at 37.4% of sample sites (Table 22) and having a cumulative cover of 7.6%. Elodea, which had been reduced below the detection threshold in 2003, had rebounded to become the second-most-abundant plant in 2004, present at 8.7% of survey sites. Naiad, variable pondweed, flat-stemmed pondweed, and thinleaf pondweed were only slightly less frequent than elodea.

Table 22. Species of submersed plants found during 2004 GPS-point survey conducted August 23–26, 2004. For each species, the number of sites where the plant was found at particular densities is noted: D = dense (>60% cover), C = common (20–60%), B = sparse (3–20%), and A = rare (<3% cover).

Name	Rare (A)	Sparse (B)	Common (C)	Dense (D)	Total	% of Survey Sites	Cumulative Cover %
Chara (muskgrass)	79	144	99	18	340	37.4%	7.6
Common Elodea	3	33	24	19	79	8.7%	3.1
Southern naiad	22	27	16	6	71	7.8%	1.6
Variable leaf	27	29	11	2	69	7.6%	1.0
Flat stem pondweed	11	18	18	10	57	6.3%	1.9
Thin leaf pondweed	20	20	8	7	55	6.1%	1.2
Curlyleaf pondweed [1]	6	20	11	4	41	4.5%	1.1
Whitestem pondweed	3	21	11	4	39	4.3%	1.1
Water stargrass		24	10	1	35	3.9%	0.8
Richardson's	6	12	12	4	34	3.7%	1.0
Large leaf pondweed	12	11	2	3	28	3.1%	0.5
Potamogeton pusillus	1	9	10	6	26	2.9%	1.1
Eurasian watermilfoil	7	12	2		21	2.3%	0.2
Wild Rice	8	7	3		18	2.0%	0.2
Water Marigold	7	6	2	2	17	1.9%	0.3
Illinois pondweed	2	5	4	3	14	1.5%	0.5
Slender naiad	1	4	2		7	0.8%	0.1
Wild celery	1	4	2		7	0.8%	0.1
Scirpus subterminalis	5	1			6	0.7%	0.0
Robbins' pondweed		3		2	5	0.6%	0.2
Potamogeton	1	2	1		4	0.4%	0.1
Bladderwort	2	1			3	0.3%	0.0
Bulrush				1	1	0.1%	0.1
Yellow waterlily		1			1	0.1%	0.0
% Cover							**23.8**
% Native Cover							**22.5**

Note: Plants identified in previous survey(s), but not identified in 2004: Broad leaf pondweed, *Sagittaria*, Floating leaf pondweed, *Nitella* (Stonewort), Coontail, White water crowfoot, Northern milfoil, and Buttercup.

[1] = non-native species.

Water marigold was found at 17 sites and Illinois pondweed at 14 sites, after not being detected in 2003. Curlyleaf pondweed, which had expanded its distribution in 2003, declined to only 4.5 of the sites in 2004, or only about one-third its frequency in 2003. For the first time since 2001, Eurasian watermilfoil was again found in the lake, occurring at 22 (2.3%) of the sample locations (Table 22). Twenty of the locations where Eurasian watermilfoil was detected were in the middle ground. The remaining location was near the location of the historic North Shore plant bed. Wild rice, which reappeared in the lake during 2003, increased to 18 sites (2.0%), 14 in the middle ground and 4 in the North bay (Figure 26). All other species were present at less than 2% of the total points sampled. In 2004, 423 points (47%) out of 908 total points sampled had submersed vegetation. By comparison, submersed vegetation was found at 513 points (56%) out of 912 total points in 2003, 680 points (74.6%) in 2002, and 705 points (77.3%) in 2001.

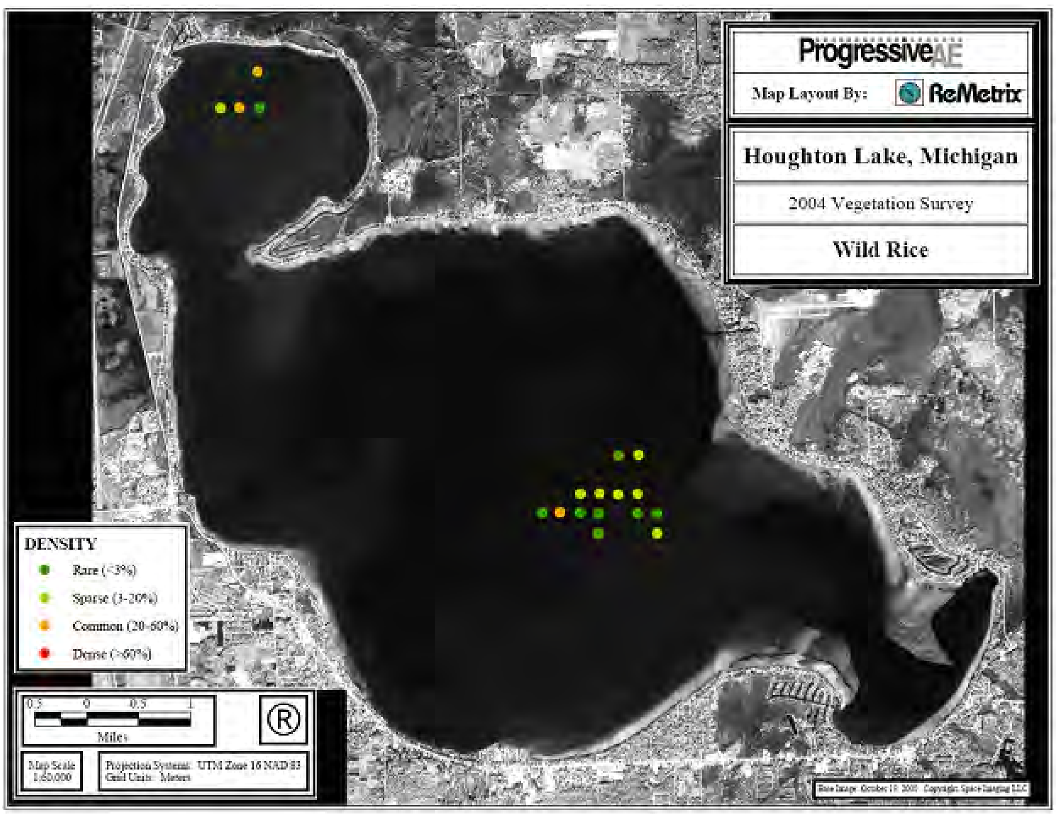


Figure 26. Locations where wild rice was found by the 2004 point-grid survey.

Cumulative plant cover, which increased from 10.0% in 2002 to 11.1% in 2003, increased further to 23.8% in 2004 (Table 22). Cumulative cover of native species, which had declined slightly from 2002 to 2003, increased from 9.4% in 2003 to 22.5% in 2004. The 2004 native plant cover of 22.5% exceeds the pre-treatment native plant cover of 13.6% measured in 2001. The increase of native plant cover between 2003 and 2004 was driven by the expansion of a number of species. Elodea was not detected in 2003 but increased to a cumulative cover of 3.1% in 2004. Naiad increased from 0.01% cover in 2003 to 1.6% in 2004. Richardson's pondweed, thin-leaved pondweed, whitestem pondweed, water marigold, Illinois pondweed, water stargrass, flatstem pondweed, and largeleaf pondweed also increased in cover from 2003 to 2004. Wild rice, which reappeared in the lake during 2003, increased from 0.01 to 0.2% cover. Eurasian watermilfoil, not detected in 2003, increased to 0.2% cover in 2004. The only plant species that declined substantially in cover from 2003 to 2004 was curlyleaf pondweed. The 2004 survey failed to detect coontail, northern watermilfoil, and white water crowfoot, three native plant species that had been found in the lake prior to treatment.

SAVEWS surveys of permanent transects

Figures 27 and 28 illustrate the results of hydroacoustic measurements of biocover and biovolume of submersed vegetation along the six lake-wide transects. Table 23 summarizes biocover and biovolume readings from 2001–2004 including corrected total average for each survey based on transect length. Plant cover ("biocover") and plant volume ("biovolume") measured along all of the acoustic transect decreased markedly from 2001 (pre-treatment) through 2002 (following fluridone treatment) and 2003 (one year post treatment) before increasing in 2004. Initially, all transects except transect 1 had biocover of 36 to 46%. Transect 1 had lower initial biocover and biovolume, though by 2003 it fell within the range represented by other transects. In 2002, biocover for these transects had declined to 11–24%. There was a further reduction to 0.1 to 14% in 2003. For all six transects, biocover declined 56% from 2001 to 2002 and an additional 67% reduction occurred from 2002 to 2003. Biovolume results for this period were similar. Except for transect 1, biovolume along the transects initially ranged from 14 to 23%. By 2002, biovolume along these transects had declined to 3–7%. By 2003, it was only 0–3%. For all six transects, average biovolume was reduced by 76% from 2001 to 2002, and by a further 79% from 2002 to 2003.

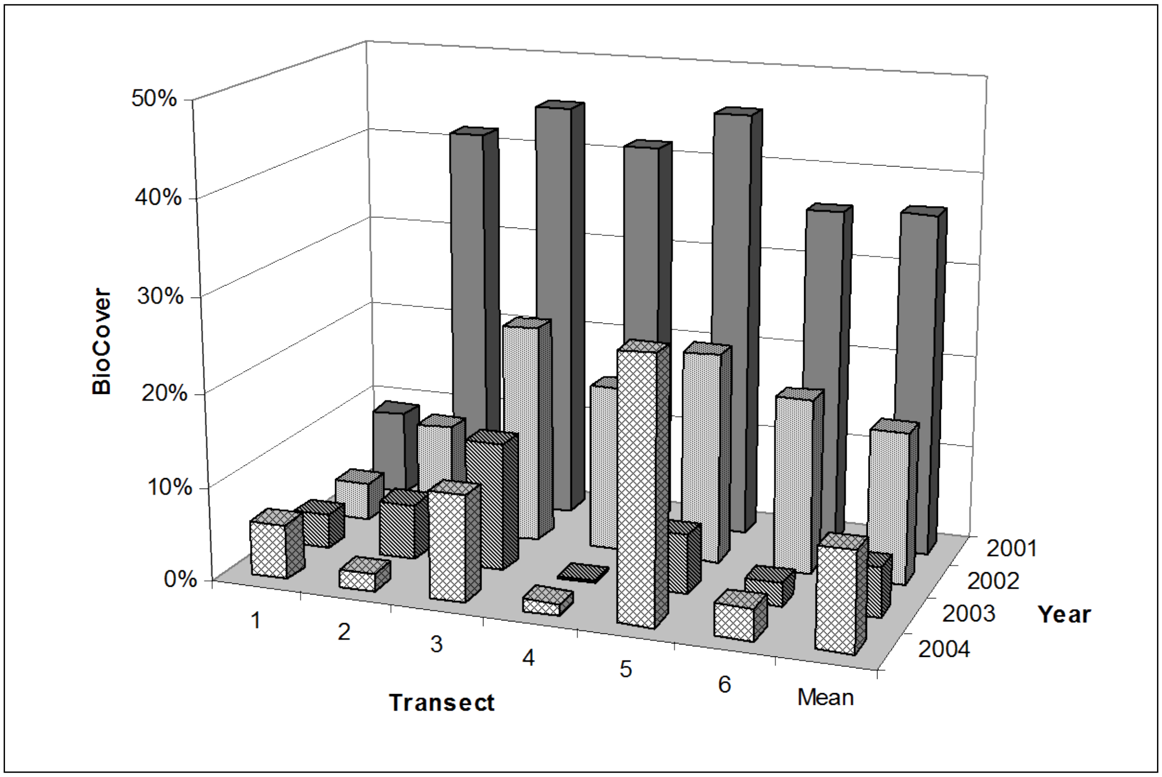


Figure 27. Biocover along the six permanent transects, 2001 through 2004.

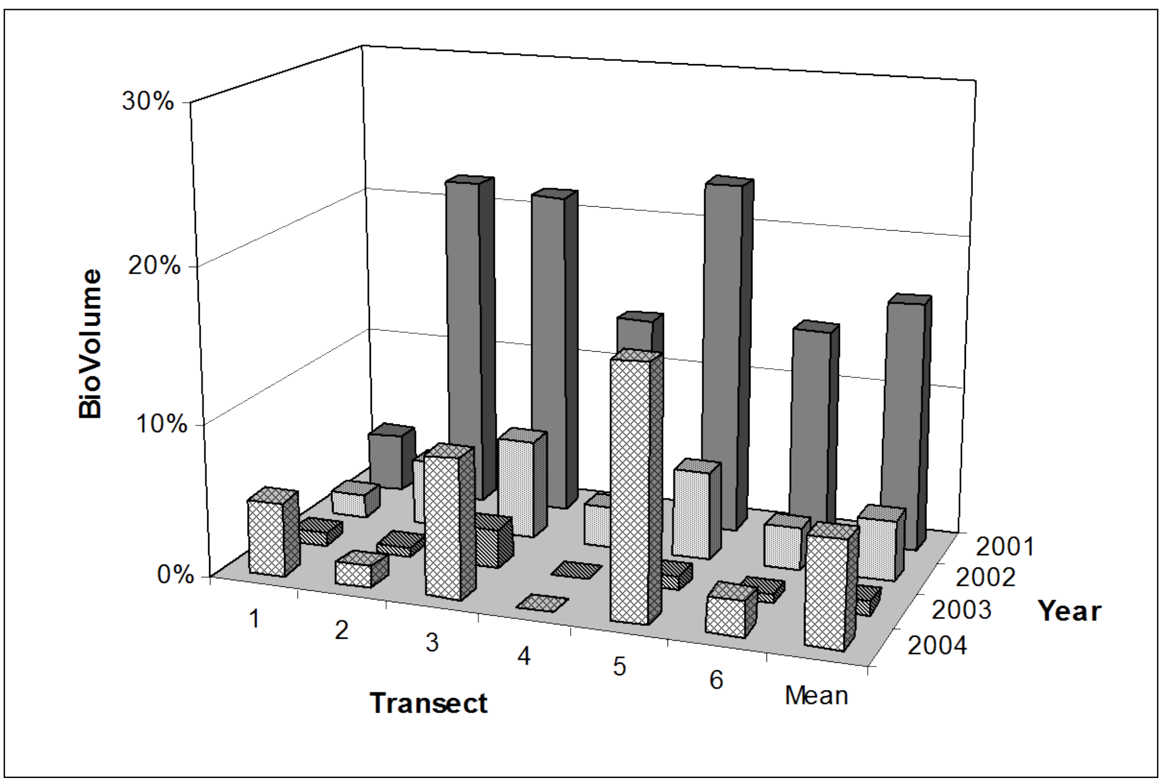


Figure 28. Biovolume along the six permanent transects, 2001 through 2004.

Table 23. Transect averages for biocover (the bottom coverage) and biovolume (the portion of water column occupied by plants) of vegetation determined from hydroacoustic assessment of Houghton Lake, Michigan, 2001–2004. Transect length analyzed is also provided and used to weight total average by length of individual transects.

Transect ID	BioCover				BioVolume				Transect Length (m)
	2001	2002	2003	2004	2001	2002	2003	2004	
1	9.1%	4.1%	3.7%	5.9%	3.8%	1.5%	0.9%	4.8%	2,898
2	41.6%	11.5%	6.0%	1.9%	21.9%	4.4%	0.6%	1.4%	8,417
3	45.2%	23.4%	13.7%	11.4%	21.4%	6.5%	2.5%	9.0%	8,117
4	41.6%	17.8%	0.1%	1.2%	13.6%	2.7%	0%	0%	8,924
5	45.7%	22.5%	6.3%	27.9%	23.1%	5.8%	0.9%	16.2%	5,494
6	36.1%	18.6%	2.4%	3.4%	14.0%	2.8%	0.5%	2.3%	4,190
Total Average	**39.9%**	**17.3%**	**5.7%**	**8.0%**	**17.8%**	**4.3%**	**0.9%**	**5.2%**	

From 2003 to 2004, biocover and biovolume increased along most of the permanent hydroacoustic transects. Only biocover on transect 2 and biovolume on transect 4 failed to exhibit a measurable increase from 2003 to 2004. Transect 2, which was very sparsely vegetated in 2003 (biocover of 6 % and biovolume of 0.6 %), exhibited a slight increase in biovolume from 2003 to 2004, but biocover along this transect fell from 6 to 2%. Transect 4, which was very sparsely vegetated by 2003 (biocover of 0.1 % and biovolume of 0.0%), exhibited an increase in biocover from 2003 to 2004, but biovolume along this transect remained less than 0.1%. Ignoring these two transects, the remaining transects increased in biocover and biovolume, achieving ranges of 3 to 28% and 2 to 16%, respectively. For all six transects, average biocover increased by 40% from 2003 to 2004. Biovolume increased by 577% from 2003 to 2004.

Figure 29 illustrates the 2004 distribution of biocover along the six permanent transects. In 2004, the highest biocover and biovolume occurred along transects 3 and 5, which pass through historic weedbeds (see Figure 4). High biocover is primarily concentrated where transect 5 passes through the “South Shore” weedbed and where transect 3 passes through the “Middle Ground” weedbed, with lesser concentrations of cover along the western flank of the sandbar on transect 5 and where transect 1 passes through one of the historic “North Bay” weedbeds.

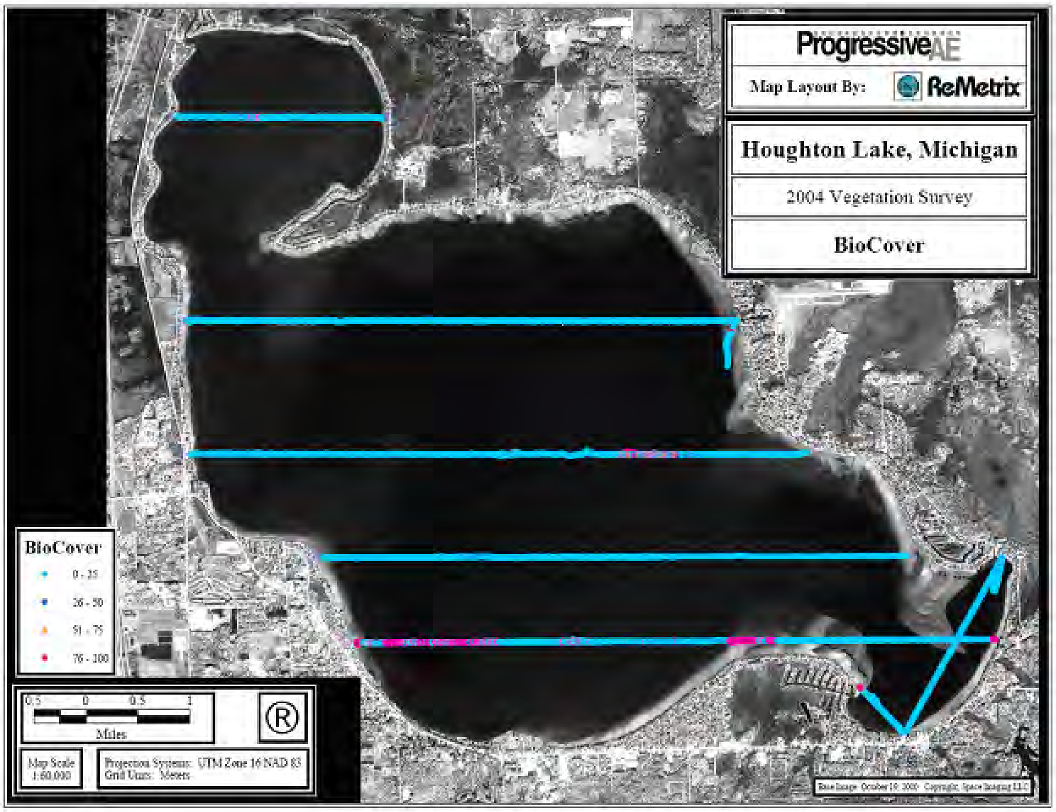
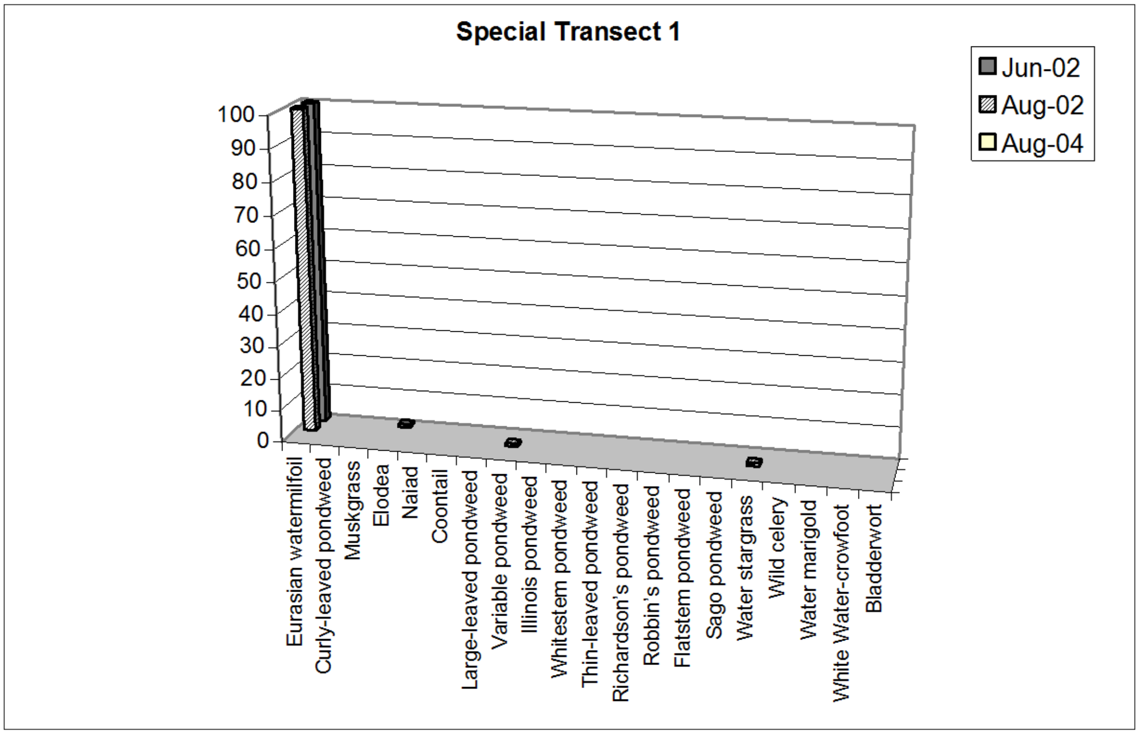


Figure 29. Map of biovolume measurements along the six permanent transects, 2004.

SCUBA diver surveys of areas of special interest

The eight diver transects represented areas of the lake having different initial (June 2002) plant communities (Figure 30) and differing in species richness (Table 24). Transects 1 and 8 had low diversity communities that were strongly dominated by Eurasian watermilfoil. Transects 2 and 5 had relatively diverse communities but were dominated by Eurasian watermilfoil. Transects 6 and 9 had diverse communities, where Eurasian watermilfoil shared dominance with native species. Transect 4 had a diverse plant community dominated by elodea with only a small amount of Eurasian watermilfoil. Transect 10 had diverse community of native plants with little Eurasian watermilfoil.

By August 2002, the impact of the fluridone treatment was just beginning to be evident. Eurasian watermilfoil was substantially reduced along five of the eight diver transects. The exceptions were transect 1, where Eurasian watermilfoil remained very abundant, transect 4, where its frequency declined only slightly, and transect 10, where it increased somewhat from a very low initial frequency. Other plant species exhibited variable responses, depending on their susceptibility to fluridone. Muskgrass and water stargrass increased along most transects.



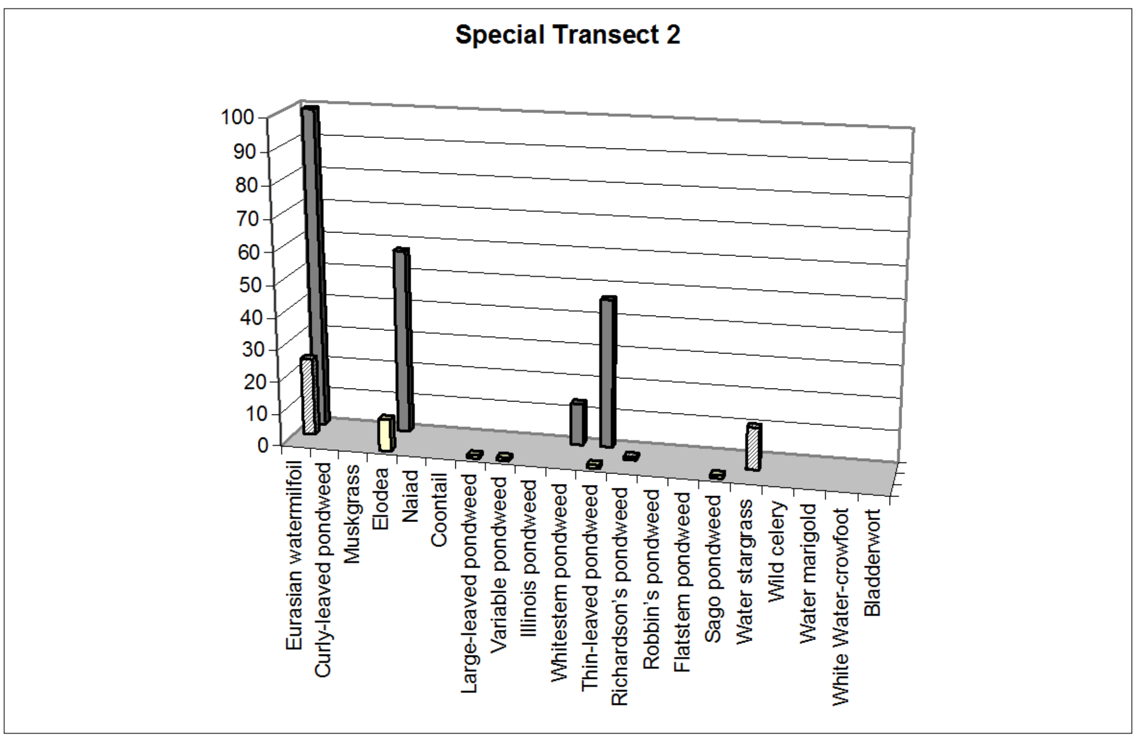
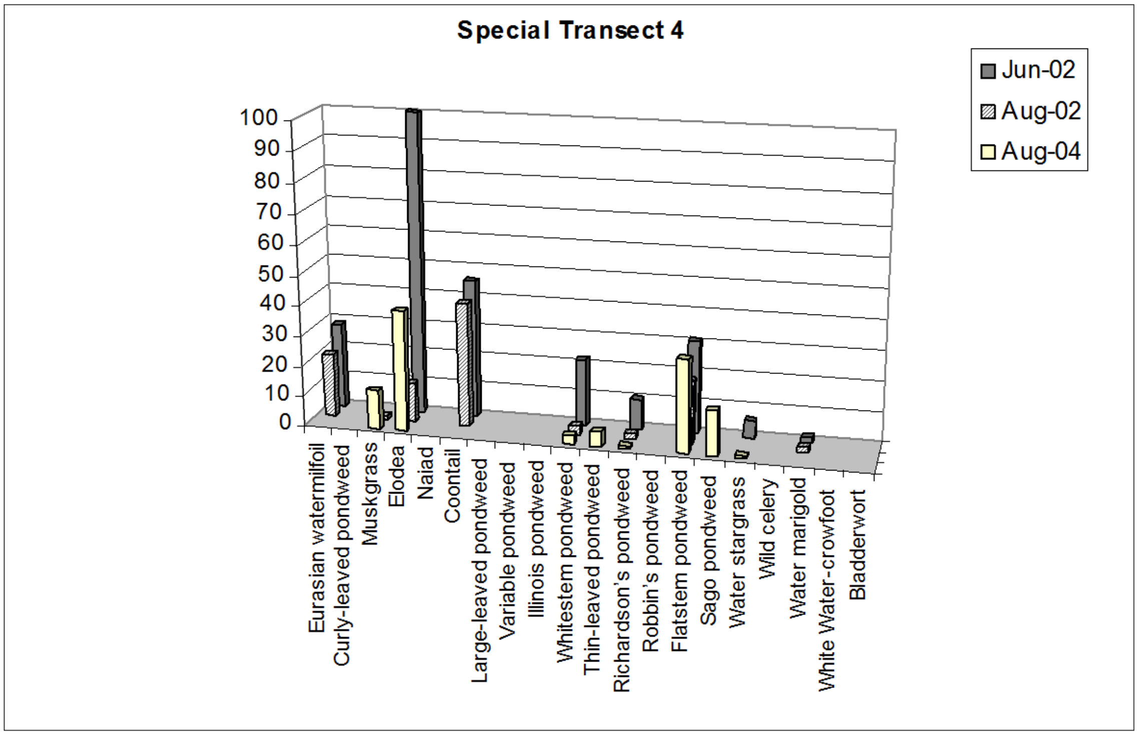


Figure 30. Frequency of the most abundant aquatic plant species along the eight diver transects, 2001 and 2004 (Sheet 1 of 4).



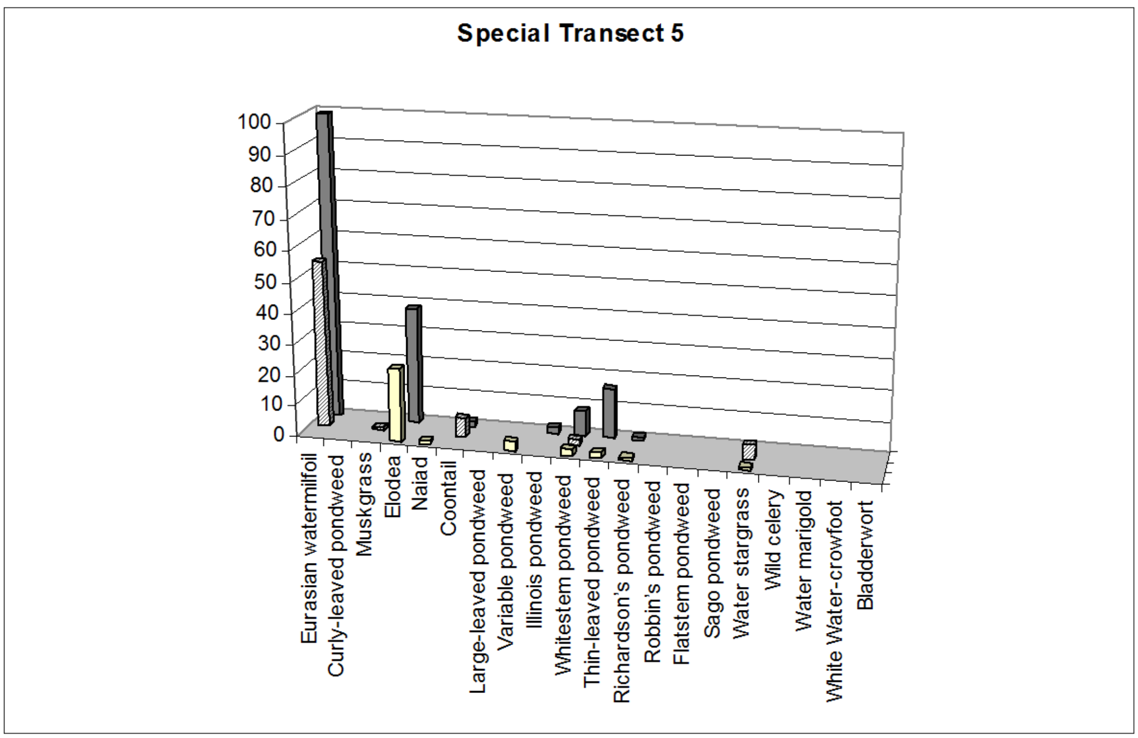
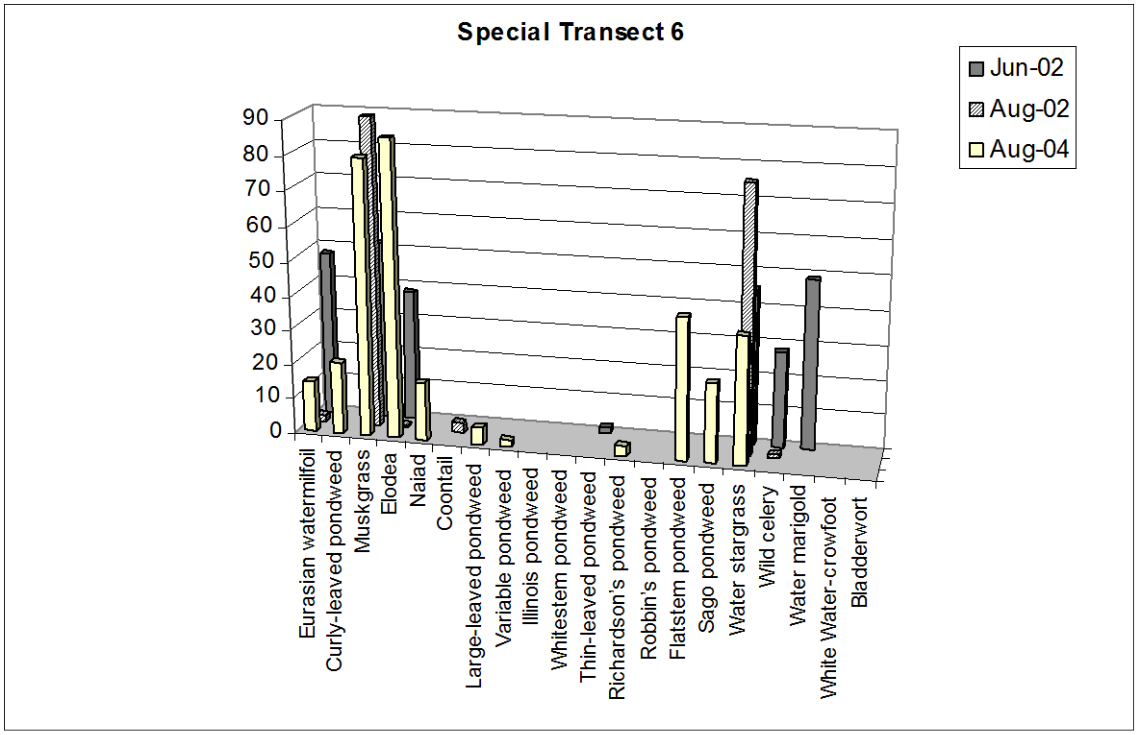


Figure 30. (Sheet 2 of 4).



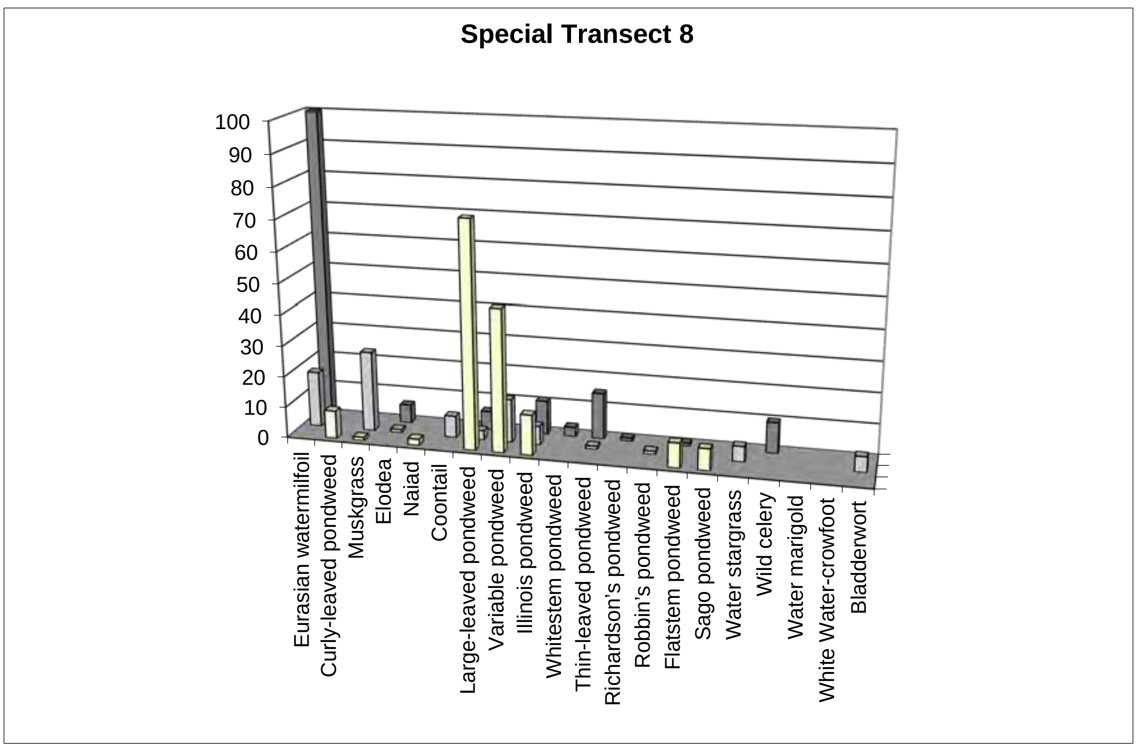
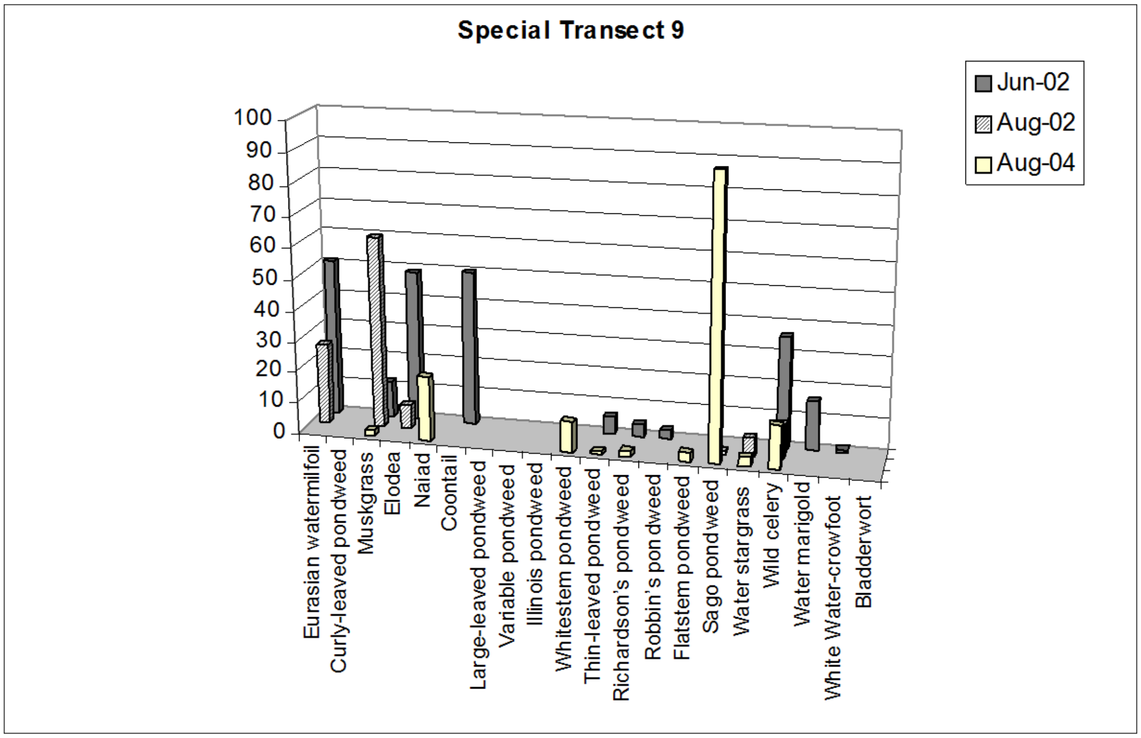


Figure 30. (Sheet 3 of 4).



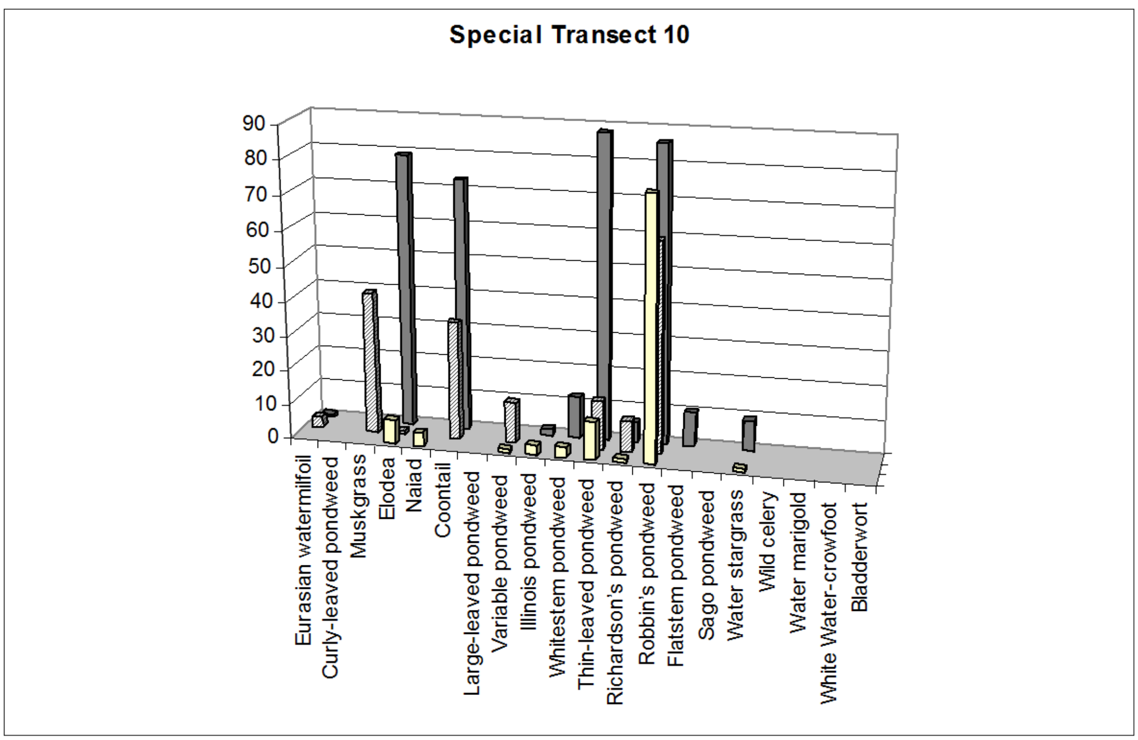


Figure 30. (Sheet 4 of 4).

Table 24. Mean species richness values of 1-m transect intervals during June and August 2002 surveys of the eight diver survey transects.

Transect No.	Mean Species per Interval		
	June 2002	August 2002	August 2004
1	1.01	1.02	NS
2	2.15	0.25	0.14
4	2.45	1.17	1.09
5	1.66	0.68	0.34
6	2.62	1.74	3.30
8	1.53	0.94	1.59
9	2.28	1.16	1.47
10	3.66	1.75	1.07

NS = not sampled.

Variable pondweed increased in frequency along the three transects (1, 8, and 10) where it occurred during 2002. Flatstem and Robbins pondweeds were infrequent, but showed little change following the treatment. Thin-leaved pondweed decreased along the transects where it was found. The frequency of elodea declined substantially everywhere it occurred. Water marigold was eliminated from two of the three transects where it occurred. Coontail initially declined along two of the transects, but unaffected or increased along four of them. The overall decrease in the abundance of most plant species was reflected by sizeable decreases in the average species richness per intercept on every transect except 1, which was dominated by Eurasian watermilfoil that had not yet declined in abundance by August 2002.

In 2004, two years after the fluridone treatment, Eurasian watermilfoil had disappeared from all diver transects except 6, which is located near the eastern end of the middle ground in the only area of the lake where Eurasian watermilfoil was detected by 2004 surveys. Other changes in the plant communities differed considerably from transect to transect. Transect 8, which had been strongly dominated by Eurasian watermilfoil in 2002, was dominated by a diverse collection of pondweeds in 2004. Transects 2 and 5, which had relatively diverse communities dominated by Eurasian watermilfoil in 2002, had communities with low species richness dominated by a little elodea with very small amounts of several pondweeds. In 2002, transects 6 and 9 had diverse communities where Eurasian watermilfoil shared dominance with native species. In 2004, transect 6 had a very species-rich community where dominance was shared by elodea, muskgrass, flatstem pondweed, water stargrass, and sago pondweed, with lesser amounts of several other species. Transect 9 had a moderately diverse community strongly dominated by sago pondweed with moderate amounts of naiad, wild celery, and whitestem pondweed and small amounts of several other species. Transect 10 was dominated by Robbins pondweed in 2002, and this species changed little in frequency along the transect from 2002 to 2004. Species richness along transect 10 declined substantially from 2002 to 2004 (Table 24), due to the loss of coontail, a substantial reduction in elodea, and reductions in water stargrass and several native pondweeds.

Plant biomass samples

Plant biomass data for May, July, and August 2002 are illustrated in Figures 31, 32, and 33, for sites 1 to 3, respectively. At all three sites, Eurasian watermilfoil shoot biomass was significantly reduced from May to August samples. Reductions in average biomass of Eurasian watermilfoil shoots over the 3-month period was 98.1% (site 1), 85.6% (site 2), and 94.4% (site 3). Elodea shoot biomass also showed significant reductions at all three sites over the 3-month period. Shoot biomass of native species other than elodea increased at sites 1 and 3 between May and August.

Plant cover and abundance estimates derived from SAVEWS hydroacoustic surveys indicate significant reductions in plant abundance following the whole-lake fluridone treatment. Plant cover estimates for permanent transects in July 2002 were 55.5% lower than pretreatment estimates from July 2001 surveys. Similarly, plant volume estimates for permanent transects were reduced by 75.5% between the July 2001 and July 2002 surveys. In special area transects, which assessed changes between June and August 2002, plant cover was reduced by 11.8% and plant volume was reduced by 53.3%.

Eurasian watermilfoil, the target of the whole-lake fluridone treatment, declined significantly in abundance from June to August 2002 at most sites surveyed. Significant reductions in the frequency of occurrence of Eurasian watermilfoil was detected along five of eight diver transects. In all, Eurasian watermilfoil occurrences were reduced from 526 transect intervals in June 2002 to 248 intervals in August 2002, equating to a 52.9% reduction in Eurasian watermilfoil occurrences. Dense Eurasian watermilfoil occurrences were essentially eliminated along all diver transects except transect 1. Eurasian watermilfoil biomass levels were also significantly reduced at the three sites where biomass samples were collected.

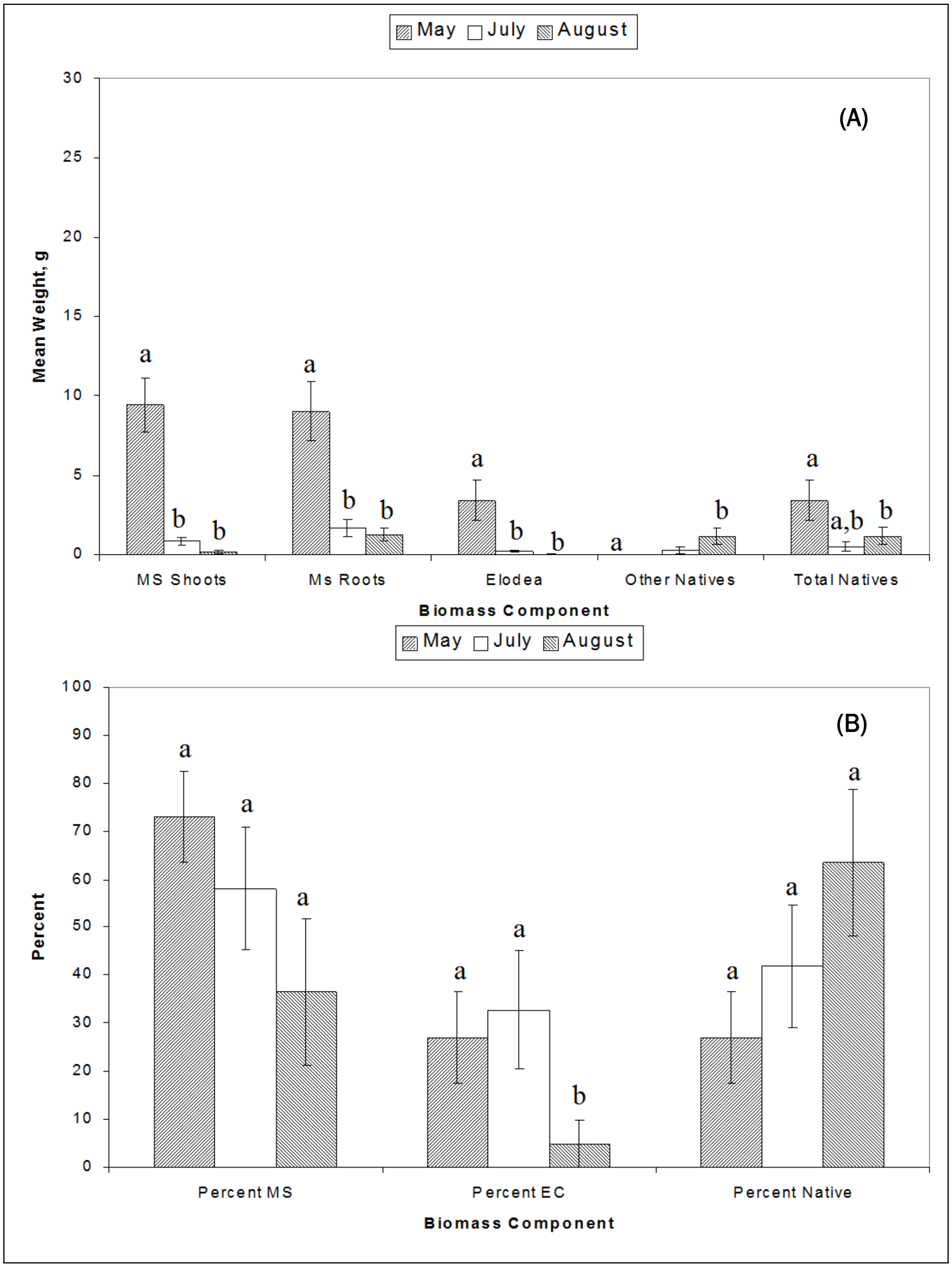


Figure 31. Site 1 biomass data: (A) Biomass estimates for Eurasian watermilfoil shoots and roots and elodea shoots, “other natives” shoots, and “total natives” shoots for May, July, and August 2002 samples. (B) Percent biomass estimates for Eurasian watermilfoil, elodea, and total natives for May, July and August 2002. For bars within the same grouping, significant differences (p = 0.05) are denoted by different letters.

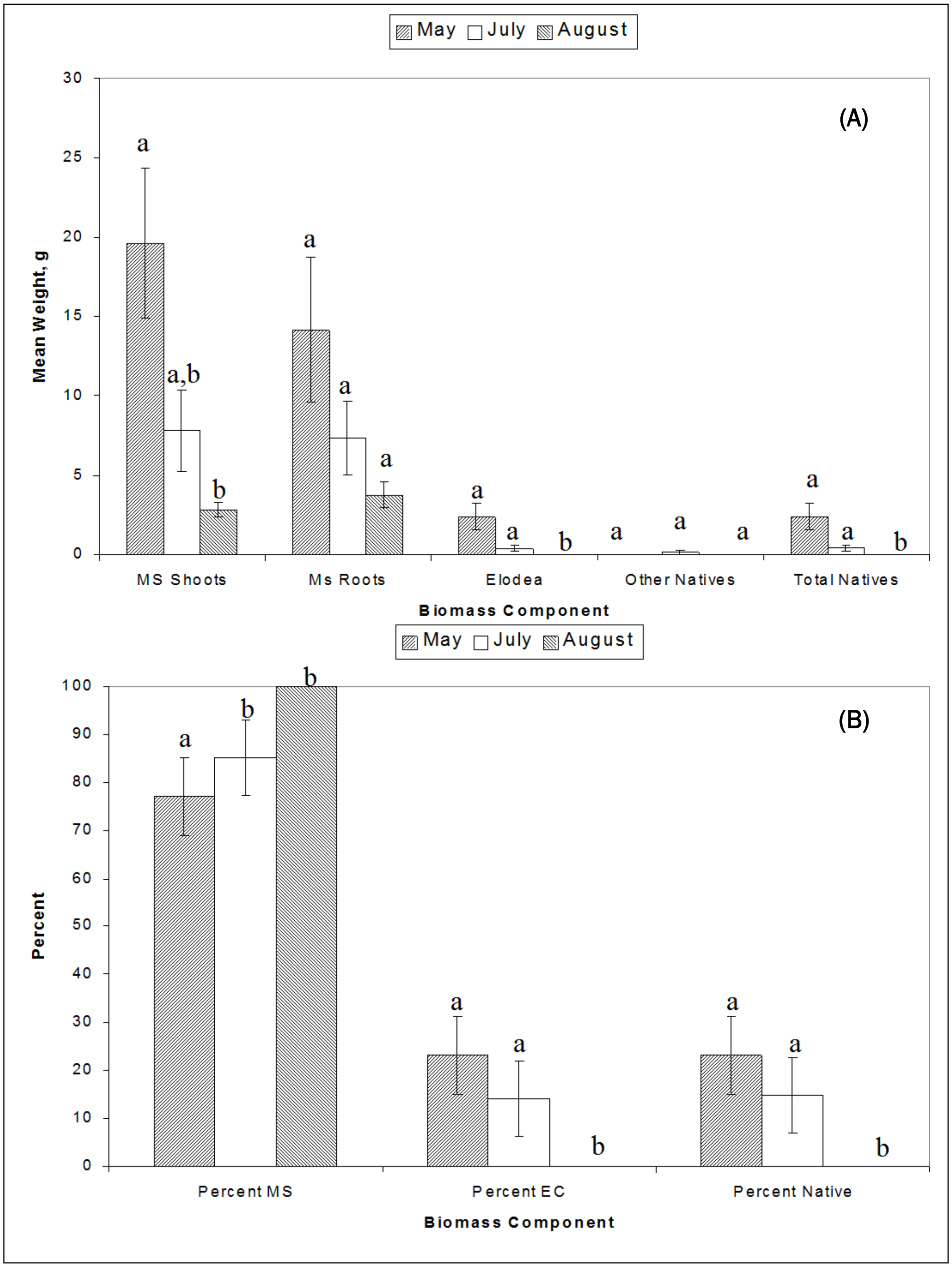


Figure 32. Site 2 biomass data: (A) Biomass estimates for Eurasian watermilfoil shoots and roots and elodea shoots, "other natives" shoots, and "total natives" shoots for May, July, and August 2002 samples. (B) Percent biomass estimates for Eurasian watermilfoil, elodea, and total natives for May, July, and August 2002. For bars within the same grouping, significant differences (p = 0.05) are denoted by different letters.

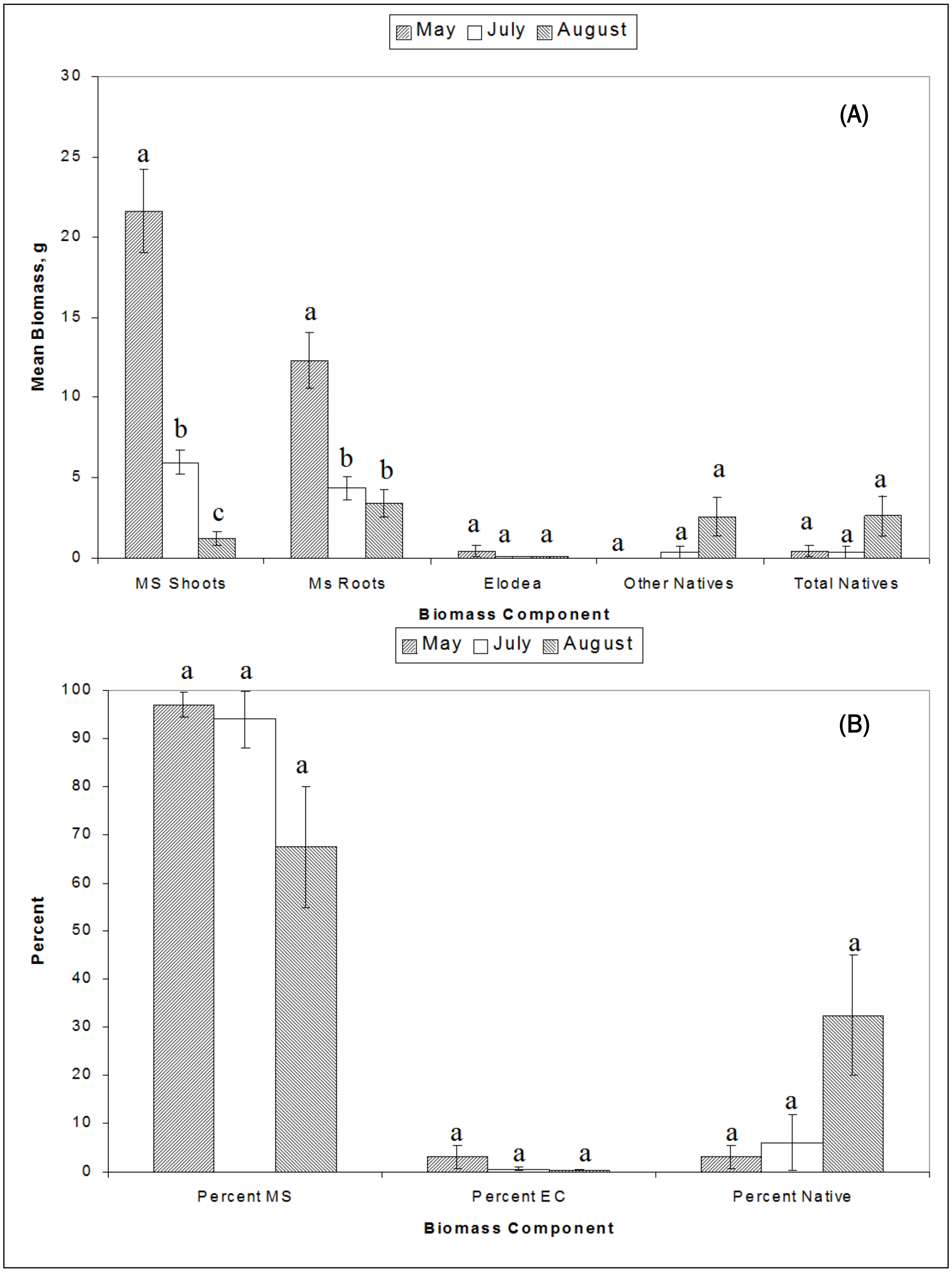


Figure 33. Site 3 biomass data: (A) Biomass estimates for Eurasion watermilfoil shoots and roots and elodea shoots, “other natives” shoots, and “total natives” shoots for May, July, and August 2002 samples. (B) Percent biomass estimates for Eurasion watermilfoil, elodea, and total natives for May, July, and August 2002. For bars within the same grouping, significant differences (p = 0.05) are denoted by different letters.

Elodea abundance was also significantly reduced at study sites between June and August 2002. Transect intervals with dense or common levels of elodea were eliminated from all transects, and only 24 sampling intervals (i.e., of the 800 sampled along the eight transects) contained sparse elodea in August 2002. Elodea biomass, which represented a relatively large portion of the total native biomass at two of three sites in June 2002, was near 0 g m^{-2} in August 2002.

In addition to observations of significant reductions to both Eurasian watermilfoil and elodea following the whole-lake fluridone treatment, several other native species were shown to experience noticeable reductions between the June and August surveys. These include water marigold, coontail, whitestem pondweed, thin-leaved pondweed, and wild celery. In contrast, muskgrass and water stargrass increased in frequency between the June and August surveys.

Satellite image analysis

The satellite image collected in 2002 is moderately hazy. The haze dulls the clarity of the image, but does not inhibit analysis of the image. Submersed features were visible to a depth of approximately 7 ft. However, below approximately 2.5 m in depth, features became vague, and different classes (e.g., sediment, vegetation, and deeper water) began to blend together. Therefore classification of the image was restricted to areas less than 5 ft deep.

The resulting classification identified 1,125 total ha (13.8% of the lake) of submersed vegetation in the 2002 satellite image. This represents a decrease of 160 ha of vegetation from 2001 to 2002. Two classes of submersed vegetation areas were identified from the image: classes 1 and 2. Class 1 covers 554 ha and Class 2 covers 571 ha. Class 1 pixels have spectral signatures characteristic of submersed vegetation, whereas class 2 pixels are near the spectral transition point between the vegetation and undifferentiated water. Thus, Class 2 may include some unvegetated pixels. Areas in the northwestern basin of the lake and along the shoreline are listed as various sediment/vegetation classes. These are feature classes that were distinguished in waters generally shallower than 5 ft, but that only have partial correlation with vegetation presence. In some parts of these areas, ground reference data indicate significant vegetation presence, and in other parts ground reference data indicate no vegetation presence (see the vegetation presence/absence map overlay on the classified image in Appendix D). For this reason, it made sense to treat these areas as combined sediment/vegetation classes and rely on the ground reference data to distinguish which areas have vegetation. It is relevant to note that the northwestern basin is one of the most hazy regions of the original image.

The satellite image analysis was cross-referenced with the point-grid results to determine which species occurred in the areas identified as aquatic vegetation on the image. Two species showed a high level of correlation: muskgrass and water stargrass. Figures 34 and 35 overlay these species on the classified satellite image. Note that the densest areas for each species correlate well with areas of vegetation identified from the satellite image.

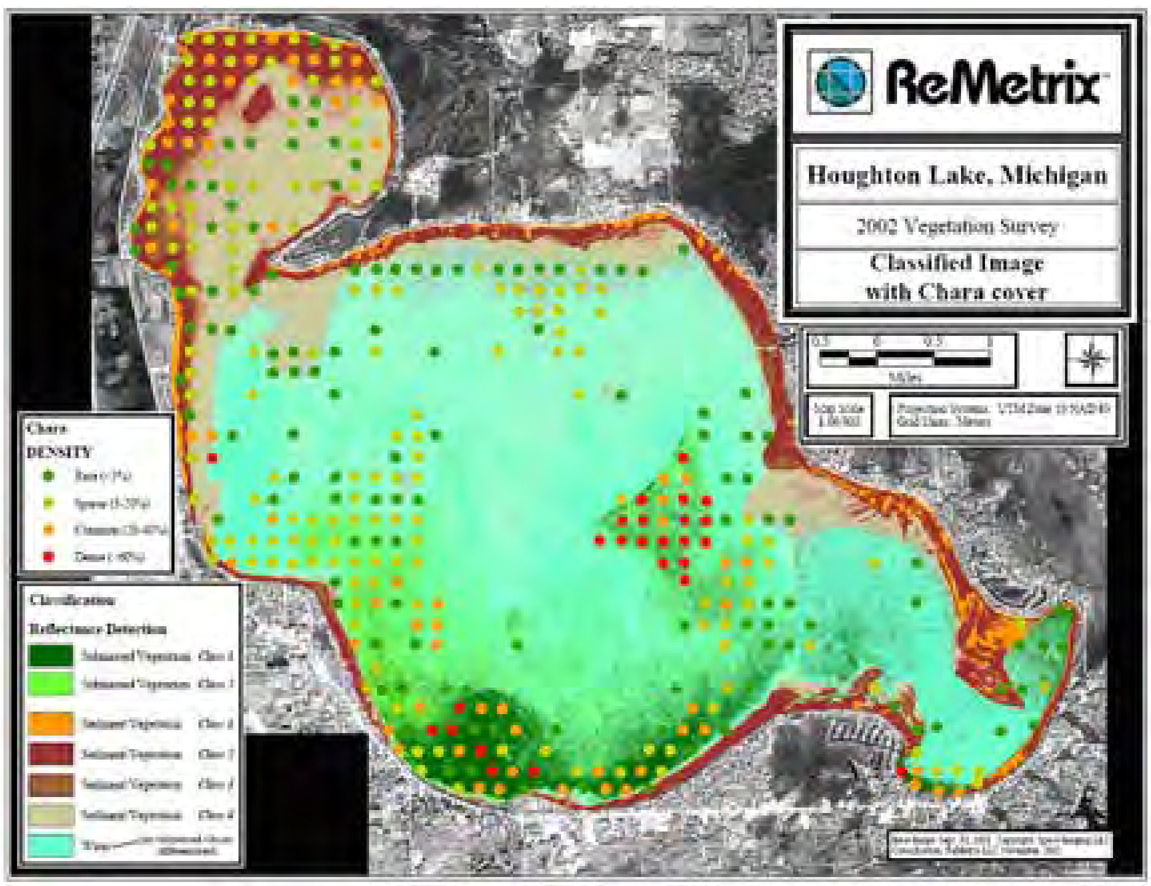


Figure 34. Distribution of muskgrass overlaid on the 2002 classified satellite image.

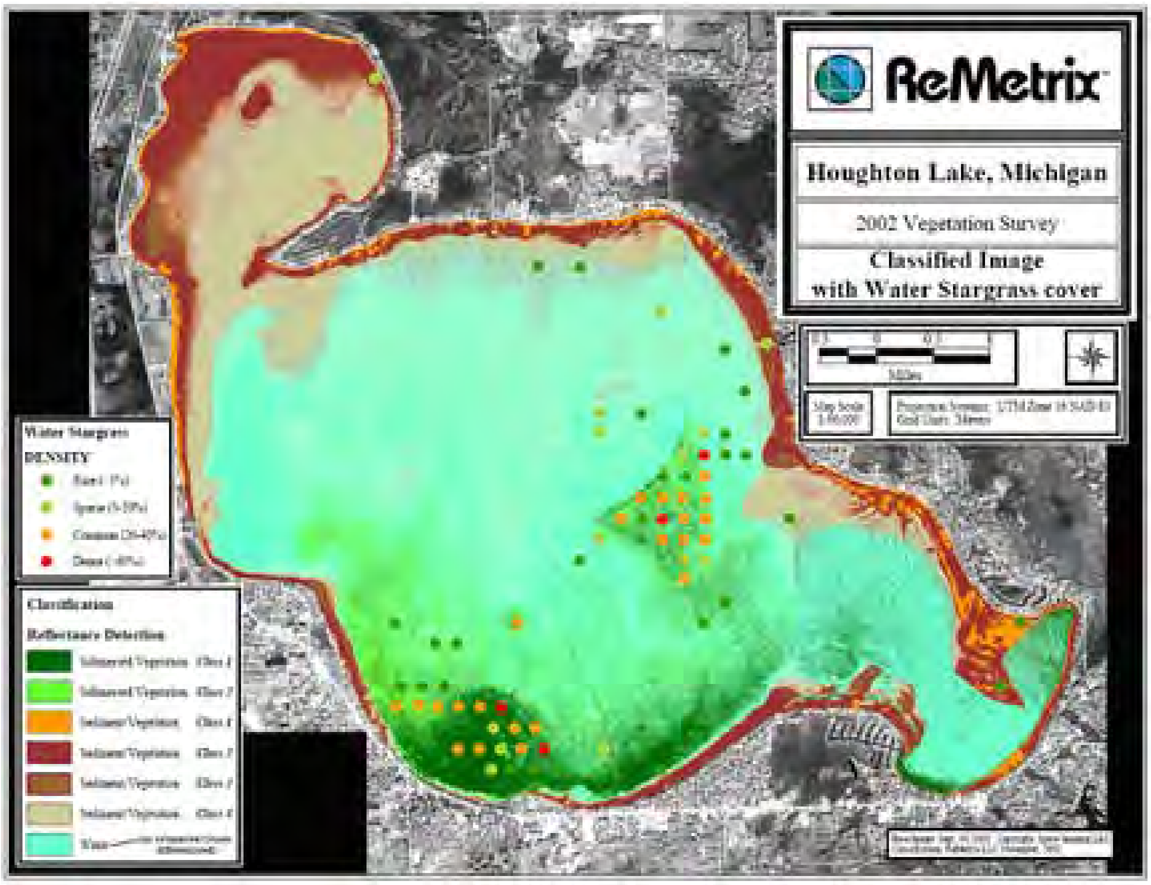


Figure 35. Distribution of water stargrass overlaid on the 2002 classified satellite image.

Water quality

Seasonal variations in water quality for the four areas (North Bay, South Bay, Main Open, and Main Vegetated areas) are illustrated in Figures 36 through 44. Statistics for the four areas and for individual stations are summarized in Tables 25 and 26. Whole-lake fluridone treatment occurred shortly after the 11 May 2002 water quality sampling date. Mean water temperature increased from near 10 °C in May to greater than 20 °C between June and August (Figure 36) in all areas. Temperatures declined in September as a result of autumnal cooling. Mean water temperature was homogeneous between the surface and bottom depths during most of the study period, indicating well-mixed conditions. Temporary stratification occurred at the South Bay, Main Open, and Main Vegetated areas in late June, as surface temperatures were greater than 1 °C than bottom temperatures.

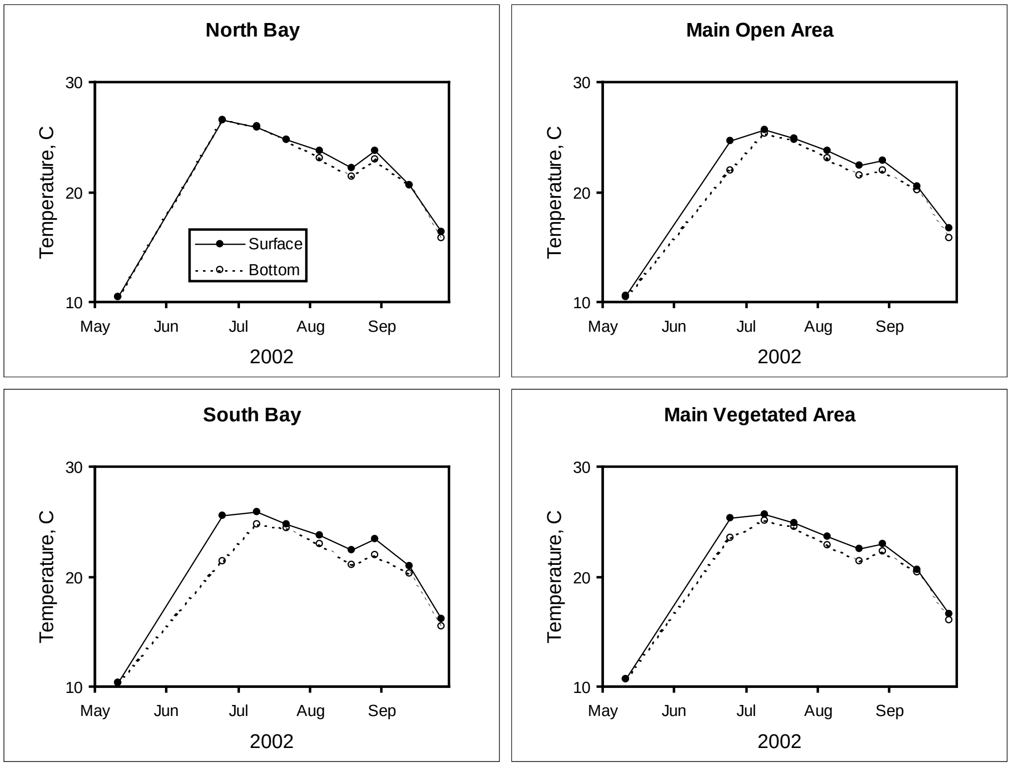


Figure 36. Seasonal variations in mean temperature at the surface and bottom depths of various areas in Houghton Lake.

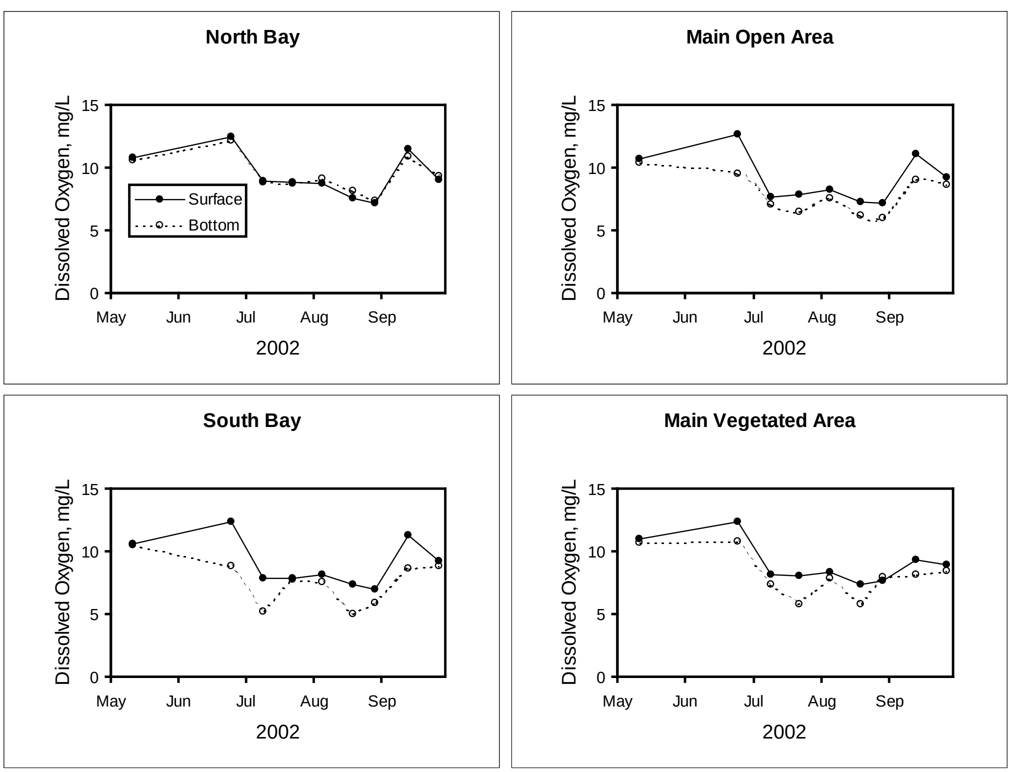


Figure 37. Seasonal variations in mean dissolved oxygen at the surface and bottom depths of various areas in Houghton Lake.

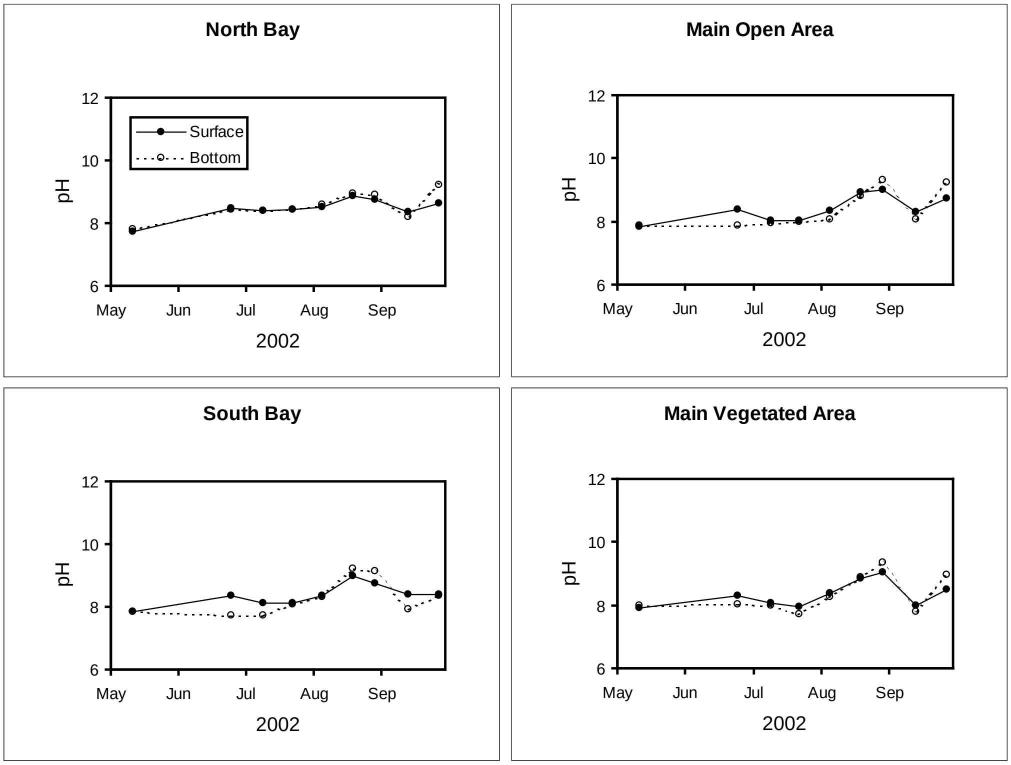


Figure 38. Seasonal variations in mean pH at the surface and bottom depths of various areas in Houghton Lake.

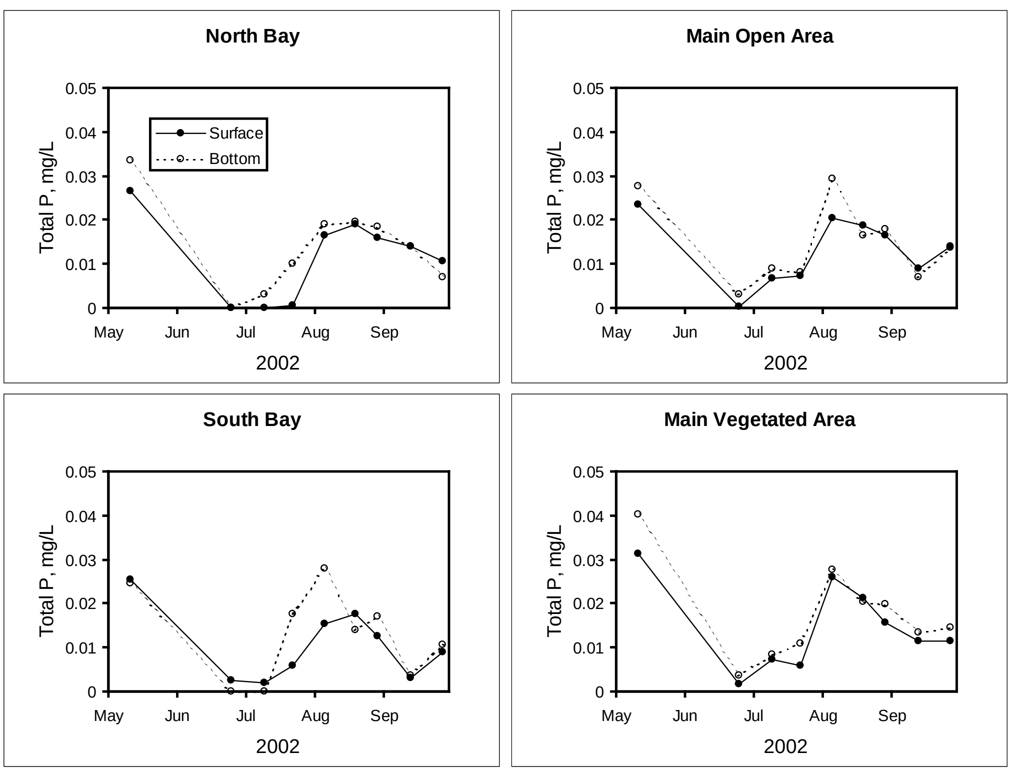


Figure 39. Seasonal variations in mean total phosphorus (P) at the surface and bottom depths of various areas in Houghton Lake.

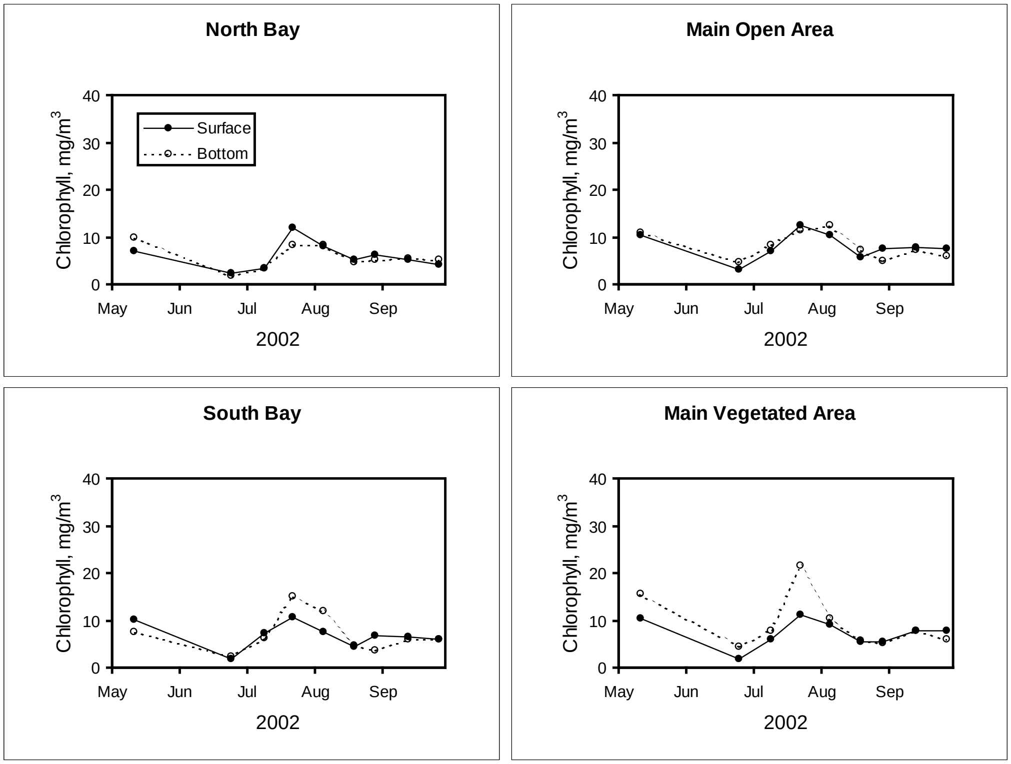


Figure 40. Seasonal variations in mean chlorophyll at the surface and bottom depths of various areas in Houghton Lake.

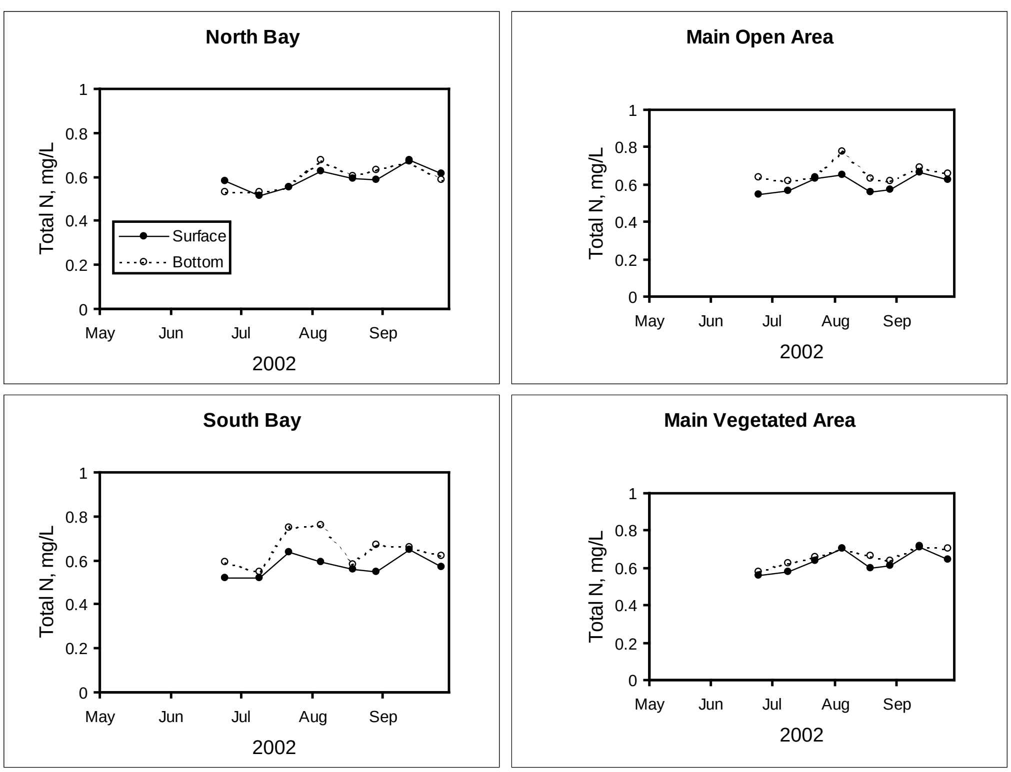


Figure 41. Seasonal variations in mean total nitrogen (N) at the surface and bottom depths of various areas in Houghton Lake. Data were not collected at the stations in May.

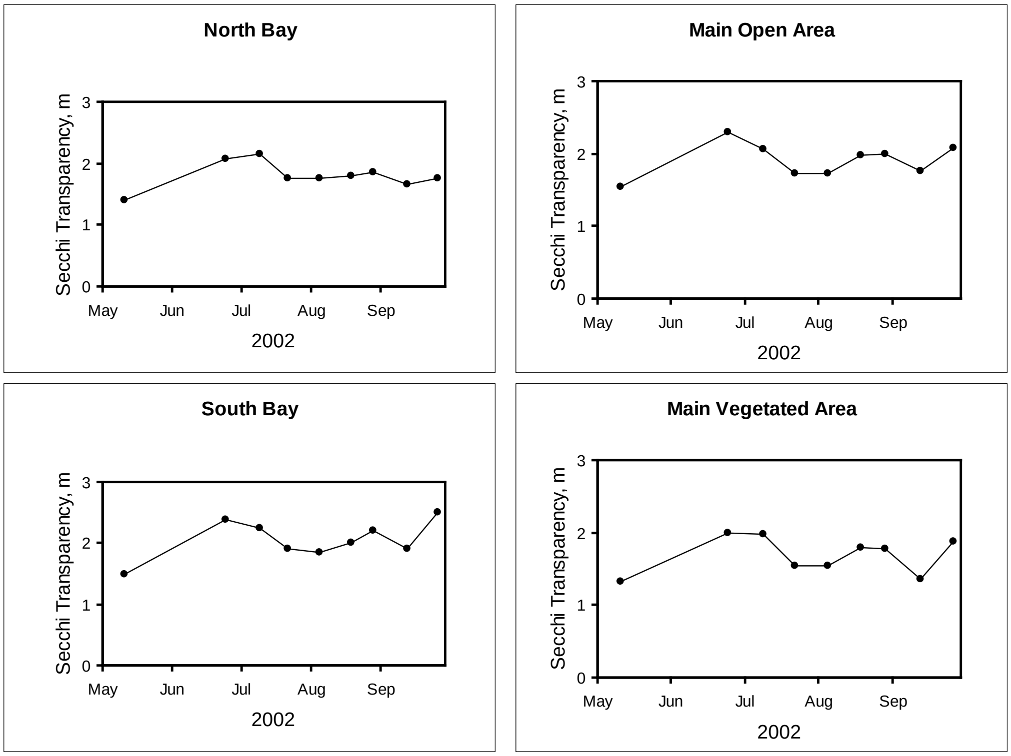


Figure 42. Seasonal variations in mean Secchi transparency at various areas in Houghton Lake.

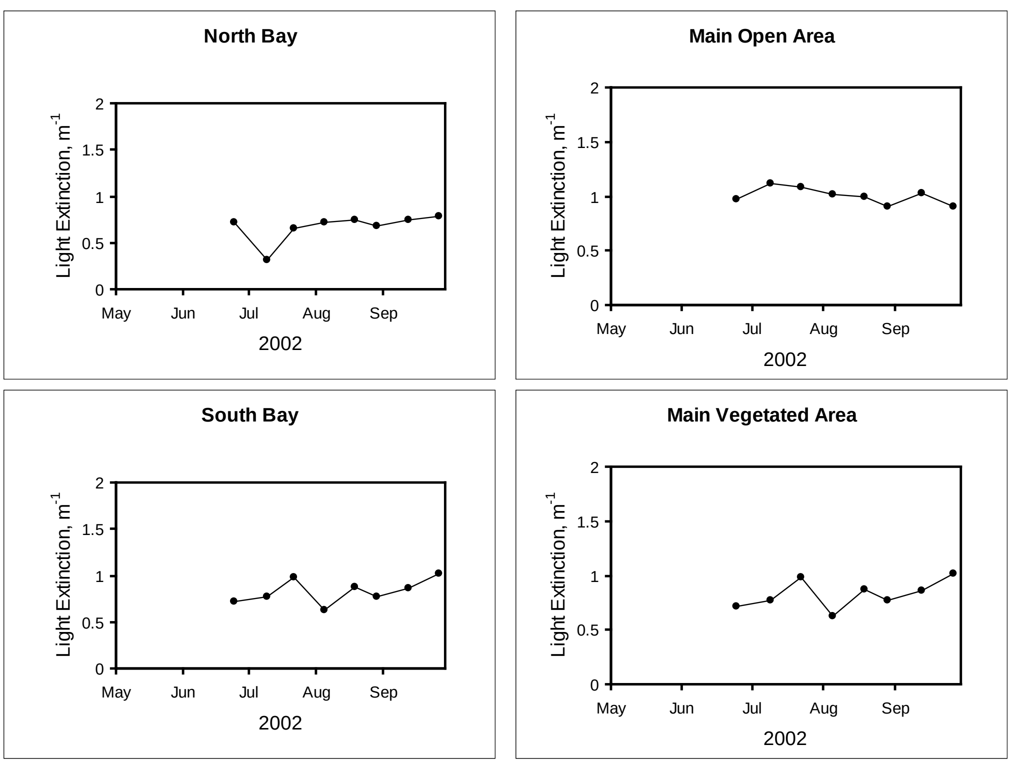


Figure 43. Seasonal variations in mean light extinction coefficients at various areas in Houghton Lake. Data were not collected at the all the stations in May.

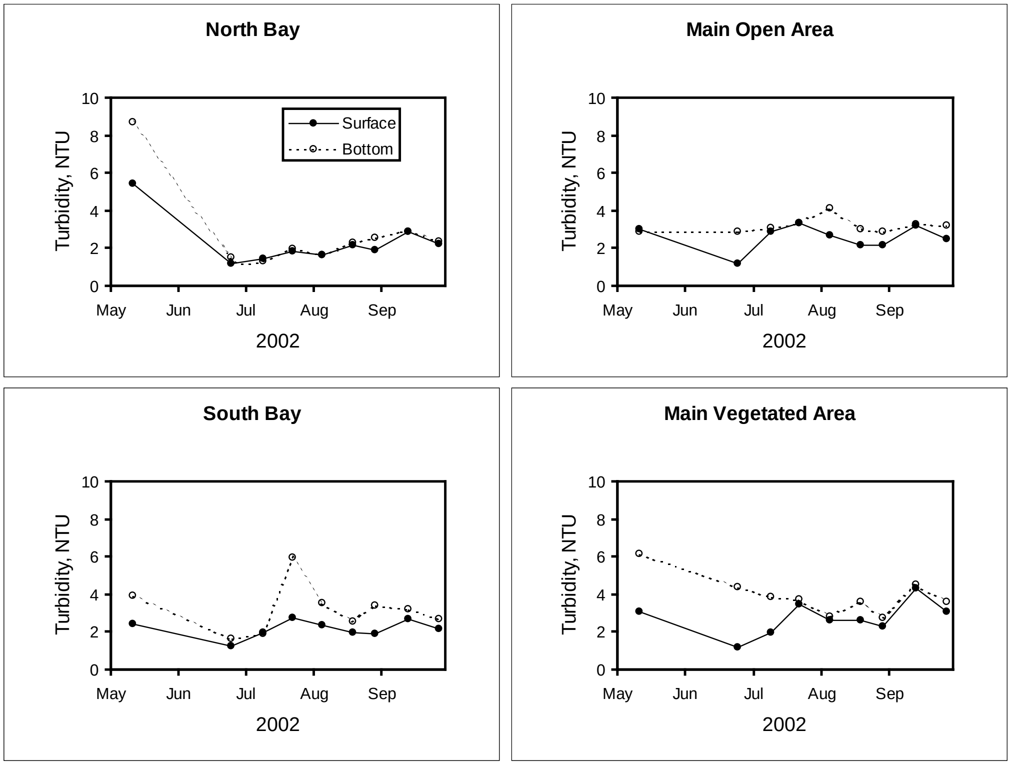


Figure 44. Seasonal variations in mean turbidity at the surface and bottom depths of various areas in Houghton Lake.

Table 25. Means, standard errors, minimum and maximum values for water quality parameters in Houghton Lake by area.

Zone	Parameter	Mean	Std Error	Minimum	Maximum
Main, no macrophytes	Secchi Depth, m	1.77	0.05	1.50	2.00
	Temperature, C	20.65	1.07	10.61	25.39
	Dissolved Oxygen, mg/L	8.01	0.53	3.42	12.93
	Conductivity, S	0.250	0.002	0.233	0.260
	pH	8.38	0.16	7.49	9.69
	Total Phosphorus, mg/L	0.017	0.002	0.002	0.025
	Total Nitrogen, mg/L	0.659	0.019	0.554	0.836
	Turbidity, NTU	2.88	0.21	1.32	5.23
	Chlorophyll, µg/L	8.22	0.77	3.54	14.36
Main, open	Secchi Depth, m	1.95	0.04	1.30	2.75
	Temperature, C	21.02	0.54	10.38	25.90
	Dissolved Oxygen, mg/L	8.59	0.24	2.65	12.86
	Conductivity, S	0.251	0.001	0.233	0.258
	pH	8.36	0.06	7.36	10.16

Zone	Parameter	Mean	Std Error	Minimum	Maximum
Main, open (cont)	Total Phosphorus, mg/L	0.013	0.001	0.000	0.046
	Total Nitrogen, mg/L	0.622	0.010	0.502	0.951
	Turbidity, NTU	2.87	0.14	0.87	8.34
	Chlorophyll, µg/L	8.00	0.38	1.13	16.39
Main, vegetated	Secchi Depth, m	1.69	0.06	0.80	2.60
	Temperature, C	21.09	0.54	10.56	26.97
	Dissolved Oxygen, mg/L	8.55	0.27	0.20	12.58
	Conductivity, S	0.251	0.001	0.234	0.279
	pH	8.33	0.07	6.96	10.67
	Total Phosphorus, mg/L	0.016	0.001	0.000	0.051
	Total Nitrogen, mg/L	0.645	0.011	0.500	0.921
	Turbidity, NTU	3.33	0.25	0.91	14.43
	Chlorophyll, µg/L	8.29	0.73	1.33	47.55
North bay	Secchi Depth, m	1.82	0.05	1.40	2.40
	Temperature, C	21.44	0.83	10.24	26.98
	Dissolved Oxygen, mg/L	9.45	0.27	7.15	13.00
	Conductivity, S	0.252	0.002	0.201	0.264
	pH	8.50	0.06	7.67	9.51
	Total Phosphorus, mg/L	0.013	0.002	0.000	0.041
	Total Nitrogen, mg/L	0.595	0.010	0.505	0.696
	Turbidity, NTU	2.55	0.39	1.15	14.95
	Chlorophyll, µg/L	5.85	0.49	1.56	16.21
South bay	Secchi Depth, m	2.05	0.05	1.50	2.80
	Temperature, C	20.88	0.79	10.28	26.12
	Dissolved Oxygen, mg/L	8.32	0.36	2.66	12.52
	Conductivity, S	0.251	0.001	0.231	0.261
	pH	8.31	0.08	7.44	9.46
	Total Phosphorus, mg/L	0.012	0.002	0.000	0.032
	Total Nitrogen, mg/L	0.610	0.014	0.501	0.871
	Turbidity, NTU	2.68	0.21	1.04	8.40
	Chlorophyll, µg/L	6.89	0.58	1.37	18.44

Table 26. Means, standard errors, minimum and maximum values by station for water quality parameters in Houghton Lake.

Station	Parameter	Mean	Std Error	Minimum	Maximum
9	Secchi Depth, m	1.69	0.04	1.50	2.00
	Temperature, C	21.49	1.21	10.24	26.98
	Dissolved Oxygen, mg/L	9.29	0.35	7.15	11.97
	Conductivity, S	0.251	0.004	0.201	0.264
	pH	8.47	0.10	7.67	9.51
	Total Phosphorus, mg/L	0.014	0.003	0.000	0.041
	Total Nitrogen, mg/L	0.598	0.015	0.505	0.696
	Turbidity, NTU	2.86	0.77	1.22	14.95
	Chlorophyll, µg/L	5.64	0.80	2.16	16.21
10	Secchi Depth, m	1.93	0.07	1.40	2.40
	Temperature, C	21.39	1.16	10.67	26.09
	Dissolved Oxygen, mg/L	9.61	0.40	7.17	13.00
	Conductivity, S	0.253	0.002	0.237	0.260
	pH	8.53	0.08	7.81	8.98
	Total Phosphorus, mg/L	0.011	0.002	0.000	0.026
	Total Nitrogen, mg/L	0.592	0.013	0.524	0.674
	Turbidity, NTU	2.24	0.16	1.15	4.05
	Chlorophyll, µg/L	6.06	0.57	1.56	10.20
11	Secchi Depth, m	1.93	0.09	1.50	2.75
	Temperature, C	21.13	1.11	10.38	25.79
	Dissolved Oxygen, mg/L	8.59	0.53	2.65	12.26
	Conductivity, S	0.251	0.002	0.235	0.257
	pH	8.32	0.08	7.81	8.84
	Total Phosphorus, mg/L	0.013	0.002	0.000	0.028
	Total Nitrogen, mg/L	0.607	0.014	0.520	0.716
	Turbidity, NTU	2.63	0.20	0.87	3.76
	Chlorophyll, µg/L	7.63	0.84	1.13	12.64
12	Secchi Depth, m	1.89	0.02	1.75	2.00
	Temperature, C	21.10	1.10	10.59	25.90
	Dissolved Oxygen, mg/L	8.60	0.55	3.76	12.86
	Conductivity, S	0.250	0.002	0.233	0.256
	pH	8.48	0.16	7.83	10.16
	Total Phosphorus, mg/L	0.016	0.002	0.000	0.030
	Total Nitrogen, mg/L	0.661	0.020	0.556	0.824
	Turbidity, NTU	3.24	0.36	1.54	8.34
	Chlorophyll, µg/L	9.56	0.71	5.06	16.39
13	Secchi Depth, m	2.11	0.07	1.70	2.50
	Temperature, C	20.76	1.11	10.42	25.49
	Dissolved Oxygen, mg/L	8.69	0.40	6.46	12.63
	Conductivity, S	0.251	0.002	0.234	0.257
	pH	8.29	0.11	7.36	9.02
	Total Phosphorus, mg/L	0.009	0.002	0.000	0.026
	Total Nitrogen, mg/L	0.591	0.012	0.517	0.681
	Turbidity, NTU	2.34	0.12	1.12	3.48
	Chlorophyll, µg/L	6.75	0.62	1.85	11.31

Station	Parameter	Mean	Std Error	Minimum	Maximum
14	Secchi Depth, m	2.01	0.05	1.50	2.25
	Temperature, C	21.09	1.15	10.28	26.12
	Dissolved Oxygen, mg/L	8.79	0.38	6.89	12.21
	Conductivity, S	0.251	0.002	0.231	0.259
	pH	8.36	0.10	7.80	9.22
	Total Phosphorus, mg/L	0.010	0.002	0.000	0.026
	Total Nitrogen, mg/L	0.598	0.015	0.501	0.740
	Turbidity, NTU	2.39	0.15	1.44	3.66
	Chlorophyll, µg/L	6.76	0.77	1.66	12.97
15	Secchi Depth, m	2.10	0.09	1.50	2.80
	Temperature, C	20.66	1.12	10.28	25.65
	Dissolved Oxygen, mg/L	7.84	0.61	2.66	12.52
	Conductivity, S	0.251	0.002	0.235	0.261
	pH	8.27	0.13	7.44	9.46
	Total Phosphorus, mg/L	0.013	0.002	0.000	0.032
	Total Nitrogen, mg/L	0.622	0.024	0.509	0.871
	Turbidity, NTU	2.97	0.38	1.04	8.40
	Chlorophyll, µg/L	7.01	0.88	1.37	18.44
16	Secchi Depth, m	1.77	0.05	1.50	2.00
	Temperature, C	20.65	1.07	10.61	25.39
	Dissolved Oxygen, mg/L	8.01	0.53	3.42	12.93
	Conductivity, S	0.250	0.002	0.233	0.260
	pH	8.38	0.16	7.49	9.69
	Total Phosphorus, mg/L	0.017	0.002	0.002	0.025
	Total Nitrogen, mg/L	0.659	0.019	0.554	0.836
	Turbidity, NTU	2.88	0.21	1.32	5.23
	Chlorophyll, µg/L	8.22	0.77	3.54	14.36
17	Secchi Depth, m	1.11	0.06	0.80	1.50
	Temperature, C	20.65	1.05	10.82	24.60
	Dissolved Oxygen, mg/L	7.43	0.75	0.20	12.55
	Conductivity, S	0.253	0.003	0.235	0.279
	pH	8.18	0.22	6.96	10.67
	Total Phosphorus, mg/L	0.024	0.003	0.000	0.051
	Total Nitrogen, mg/L	0.739	0.024	0.554	0.921
	Turbidity, NTU	4.75	0.76	1.21	14.43
	Chlorophyll, µg/L	11.16	2.37	1.95	47.55
18	Secchi Depth, m	1.61	0.08	1.00	2.10
	Temperature, C	21.29	1.12	10.75	26.97
	Dissolved Oxygen, mg/L	8.81	0.41	6.56	12.11
	Conductivity, S	0.253	0.002	0.234	0.259
	pH	8.27	0.09	7.74	9.06
	Total Phosphorus, mg/L	0.016	0.002	0.006	0.046
	Total Nitrogen, mg/L	0.663	0.014	0.592	0.785
	Turbidity, NTU	3.66	0.46	1.07	8.65
	Chlorophyll, µg/L	7.94	0.97	1.74	15.41

Station	Parameter	Mean	Std Error	Minimum	Maximum
19	Secchi Depth, m	2.02	0.09	1.30	2.60
	Temperature, C	21.13	1.10	10.56	25.88
	Dissolved Oxygen, mg/L	8.74	0.45	6.13	12.58
	Conductivity, S	0.251	0.002	0.234	0.260
	pH	8.42	0.15	7.69	10.12
	Total Phosphorus, mg/L	0.013	0.003	0.000	0.036
	Total Nitrogen, mg/L	0.597	0.016	0.506	0.699
	Turbidity, NTU	2.63	0.26	0.97	4.95
	Chlorophyll, µg/L	7.64	0.96	1.33	14.75
20	Secchi Depth, m	2.01	0.09	1.30	2.50
	Temperature, C	21.28	1.12	10.59	25.99
	Dissolved Oxygen, mg/L	9.20	0.39	7.16	12.43
	Conductivity, S	0.250	0.002	0.234	0.258
	pH	8.45	0.10	7.69	9.18
	Total Phosphorus, mg/L	0.013	0.002	0.000	0.031
	Total Nitrogen, mg/L	0.588	0.013	0.500	0.669
	Turbidity, NTU	2.36	0.23	0.91	4.45
	Chlorophyll, µg/L	6.40	0.79	1.35	11.90
21	Secchi Depth, m	1.91	0.07	1.30	2.30
	Temperature, C	21.09	1.12	10.42	25.50
	Dissolved Oxygen, mg/L	8.48	0.47	5.13	12.38
	Conductivity, S	0.251	0.002	0.236	0.258
	pH	8.37	0.14	7.61	9.95
	Total Phosphorus, mg/L	0.014	0.003	0.000	0.046
	Total Nitrogen, mg/L	0.631	0.025	0.502	0.951
	Turbidity, NTU	3.27	0.34	1.07	7.19
	Chlorophyll, µg/L	8.05	0.79	2.21	15.17

Mean dissolved oxygen generally remained above 5 mg L^{-1} at both the surface and bottom throughout the study period in all four areas of the lake (Figure 37 and Table 25). However, the concentration declined to a minimum of 0.2 mg L^{-1} near the lake bottom at station 17 (23 July) and reached a minimum of less than 5 mg L^{-1} near the lake bottom at stations 11 (23 July), 12 (20 August), 15 (20 August), and 16 (14 September). Patterns at these stations were apparently isolated incidents, and concentrations at bottom depths at these and other stations were usually much greater on other dates.

Mean pH reached peaks in August and September in the four areas (Figure 38; Tables 25 and 26). Over all stations and depths, pH ranged between 7 and 10.7. High pH during the latter part of summer was probably due to photosynthesis by algae and aquatic plants.

Mean total P in the four areas exhibited a peak in May, before the fluridone treatment (Figure 39; Tables 25 and 26). Mean values declined to near zero in all areas in late June through early July and increased to another peak in late July through early August. A maximum in TP of 0.051 mg L^{-1} occurred at station 17 near the lake bottom on 6 August 2002. Mean concentrations in the four areas were usually similar between surface and bottom depths. However, mean bottom concentrations of TP exceeded those of the surface in the North Bay, Main Open area, and the South Bay in late July.

Mean chlorophyll in the four areas followed similar seasonal patterns as mean TP, suggesting incorporation of P as algal biomass (Figure 40; Tables 25 and 26). Peaks in mean chlorophyll in May and July coincided with similar peaks in mean TP in the four areas. Declines in mean chlorophyll concentrations in late June and early July may have been associated with grazing pressure from zooplankton. The highest chlorophyll concentration observed during the summer, occurring at the bottom depth of station 17 on 23 July, was 47 μg L^{-1} (Table 26).

Mean TN concentrations were nearly homogeneous with depth in the four areas and exhibited peaks in July that coincided with those in mean TP and chlorophyll (Figure 41; Tables 25 and 26). The mean TN:TP ratio was between 40 and 50 at all stations, suggesting phosphorus limitation of algal productivity.

Variations in Secchi transparency, the light extinction coefficient, and turbidity in the four areas of the lake are shown in Figures 42 through 44, respectively. Mean Secchi transparency fluctuated between 1 and 2.5 m at all areas and exhibited a peak in late June, which coincided with minima in chlorophyll. Secchi transparency was often equivalent to the depth of the water column at many shallow stations (not shown). The mean light extinction coefficient was generally 1 m^{-1} or less, indicating good light penetration. Mean turbidity was very low throughout the study period at all areas, suggesting minimal sediment resuspension. Lack of resuspension may be attributed to the occurrence of native aquatic vegetation, such as muskgrass, which was not affected by fluridone and stabilized the sediment from wave-induced shear stress. A minor peak in turbidity was observed in all areas in early May, before the fluridone treatment. However, mean values were very low (<10 NTU) in all areas during this period.

The Carlson TSI ranged between 40 and 52 for the four areas, indicating that the lake was mesoeutrophic or only moderately productive (Table 27). In contrast, values greater than 60 are indicative of highly productive, nutrient-enriched aquatic systems that exhibit frequent algal blooms (chlorophyll usually much greater than 30 µg L^{-1}), high TP, and hypoxia/ anoxia in the bottom waters.

Table 27. Carlson Trophic State Index (TSI) values for different areas of Houghton Lake. TSI values Secchi transparency (TSI_{SD}), chlorophyll (TSI_{CHLA}) and phosphorus (TSI_{TP}) represent the average over the summer study period.

Area	Mean Secchi Transparency (m)	Mean Chlorophyll (µg/L)	Mean Total Phosphorus (mg/L)	TSI_{SD}	TSI_{CHLA}	TSI_{TP}
North Bay	1.8	5.8	.013	51	48	41
South Bay	2.1	6.9	.012	49	50	40
Main Open	2.0	8	.014	50	51	42
Main Vegetated	1.7	8.3	.016	52	51	44

Comparing these results with pre-treatment water quality data, no negative impacts on Houghton Lake water quality were detected following the fluridone treatment. One reason for a lack of negative water quality impacts is that fluridone-induced dieback is slow (i.e., over a few months) compared to more conventional herbicide treatments, which typically kill plants in a few days or weeks. Dissolved oxygen, which can become depleted rapidly in bottom waters as a result of plant decomposition, remained above 5 mg L^{-1} over most of the lake throughout the summer. Anoxic conditions (DO< 0.5 mg L^{-1}) were observed in the bottom waters of station 17 in July. This limited area of anoxia is not necessarily the result of decomposition of treated plant biomass. Areas of anoxia have been reported in the bottom waters of actively growing plant beds in other aquatic systems in the absence of any herbicide treatment (James et al. 1996, 2002) and a dissolved oxygen concentration near 5 mg L^{-1} was reported at this location in Houghton Lake during 2001.

Turbidity was very low at all stations and depths throughout the summer, suggesting minimal resuspension of sediments. One of the concerns about a whole-lake fluridone treatment removing all the watermilfoil at once was the potential widespread exposure of sediments to wind-induced wave activity, leading to an increase in sediment resuspension. In this case, it appeared that selectively controlling watermilfoil allowed sufficient native species growth to stabilize the sediment. Had the treatment controlled all the aquatic plants in the lake, dramatically increased resuspension and much higher turbidity might have been expected during the summer, as was reported in Lake Champlain after mechanical shredding of water chestnut canopies (James et al. 2002).

Senescence of aquatic plants can lead to short-term leaching of nutrients (i.e., N and P) from decaying tissue, which can stimulate nuisance algal growth. Only modest peaks in N and P and chlorophyll were observed during the summer, suggesting that fluridone treatment had only a minimal impact, if any, on the productivity of Houghton Lake. Chlorophyll concentration peaks during the summer of 2002 following treatment differed little from concentrations observed prior to treatment in May 2002 and September 2001. The TP exhibited a similar pattern of high concentrations prior to treatment. The lack of recent chlorophyll and phosphorus measurement during the summer growing season made it difficult to assess the impacts of fluridone treatment on these aspects of water quality. However, chlorophyll and associated phosphorus concentrations were low throughout the summer relative to productive, nutrient-enriched lakes, and the Carlson TSI fell within the range of moderately productive lakes, suggesting that impacts of plant dieback on the lake's productivity were modest or nonexistent.

Summary of post-treatment conditions

The whole-lake fluridone application was extremely successful in controlling Eurasian watermilfoil with minimal, mostly short-term impact on most native plant species. After the 2002 treatment, Eurasian watermilfoil was not detected during 2003, and only a very small amount had returned to the lake by 2004. The treatment initially reduced native plant abundance, though a number of plant species were relatively unaffected or increased during the year of treatment. Most native plant species had recovered by 2004.

The overall frequency of vegetation declined only slightly from 2001 to 2002, then declined more rapidly from 2002 through 2004 (Figure 45). By 2004, the frequency of vegetation had declined to 47%, or only 61% of the pre-treatment frequency. The decline from 2002 to 2003 could easily reflect plants that had been weakened by the treatment and died after the

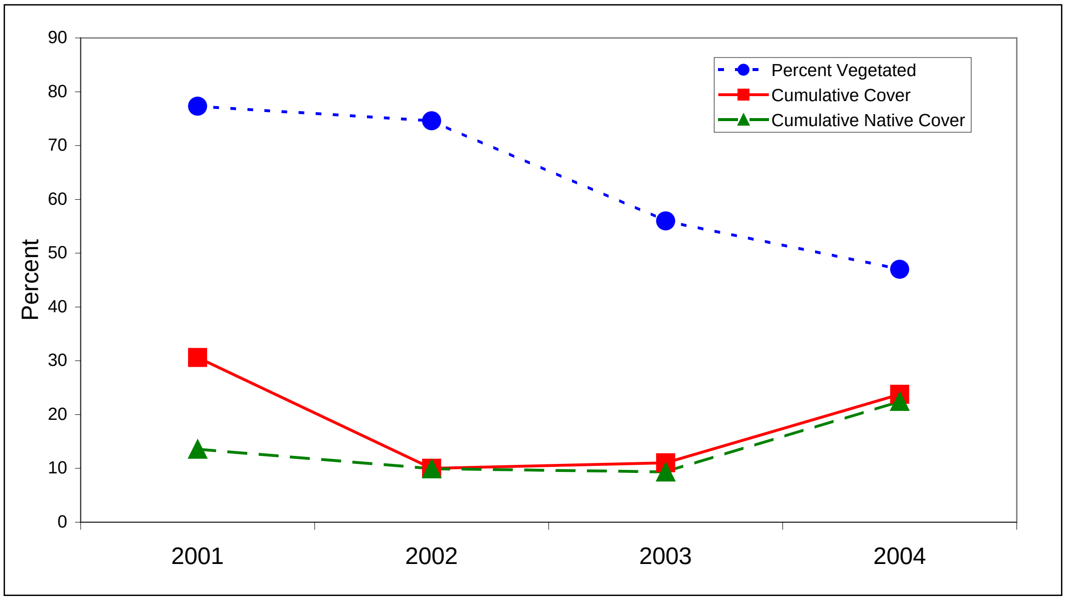


Figure 45. Percent of lake vegetated and cumulative cover, 2001–2004.

2002 sampling. For example, coontail was still present in the 2002 point-grid survey but disappeared by 2003. There is no obvious connection between the treatment and the continued decline in the frequency of vegetation from 2003 to 2004. Total cumulative cover of aquatic plant species declined by about two-thirds from 2001 through 2002 and 2003, then increased by more than double from 2003 to 2004 (Figure 45). Most of the loss of cumulative cover from 2001 through 2002 and 2003 resulted from the elimination of Eurasian watermilfoil; cumulative cover of native species declined only slightly. The increase in cover from 2003 to 2004 was nearly all the result of increased cover of native species. The 2004 cumulative cover of native plants was approximately 1.5 times that in 2001. The increase by 2004 in native plant cover despite the declining frequency of vegetated sites indicates a loss of some vegetated areas accompanied by the filling in of remaining plant beds.

Changes in the cumulative cover of the more commonly encountered plant species from 2001 through 2004 are illustrated in Figure 46. Eurasian watermilfoil was temporarily eliminated from the lake in 2003 and remained dramatically below pretreatment levels in 2004. Curlyleaf pondweed increased considerably in 2003, but fell to about half its 2003 cover in 2004. Native plant species exhibited a range of responses. Muskgrass and water stargrass increased during the year of treatment. Variable pondweed, Illinois pondweed, flatstem pondweed and largeleaf pondweed increased following the treatment and had 2004 cover substantially higher

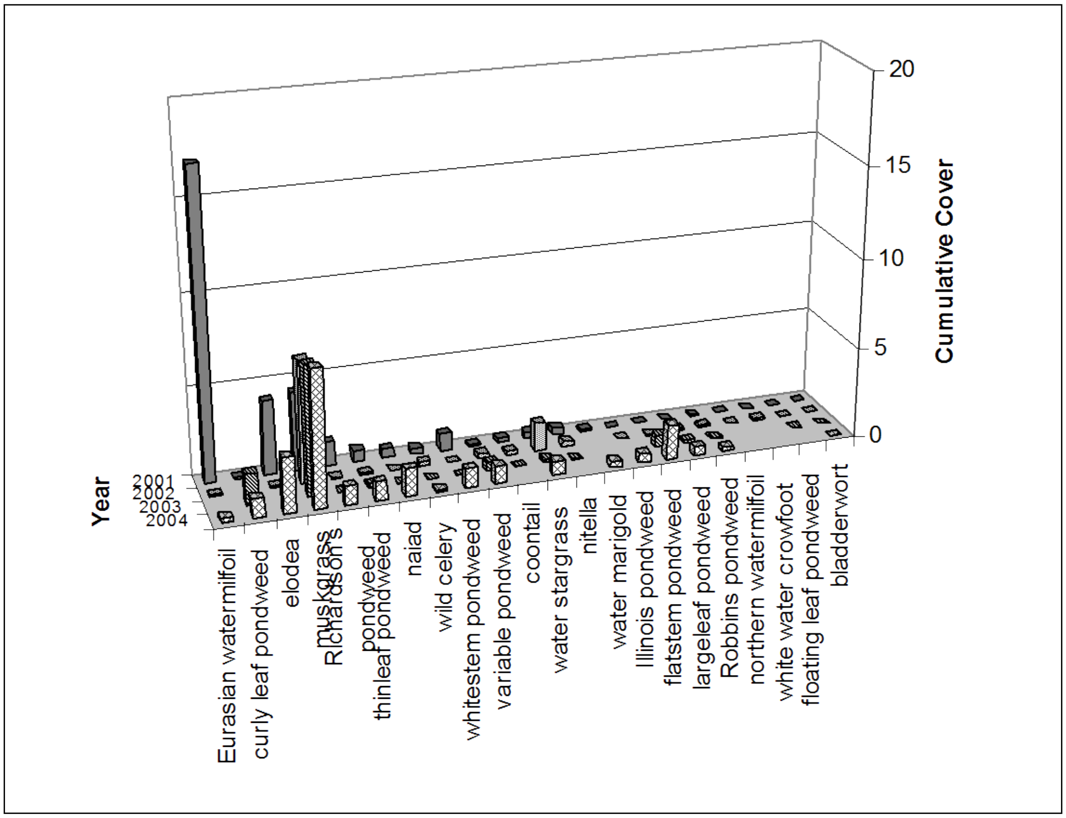


Figure 46. Cumulative cover of more common plant species, 2001–2004.

than that present in 2001. Robbin's pondweed and bladderwort were apparently unaffected by the treatment. Elodea was drastically reduced by the treatment but had nearly recovered by 2004. Richardson's pondweed, thinleaf pondweed, naiad, whitestem pondweed, and water marigold were all considerably reduced in 2002 and 2003, but by 2004 had recovered cumulative cover to levels present in 2001 or higher. Wild rice, which had been absent or greatly reduced in the lake prior to treatment, reappeared in the lake during 2003 and expanded from 2003 to 2004. Longer-term adverse effects of the treatment were confined to wild celery, which decreased following the treatment and had not recovered to pretreatment cover by 2004, and to coontail, northern watermilfoil, and white water crowfoot which were apparently eliminated from the lake and had not reappeared by 2004.

SAVEWS hydroacoustic sampling produced results very similar to those from the point-grid survey. Both biocover and biovolume decreased from 2001 through 2003 and then increased from 2003 to 2004. SAVEWS transects evaluated in 2004 showed that most of the plant biocover and biovolume were in areas where historic plant beds had occurred. These results demonstrate the utility of SAVEWS as a rapid quantitative method for evaluating changes in overall plant cover and abundance, the one drawback of SAVEWS being that it provides no information on the species composition of the plant community. Despite this limitation, SAVEWS is a very valuable tool for locating and evaluating plant beds or quantitatively evaluating the impacts of control efforts, particularly on monospecific beds of nuisance plants.

Plant community changes along diver transects illustrate a range of responses to the whole-lake fluridone treatment. In 2004, two years after the treatment, Eurasian watermilfoil had disappeared from all diver transects except one. One of the transects that had been strongly dominated by Eurasian watermilfoil in 2002 was dominated by a diverse collection of pondweeds in 2004. The other two had recovered only a little and had 2004 communities with low species richness. Transects where diverse communities of native plants had initially shared dominance with Eurasian watermilfoil remained relatively species rich in 2004. An exception occurred where one of the species eliminated by the treatment (e.g., coontail) had been a major component of the community in 2002.

No adverse impacts on water quality were measured during 2002 following the herbicide application. Dissolved oxygen, which can become depleted rapidly in bottom waters as a result of plant decomposition, remained above 5 mg L^{-1} except at the bottom in a location where dissolved oxygen concentrations near 5 mg L^{-1} had been observed during 2001. Turbidity remained very low at all stations and depths throughout the summer, suggesting minimal resuspension of sediments. Chlorophyll and nutrient (N and P) concentration patterns during the summer of 2002 differed little from concentrations observed prior to treatment, suggesting that the treatment had little impact, if any, on the productivity of the lake.

6 Phase 2: Maintenance Control: 2004–2006

Following the initial whole-lake fluridone phase in 2002, the long-term management plan for Houghton Lake also called for integrated use of milfoil weevils, mechanical harvesting, and selective, systemic herbicides to control recovering populations of Eurasian watermilfoil. Starting in 2004, these integrated management techniques were utilized to sustain long-term control of Eurasian watermilfoil. In 2005 and 2006, additional lake-wide vegetation assessments were conducted to follow the status of maintenance control of Eurasian watermilfoil and related changes in the aquatic plant community of Houghton Lake.

Milfoil weevil stocking and mechanical: 2004–2006

The integrated plan adopted by the HLIB in 2002 called for a post-fluridone maintenance strategy that included stocking of milfoil weevils to areas of recovering Eurasian watermilfoil. Two stockings of milfoil weevils occurred through 2006. In 2004, 5,000 weevils were stocked in a canal at the east end of the lake. In 2005, a larger stocking of 33,000 weevils was made to the Houghton Lake Flats nature area immediately adjacent to the west shore of the lake. Evaluations of the outcome of these stockings are not available for this report.

In addition to weevil stocking, mechanical harvesting was also utilized starting in 2004 to primarily harvest nuisance levels of curlyleaf pond-weed. Through 2006, 112 ha were mechanically harvested, primarily in southern sections of the lake. Table 28 summarizes the lake area managed annually through weevil stocking and mechanical harvesting.

Table 28. Houghton Lake plant control history, 2002–2006.

Year	Herbicides (acres treated)			Acres Harvested	Milfoil Weevils (# Stocked)
	Sonar®	Contacts	Systemic		
2002	20,044	17			
2003			32		
2004			44	81	5,000
2005		50	395	84	28,000
2006		59	444	105	

Targeted application of aquatic herbicides: 2005–2006

Continued maintenance control of Eurasian watermilfoil has also included targeted application of aquatic herbicides with an emphasis on selective, systemic herbicides. In the two years following whole-lake fluridone treatment (2003 and 2004), only 32 ha of the lake system were treated, and all of these treatments occurred within man-made canals attached to the main lake. In 2005, 185 ha were treated with herbicides with 165 ha treated with selective, systemic herbicide (2,4-D), primarily in the shallow Middle Ground weed bed in the east central area of the lake.

In 2006, 210 total ha were treated (185 ha with systemic herbicide) with focus again in the Middle Ground weed bed. Overall, less than 3% of the total lake area was treated with herbicides in 2006, indicating the success of the maintenance control strategy designed to prevent expansion of Eurasian watermilfoil in the years following the 2002 whole-lake fluridone treatment. In the original feasibility study, 2006 (4 years post-Sonar treatment) was described as a potential year for a second whole-lake treatment. Due to successful maintenance control, this second fluridone treatment has not been necessary. Table 28 is a multi-year summary of lake acres managed annually through chemical herbicide treatment.

Vegetation assessment: 2005–2006

In 2005 and 2006, lake-wide vegetation assessments were performed in mid-late August using methods similar to the 2001–2004 surveys of Houghton Lake. The 2005 aquatic plant rake survey was conducted from August 22 through 24, while the 2006 survey was performed August 21 through 23. Both surveys were conducted and analyzed using the point intercept method (Madsen 1999) and data collection on the grid of 912 GPS sampling points established in 2001 at 300-m intervals across the lake (Figure 5). At each sampling point, a double-sided thatch rake attached to a line was dragged for approximately 4 m in two rake tosses, one on each side of the boat, and species presence or absence was recorded. Note that some species were lumped together as a genus in 2001 and were recorded as separate species in subsequent annual surveys. These include *Potamogeton epihydrus* and *P. diversifolius* lumped as thin-leaf pondweed and *Najas flexilis* and *N. guadalupensis* lumped as naiad. In 2006, the SAVEWS hydroacoustic survey of the six permanent transects was conducted August 23–24. The hydroacoustic survey was not performed in 2005.

Results and discussion

In 2005, 23 aquatic plant species were identified in Houghton Lake. The five most common plants in 2005 were chara (417 out of 912 survey sites), elodea (167 sites), naiads (158 sites or 79 each of two naiad species), small pondweed (94 sites), and thin-leaf pondweeds (77 sites) (Table 29). In 2006, 27 aquatic plant species were found in the lake with the five most common being chara (320 sites), elodea (184 sites), Eurasian watermilfoil (156 sites), variable pondweed (147 sites), and water stargrass (106 sites) (Table 30).

Figure 47 compares frequency of occurrence for all species found in 2006 versus 2001 pre-treatment survey results. Figures 48–53 illustrate changes in species abundance from 2001–2006 for species groupings ranging from the most abundant to the least abundant plants in the lake. Figure 54 presents the distribution and estimated density map for Eurasian watermilfoil for the 2006 rake survey.

In total, results of 2005 and 2006 rake surveys indicate that a diverse community of aquatic vegetation was present in Houghton Lake and continued management through 2006 continued to prevent Eurasian watermilfoil from reaching pre-treatment densities. The most common native plant in Houghton Lake according to the 2001 survey was elodea, which could not be detected in 2003 one-year post-treatment. However, elodea was found at 20% of all survey locations in 2006, and most other native species found showed similar increases since 2003. After the target invasive plant was not detected in the 2003 survey, the frequency of occurrence of Eurasian watermilfoil increased significantly in 2005 (5.3% of survey sites) and 2006 (17.1% of sites). However, dense Eurasian watermilfoil was found at only one survey site and observed density across sites where it was found was generally low (Figure 54).

Table 29. Results of 2005 aquatic vegetation assessment of 912 survey sites in Houghton Lake.

Common Name	Scientific Name	Number of Sites Where Present
Chara	*Chara* sp.	417
Elodea	*Elodea canadensis*	167
Small pondweed	*Potamogeton pusillus*	94
Naiad	*Najas flexilis*	79
Southern naiad	*Najas guadalupensis*	79
Illinois pondweed	*Potamogeton illinoensis*	69
Whitestem pondweed	*Potamogeton praelongus*	63
Thin-leaf pondweed	*Potamogeton* sp.	60
Water stargrass	*Heteranthera dubia*	57
Variable pondweed	*Potamogeton gramineus*	53
Eurasian milfoil	*Myriophyllum spicatum*	48
Flat-stem pondweed	*Potamogeton zosteriformis*	40
Large-leaf pondweed	*Potamogeton amplifolius*	36
Richardson's pondweed	*Potamogeton richardsonii*	19
Wild celery	*Vallisneria americana*	17
Ribbon-leaf pondweed	*Potamogeton epihydrus*	10
Variable-leaf pondweed	*Potamogeton diversifolius*	7
Robbins pondweed	*Potamogeton robbinsii*	7
Wild rice	*Zizania aquatica*	6
Bulrush	*Scirpus* sp.	5
Nitella	*Nitella* sp.	3
Coontail	*Ceratophyllum demersum*	3
Floating-leaved pondweed	*Potamogeton natans*	1
Bladderwort	*Utricularia vulgaris*	1
Yellow waterlily	*Nuphar* sp.	1
Curly-leaf pondweed	*Potamogeton crispus*	1

Table 30. Results of 2006 aquatic vegetation assessment of 912 survey sites in Houghton Lake.

Common Name	Scientific Name	Number of Sites Where Present
Chara	*Chara* sp.	320
Elodea	*Elodea canadensis*	184
Eurasian milfoil	*Myriophyllum spicatum*	156
Variable pondweed	*Potamogeton gramineus*	147
Water stargrass	*Heteranthera dubia*	106
Richardson's pondweed	*Potamogeton richardsonii*	93
Southern naiad	*Najas guadalupensis*	63
Large-leaf pondweed	*Potamogeton amplifolius*	57
Whitestem pondweed	*Potamogeton praelongus*	54
Illinois pondweed	*Potamogeton illinoensis*	41
Wild celery	*Vallisneria americana*	37
Flat-stem pondweed	*Potamogeton zosteriformis*	33
Naiad	*Najas flexilis*	22
Small pondweed	*Potamogeton pusillus*	18
Nitella	*Nitella* sp.	14
Wild rice	*Zizania aquatica*	11
Robbins pondweed	*Potamogeton robbinsii*	9
Sago pondweed	*Stuckenia pectinata*	9
Ribbon-leaf pondweed	*Potamogeton epihydrus*	7
Bulrush	*Scirpus* sp.	6
Curly-leaf pondweed	*Potamogeton crispus*	5
Coontail	*Ceratophyllum demersum*	4
Thin-leaf pondweed	*Potamogeton* sp.	2
White waterlily	*Nymphaea odorata*	2
Yellow waterlily	*Nuphar* sp.	2
Variable-leaf pondweed	*Potamogeton diversifolius*	2
Northern milfoil	*Myriophyllum sibiricum*	1

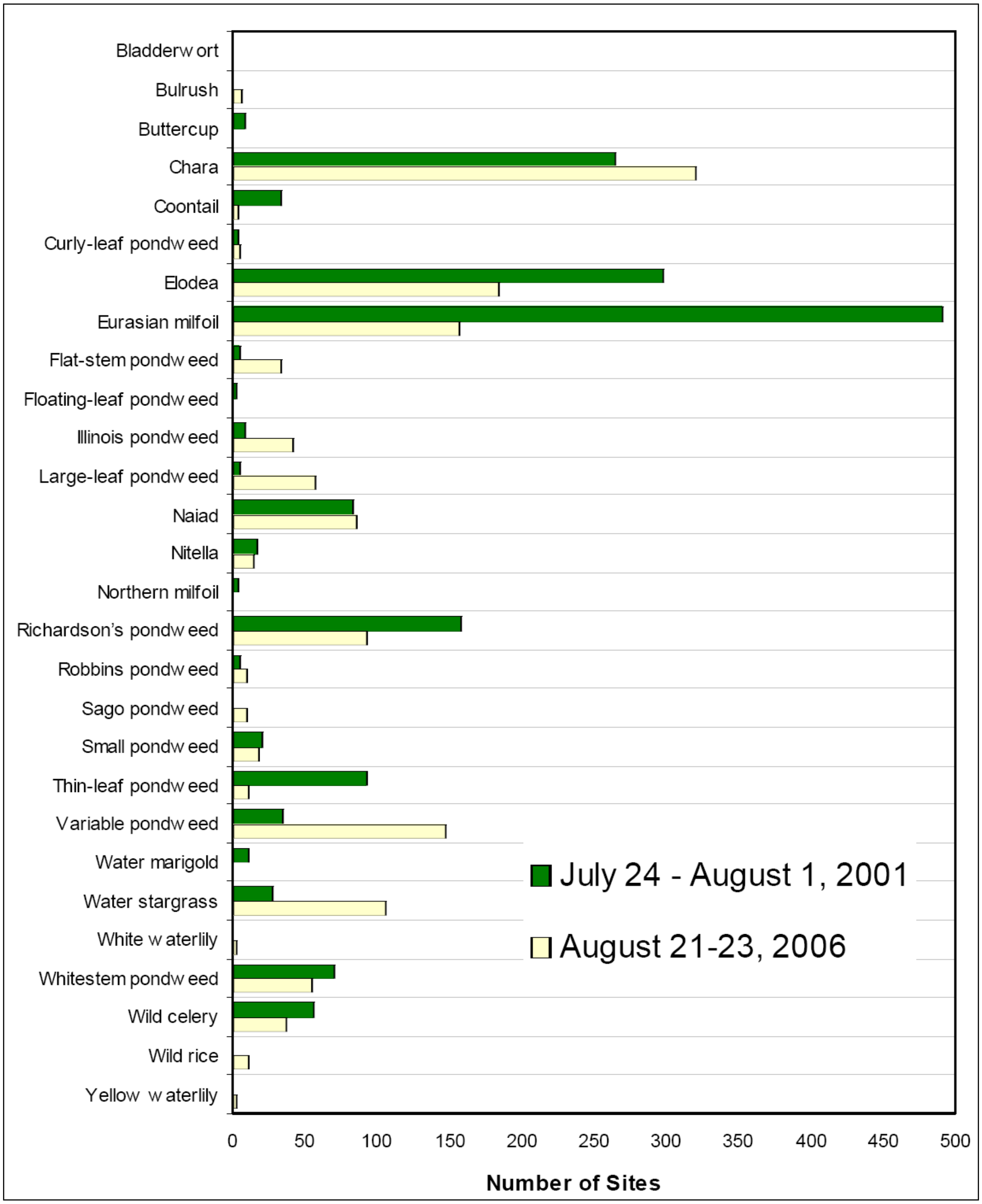


Figure 47. Number of survey sites per plant species in Houghton Lake 2001 (pre-fluridone treatment) and 2006 (4 years post-fluridone treatment).

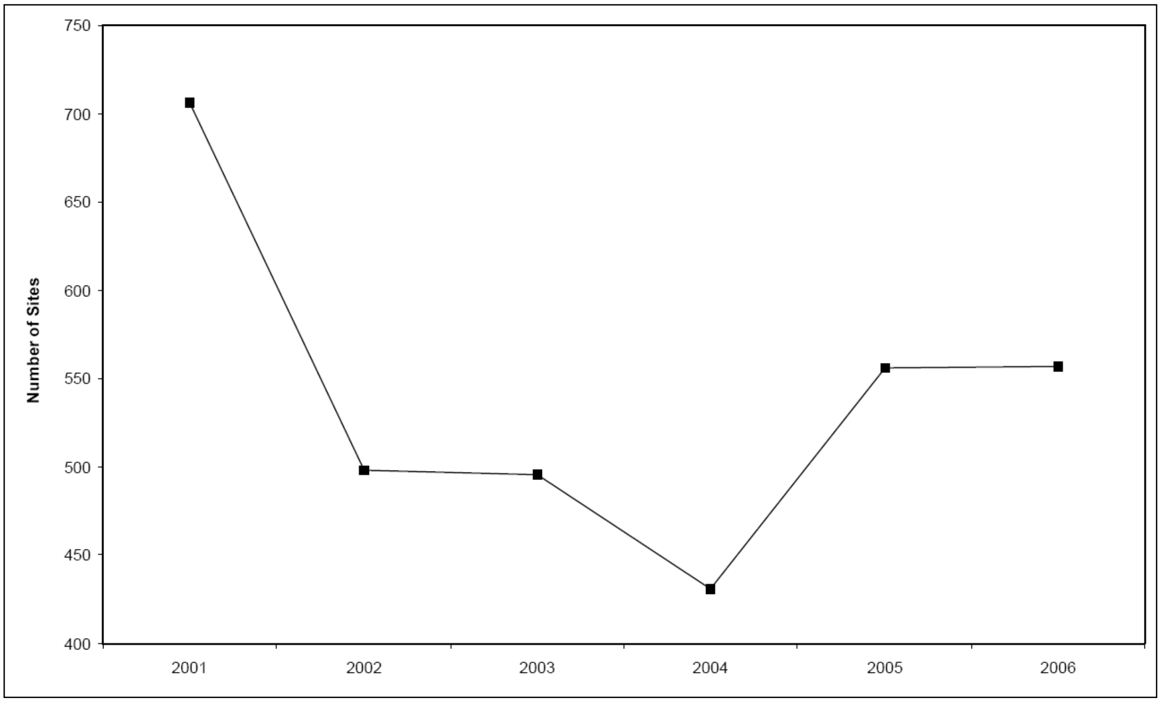


Figure 48. Total number of survey sites in Houghton Lake with aquatic plants present: 2001–2006.

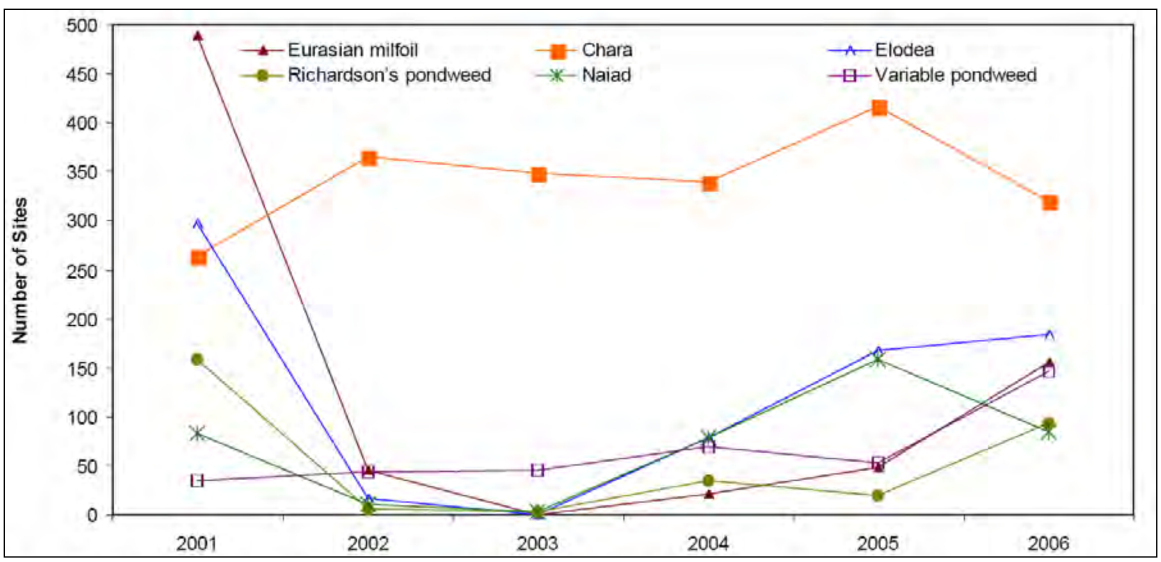


Figure 49. Frequency of occurrence of aquatic plant species in Houghton Lake between 2001 and 2006: Species occurrence greater than 140 sites in at least one of the annual surveys.

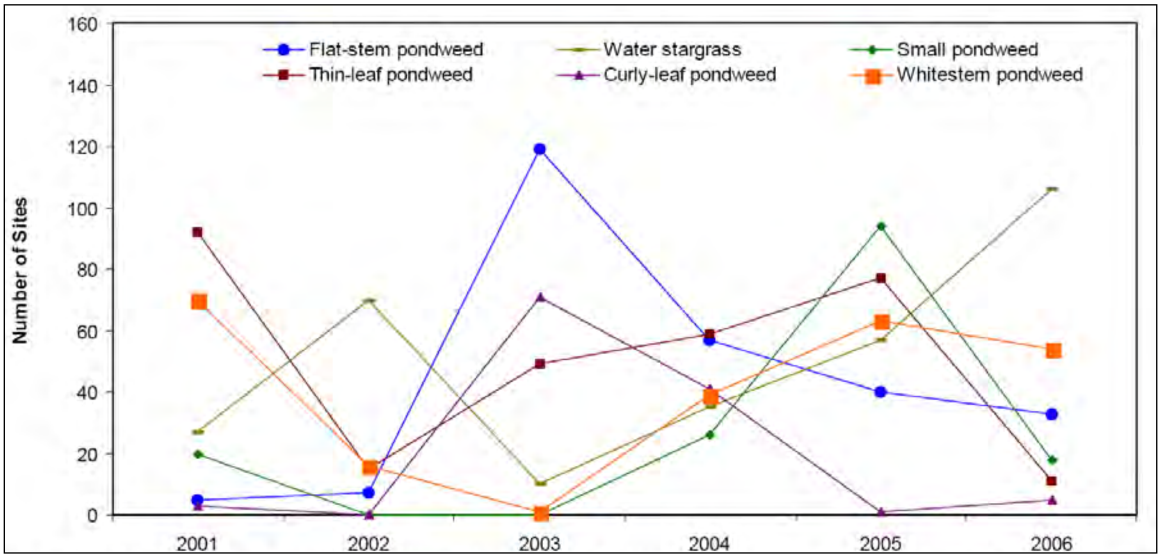


Figure 50. Frequency of occurrence of aquatic plant species in Houghton Lake between 2001 and 2006: Species occurrence between 70 and 120 sites in at least one of the annual surveys.

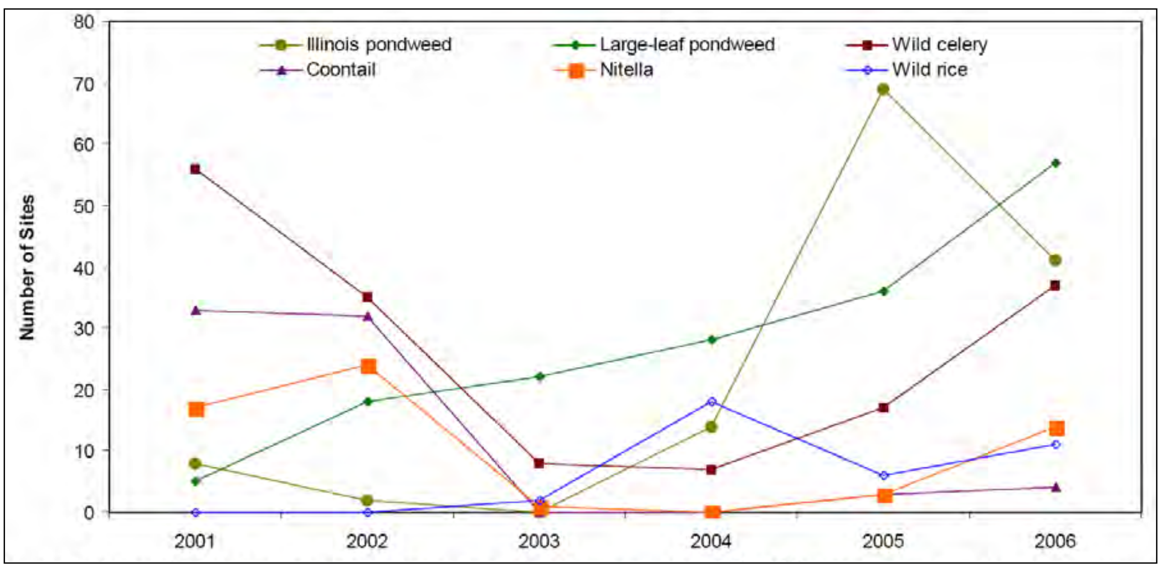


Figure 51. Frequency of occurrence of aquatic plant species in Houghton Lake between 2001 and 2006: Species occurrence between 18 and 69 sites in at least one of the annual surveys.

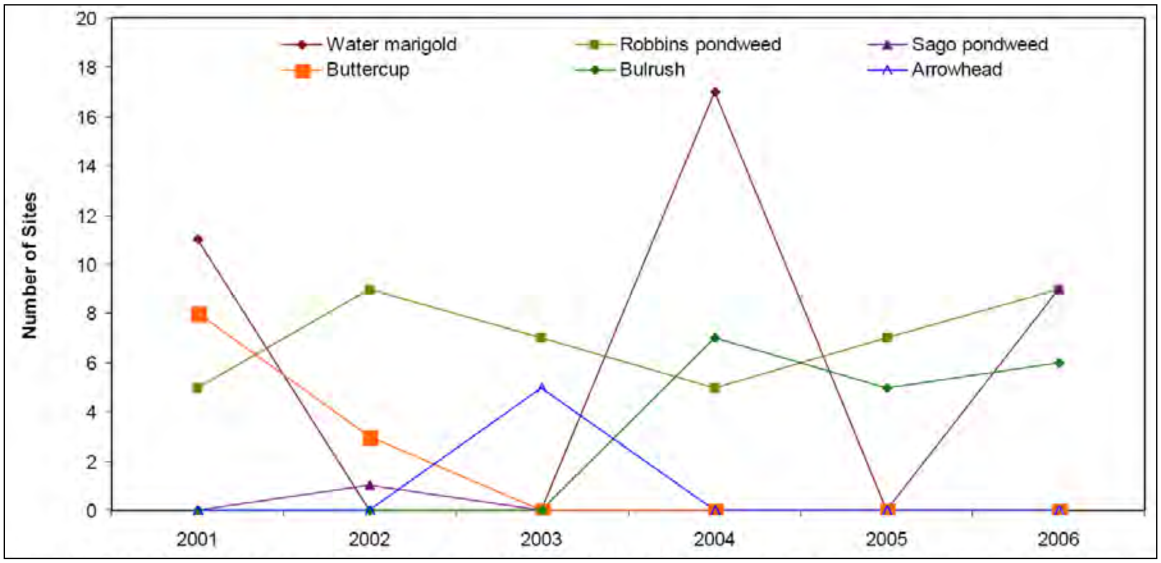


Figure 52. Frequency of occurrence of aquatic plant species in Houghton Lake between 2001 and 2006: Species occurrence between 5 and 17 sites in at least one of the annual surveys.

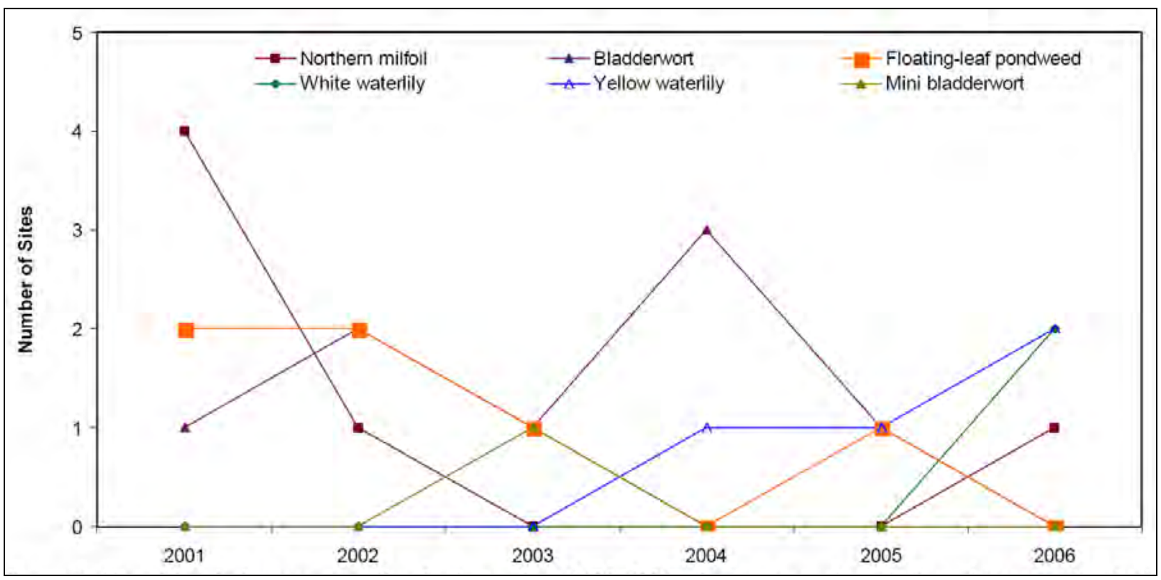


Figure 53. Frequency of occurrence of aquatic plant species in Houghton Lake between 2001 and 2006: Species occurrence between 1 and 4 sites in at least one of the annual surveys.

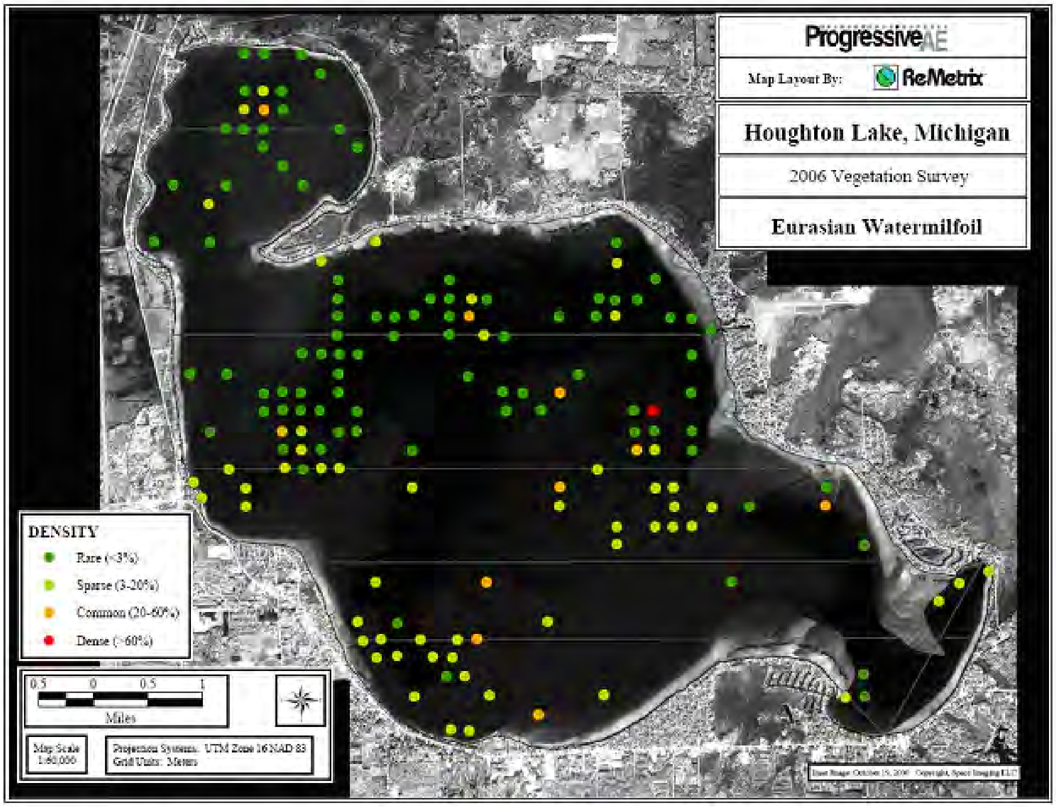


Figure 54. Locations of Eurasian watermilfoil from the 2006 point-grid survey.

Figure 55 is a map of SAVEWS hydroacoustic results from the 2006 survey, and Table 31 and Figure 56 compare biocover and biovolume measurements from 2006 to earlier years of hydroacoustic collection. From 2004 to 2006, average biocover on the six permanent transects increased 225%. A comparison of 2006 (Figure 54) and 2004 (Figure 29) biocover maps shows that the increase was in part due to increased vegetation in areas of the lake outside the primary historical weed beds. Average biovolume actually decreased 62% from 2004 to 2006, indicating that the increased distribution of vegetation in 2006 did not result in large changes in functional architecture of the lake's aquatic plant community or nuisance levels of aquatic plant growth. The lower biovolume lake-wide suggests possible interannual shifts in overall plant community growth due to climatic or other related environmental factors. The increased distribution of Eurasian watermilfoil also indicates that at least part of the increased hydroacoustic detection of plant cover is likely due to expanded milfoil presence. Additional years of hydroacoustic and other vegetation assessment should capture whether the trend from 2004–2006 in increased Eurasian watermilfoil abundance can be held in check by continued small-scale maintenance treatments or whether larger-scale control efforts including a second fluridone treatment may eventually be necessary.

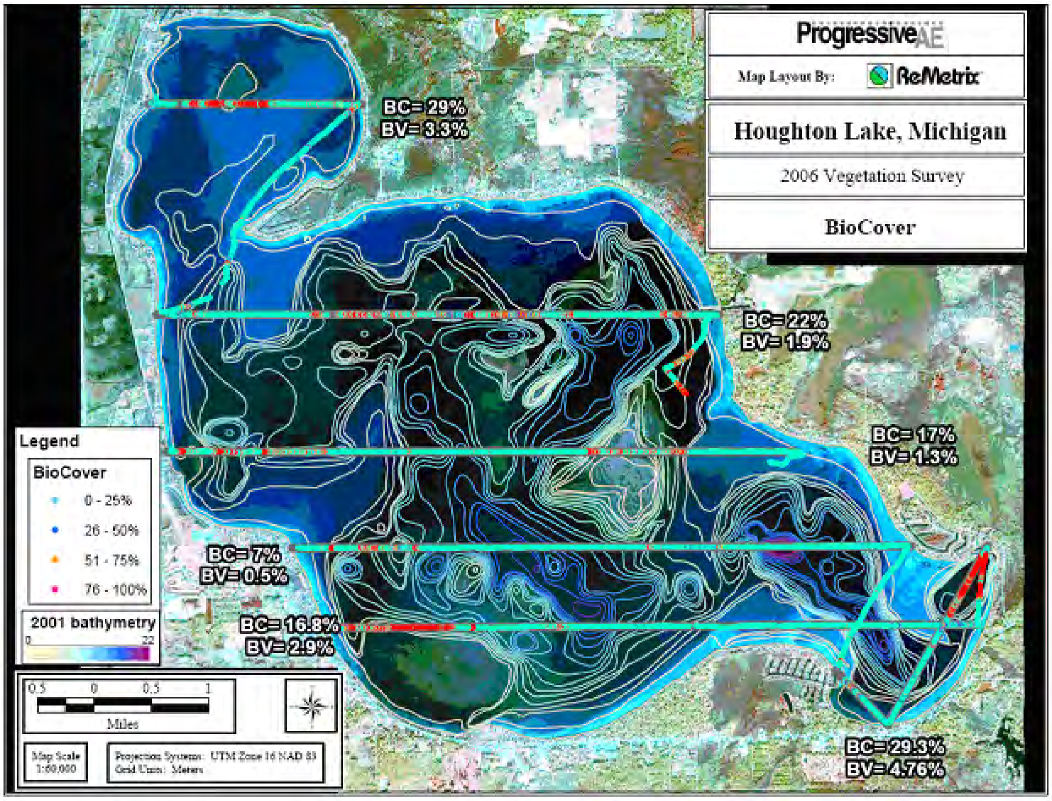


Figure 55. Map of biocover measurements along the six permanent transects, 2006.

Table 31. Transect averages for biocover (the bottom coverage) and biovolume (the portion of water column occupied by plants) of vegetation determined from hydroacoustic assessment of Houghton Lake, Michigan, 2001–2004 and 2006. Transect length analyzed is also provided and used to weight total average by length of individual transects.

Transect ID	BioCover					BioVolume					Transect length (m)
	2001	2002	2003	2004	2006	2001	2002	2003	2004	2006	
1	9.1%	4.1%	3.7%	5.9%	29%	3.8%	1.5%	0.9%	4.8%	3.3%	2,898
2	41.6%	11.5%	6.0%	1.9%	22%	21.9%	4.4%	0.6%	1.4%	1.9%	8,417
3	45.2%	23.4%	13.7%	11.4%	17%	21.4%	6.5%	2.5%	9.0%	1.3%	8,117
4	41.6%	17.8%	0.1%	1.2%	7.0%	13.6%	2.7%	0%	0%	0.5%	8,924
5	45.7%	22.5%	6.3%	27.9%	16.9%	23.1%	5.8%	0.9%	16.2%	2.9%	5,494
6	36.1%	18.6%	2.4%	3.4%	29.3%	14.0%	2.8%	0.5%	2.3%	4.8%	4,190
Total Avg.	**39.9%**	**17.3%**	**5.7%**	**8.0%**	**18.0%**	**17.8%**	**4.3%**	**0.9%**	**5.2%**	**2.0%**	

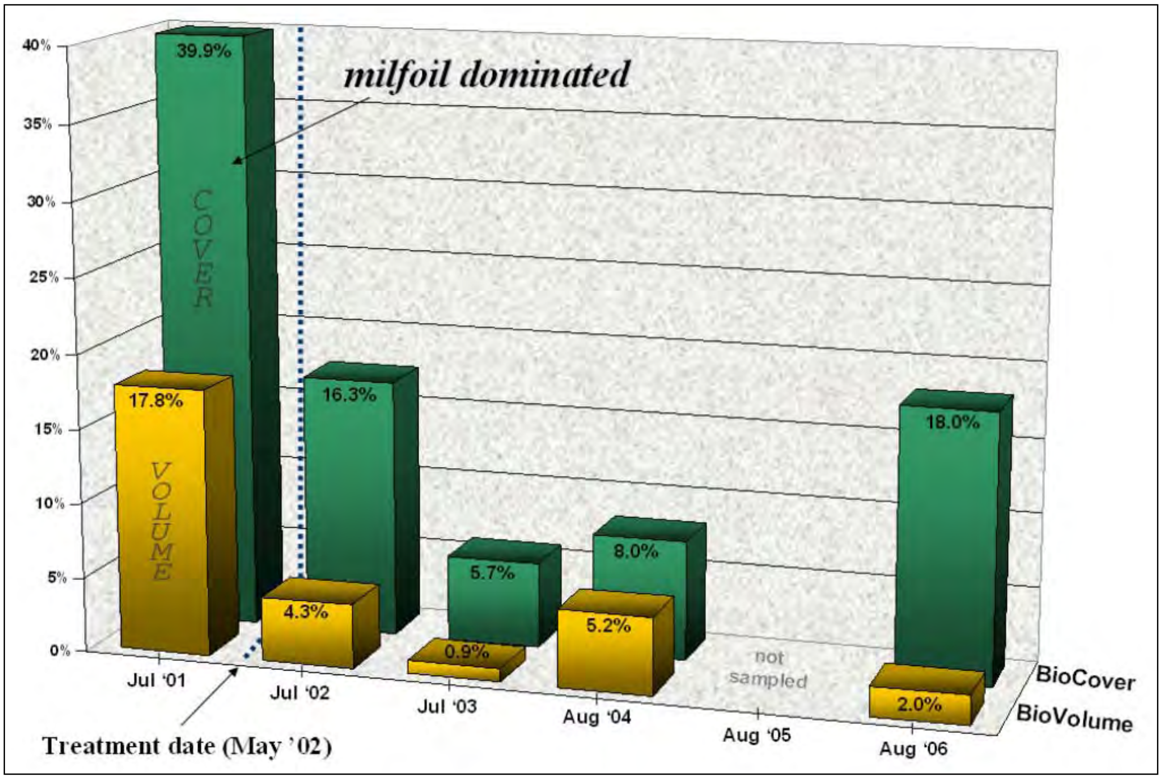


Figure 56. Summary of average biocover and biovolume determined hydroacoustically along six permanent transects in Houghton Lake from 2001–2004 and 2006.

7 Conclusions and Recommendations

Conclusions

Based on the results of this report, the following conclusions were drawn:

1. The whole-lake fluridone treatment phase on Houghton Lake (2002–2004) was successful in controlling Eurasian watermilfoil with minimal, mostly short-term impacts on most native plant species, and no measured impacts on water quality. A shift in the plant community occurred during this phase, with some native plants (e.g., elodea, coontail, and wild celery) recognized as valuable components in northern lakes decreasing, and other ecologically important species (e.g., wild rice, muskgrass, and water stargrass) increasing.
2. The maintenance control phase on Houghton Lake (2004–2006) utilizing an integrated management approach (e.g., targeted spot-treatments with herbicides, establishment of milfoil weevils, and limited mechanical harvesting) kept Eurasian watermilfoil under control. This maintenance control strategy was cost-effective and precluded the need for a second, whole-lake fluridone application.
3. The quantitative vegetation assessments conducted before and in years following fluridone treatment documented management impacts on the plant community of Houghton Lake. The successful combination of georeferenced physical surveys and hydroacoustics (i.e., Submersed Aquatic Vegetation Early Warning System) demonstrates the value of high-quality assessment of target and non-target vegetation following selective management of nuisance aquatic plant species.

Recommendations

Based on the results of this work, the following actions are recommended:

1. A maintenance management program, utilizing a targeted and species-selective approach, should be continued on an annual basis to control Eurasian watermilfoil and other invasive aquatic plants on Houghton Lake.
2. This maintenance plan should be predicated on, and developed, using annual, quantitative lake-wide plant surveys.

3. Houghton Lake community stakeholders should organize and maintain support for continued management of invasive plants in the lake on a regular basis.
4. The Houghton Lake aquatic plant management experience is a viable model for long-term control of Eurasian watermilfoil in other large water bodies in the northern tier states.

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Appendix A: Field Notes from 2001 Houghton Lake Water Quality Survey by the Michigan Water Research Center at Central Michigan University

THE MICHIGAN WATER RESEARCH CENTER
CENTRAL MICHIGAN UNIVERSITY

Houghton Lake Field Notes
23 September 2001

Inflowing Streams

Site 1: Sucker Creek @ Houghton Lake Drive 3:13 pm
The creek is not currently flowing. No water is in most of the channel upstream of the road and only a little water remains in a few holes. Samples were taken from the hole downstream of the road, but these should not be considered indicative of water quality during periods of the year when the creek is flowing. A variety of emergent macrophytes are found in the river channel.

Site 2: 3:32 pm
No water exists here now. No water samples collected. The creek appears to be little more than a roadside ditch that drains a swamp on the north side of the road.

Site 3: The Cut River (labeled Bachus Creek on our map) 3:55 pm
The Cut was hard to follow below E. Houghton Dr. because so many canals have been dredged to accommodate boaters. The sample was taken off the bridge to ensure that it was representative of the river and not stagnant canal water or in-flowing lake water (which may influence water in the river or channel south of here if the mouth is dredged. The end of Markey Road provides access to the canal area.

At E. Houghton Lake Bridge, the river was about 1.5 meters deep at maximum. Emergent Bur reeds and grasses lined the banks. Recent rains have swollen the river, resulting in flooded vegetation up to 30 feet from the banks. Despite this, the river is clear, though slightly tannin-stained. The thalweg has many macrophytes including *Vallisneria* and *Potamogeton sp*. Substrate is sand and organic material.

Site 4: 4:33 pm
The light rain that was falling since I arrived just turned to a steady downpour. This site appears to be nothing more that a canal. It is not marked on the Delorme Atlas. I assume that some tiny 1st order stream pours into the canal somewhere upstream from here. Most of the water in the canal may come from the lake depending on the water level, wind and seiche, etc. There appears to be no current here at all, but the tannin–stained water is evidence of some input from surrounding wetlands. Aquatic plants are diverse and abundant.

Site 5: Spring Brook Creek 5:04 pm
A nice little cold-water creek with good flow to it. Narrow (6-15') and shallow (8" max) near the bridge. Small fish are abundant (chubs?). Probably holds brook trout. Substrate is sand and detritus.

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Site 6: Denton Creek 5:17 pm
Still raining hard. The creek has cement seawalls on both sides. Substrate is sand. Milfoil and water lilies grow in the creek. No fish apparent.

Site 7: Knappen Creek 5:34 pm
Still raining hard. Overland flow entering at road crossing had discolored margins of the river with turbid rainwater. Samples were taken away from turbid area in the thalweg (<0.3 m deep). This creek isn't built up with seawalls like Denton Creek, but it is similar in size. Most of the creek bottom is sand with detritus in depositional zones. A few small minnows were seen under the bridge.

Outflowing Stream
Site 8: Muskegon River @ old 27 2:33 pm
Sediments were rich in organic matter. Abundant macrophytes, water lilies and pickerel weed, along margins with milfoil in thalweg. River barely flows here and water is clear despite the light rain that has been falling for a couple of hours. Water spiders and aphids were abundant in pickerel weed. Hydrolab readings were taken from the bridge over thalweg. Water bottles were filled at the edge of emergent vegetation.

22 September 2001

North Bay: Open Water Sites
Site 9: 9:53 am
Sun is just starting to burn off the thick fog. Not rooted macrophytes, just organic sediments with some sand and *Cladophora*. Some Eurasian Milfoil segments were observed drifting.

Site 10: near constriction in lake 10:21 am
Depth here was less than 2 m. Rooted vegetation was fairly sparse. Sediment was mostly clay. Saw some broad-leafed pondweeds.

Main Body Open Water Sites
Site 11: 11:14 am
This site was deeper than North Bay sites with abundant, but not excessively dense, macrophytes -- lots of broad-leafed *Potamogeton sp.* and *Myriophyllum.* Some adult Chironomids were observed. Filamentous green algae found amongst macrophytes. This area is not as open as some other main body locations.

Site 12: 1:33 pm
We found the sunken island north of here, but it was fairly weedy, so we decided to use this as our #12 open water site. The weeds here were sparse and diverse—*Elodea,*

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Potamogeton, Myriophyllum. Weather was now partly cloudy. Saw a flock of ~ 40 cormorants headed to this site. Sediments were organic muck.
Site 16: Deep Hole 3:01 pm
No weed growth present. Not stratification apparent. Clay bottom.

Site 21: Deep Hole 3:45 pm
As deep as site 16, but with abundant Milfoil growing. Some clumps of Milfoil reach 6 feet from the surface. Growth is not excessively dense here though. Clay/organic sediments were present.

Site 13: Deep Hole 4:08 pm
No macrophytes present. Clay bottom. Cloudy sky.

Main Body Weed Sites
Site 20: 11:51 am
Area due east of site 11 was quite weedy. This site has dense stands of Milfoil with almost nothing else, but the plants do not reach the surface.

Site 19: 12:18 pm
Extremely dense *Myriophyllum* bed with no other species present. Not sure it was where 19 was supposed to be, but it was an excellent weed site. Some Chironomids were active. Sun was bright and no clouds or fog overhead.

Site 17: 1:08 pm
There was a *very dense* Milfoil monoculture here, also abundant Chironomids and young fish, mostly Centrarchids. Observed two large fish feeding (bass?). Some dragonflies present, mating. Weeds here reached surface and in some nearby areas formed what appeared to be a very dense green carpet. Fish were more abundant here than at previous sites. Bottom was rich organic matter.

Site 18: 2:33 pm
Site 18 was located just off weed bed in front of launch due to the fact that we saw no comparable weed bed at map location for site 18 on the way in. Here, there was dense Milfoil with few other plants (some *Potamogeton*). Sediments were organic.

Southeast Bay
Site 15: Open Water, Deep Hole 4:40 pm
No rooted macrophytes here. Looks like a good migration route for fish—the hole was in a channel between a shallow sandbar with a steep drop-off and another steep drop-off. Sediments mostly fine organics with coarse organic matter also appearing. Decomposing wood and leaves came up on the anchor.

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Site 14: Open Water Site 5:01 pm
Myriophyllum was present, though not dense. Water was 3.5 m deep with macrophyte tips at least 1.5 m from surface. Sediments were organic.

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Appendix B: 2001 ReMetrix Vegetation Assessment

Final vegetation maps for various species and cumulative density maps

Survey Sites
Eurasian Watermilfoil – Distribution and Abundance
Elodea – Distribution and Abundance
Muskgrass – Distribution and Abundance
Clasping-leaved Pondweed – Distribution and Abundance
Thin-leaved Pondweed – Distribution and Abundance
Naiad – Distribution and Abundance
Whitestem Pondweed – Distribution and Abundance
Wild Celery – Distribution and Abundance
Variable-leaved Pondweed – Distribution and Abundance
Coontail – Distribution and Abundance
Water Stargrass – Distribution and Abundance
Nitella – Distribution and Abundance
Water Marigold – Distribution and Abundance
Illinois Pondweed – Distribution and Abundance
Buttercup – Distribution and Abundance
Large-leaved Pondweed – Distribution and Abundance
Flatstem Pondweed – Distribution and Abundance
Northern Watermilfoil – Distribution and Abundance
Robbins' Pondweed – Distribution and Abundance
Curly-leaved Pondweed – Distribution and Abundance
Floating-leaved Pondweed – Distribution and Abundance
Bladderwort – Distribution and Abundance
Number of Submersed Species
Vegetation Density (All Species) – Summer 2001
Plant Architecture (All Species) – Summer 2001

Hydroacoustic transects for vegetation assessment – July 24, 2001

Map of positions of six hydroacoustic transects

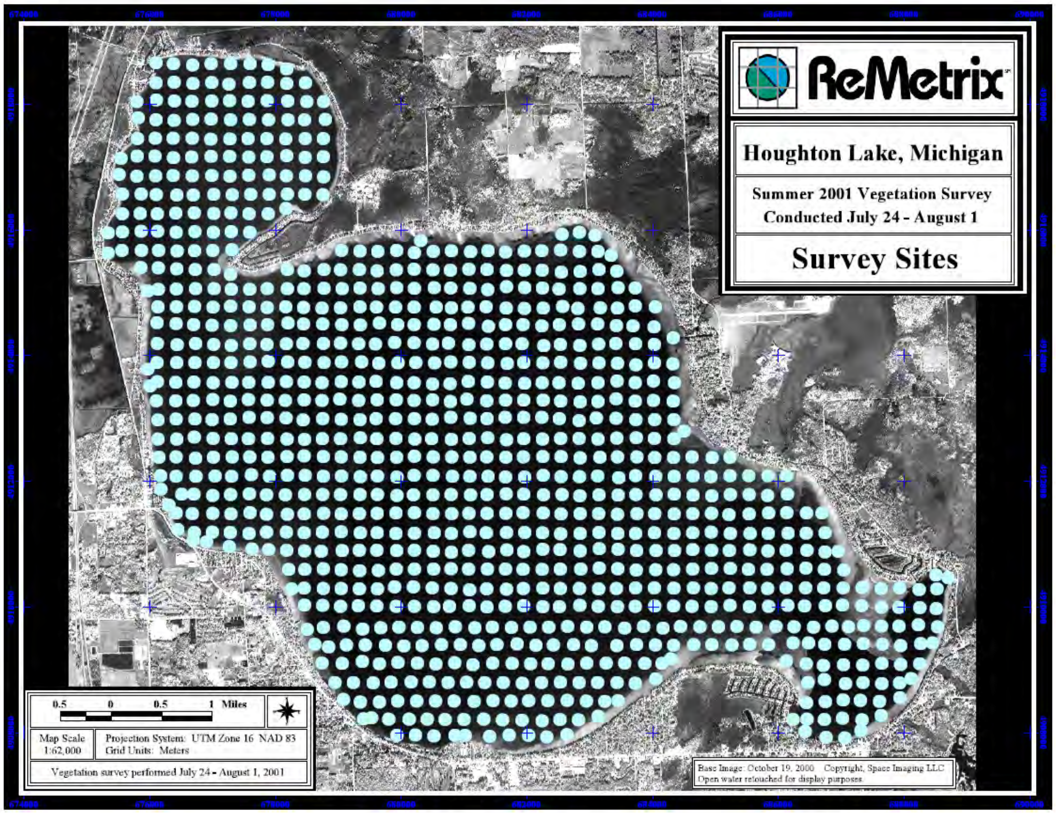
Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transects 1-6 (July 24, 2001)

2001 Houghton Lake satellite base imagery and classification (August 6 and September 30)

True Color IKONOS satellite image of Houghton Lake, Michigan
False Color IKONOS satellite image of Houghton Lake, Michigan

Classification of IKONOS satellite image of Houghton Lake, Michigan

IKONOS classification with overlay of common and dense Eurasian watermilfoil sites


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Conducted July 24 - August 1
Survey Sites
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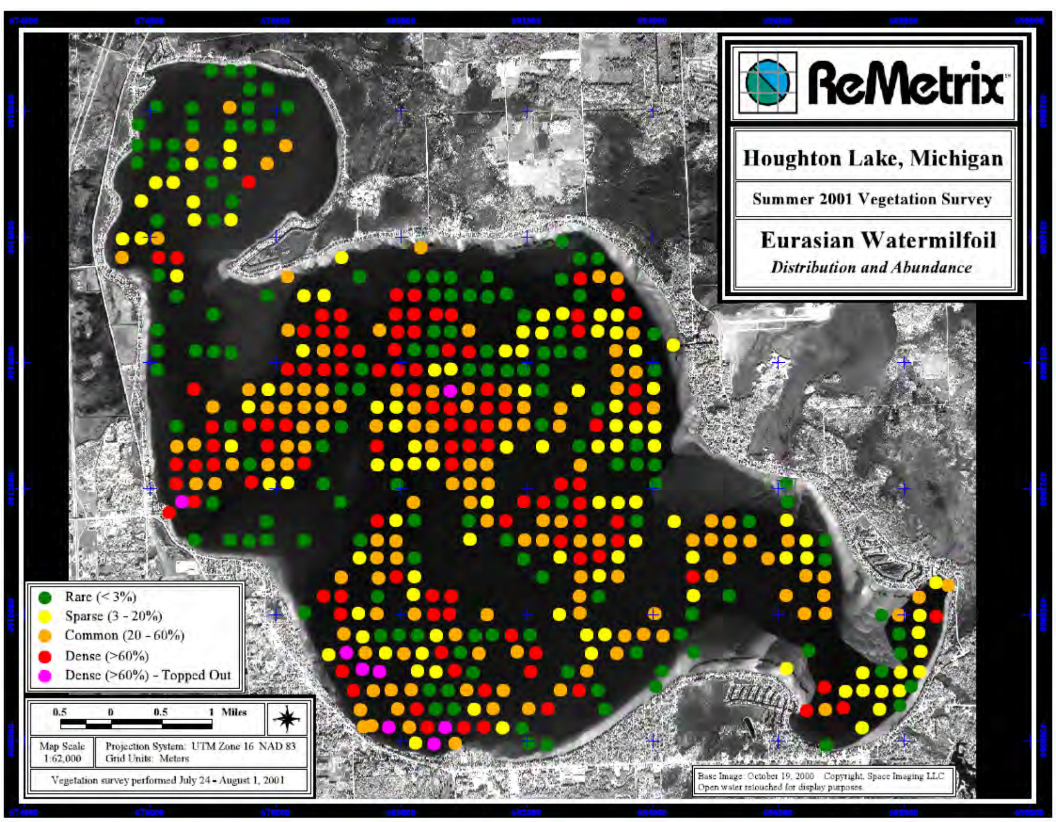
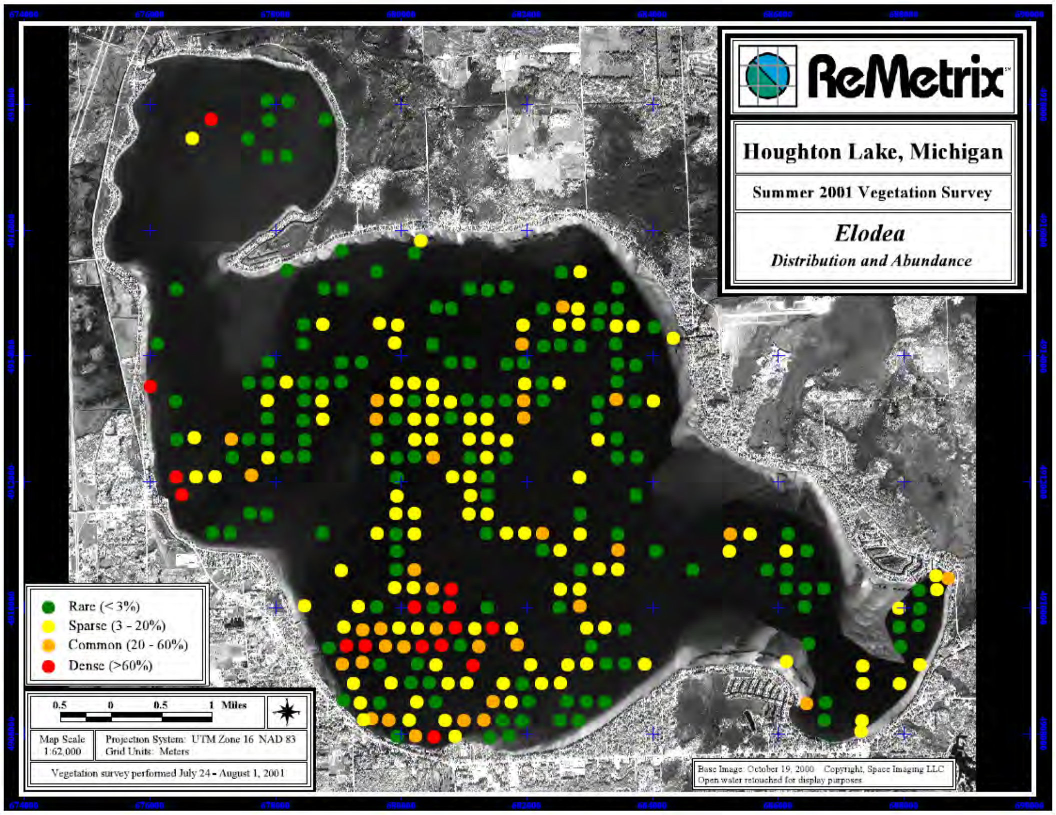
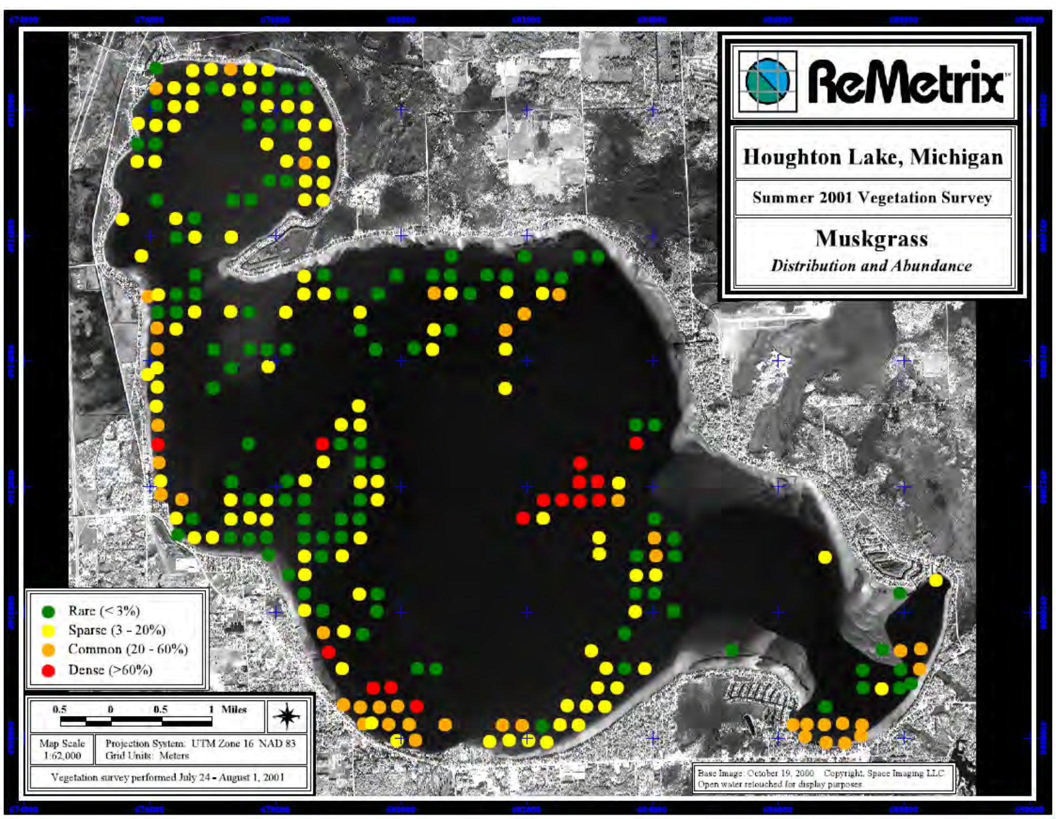
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes.


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Eurasian Watermilfoil
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
Dense (>60%) - Topped Out
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes.


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Elodea
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Muskgrass
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
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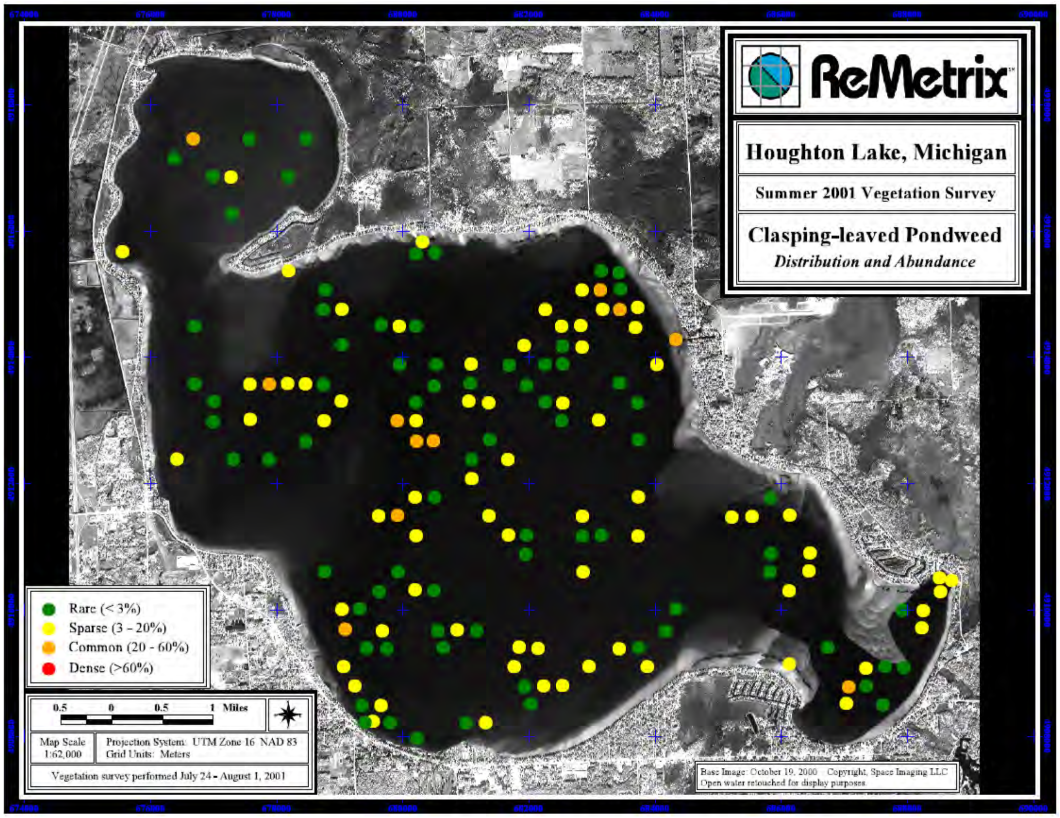
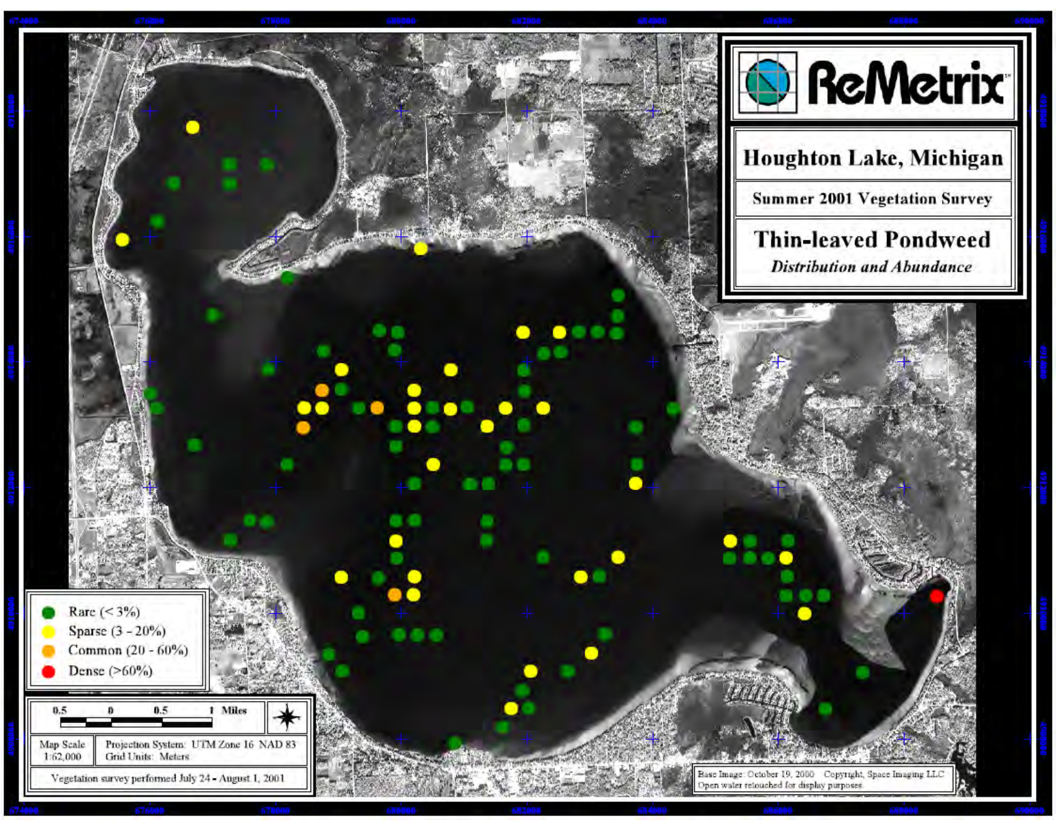
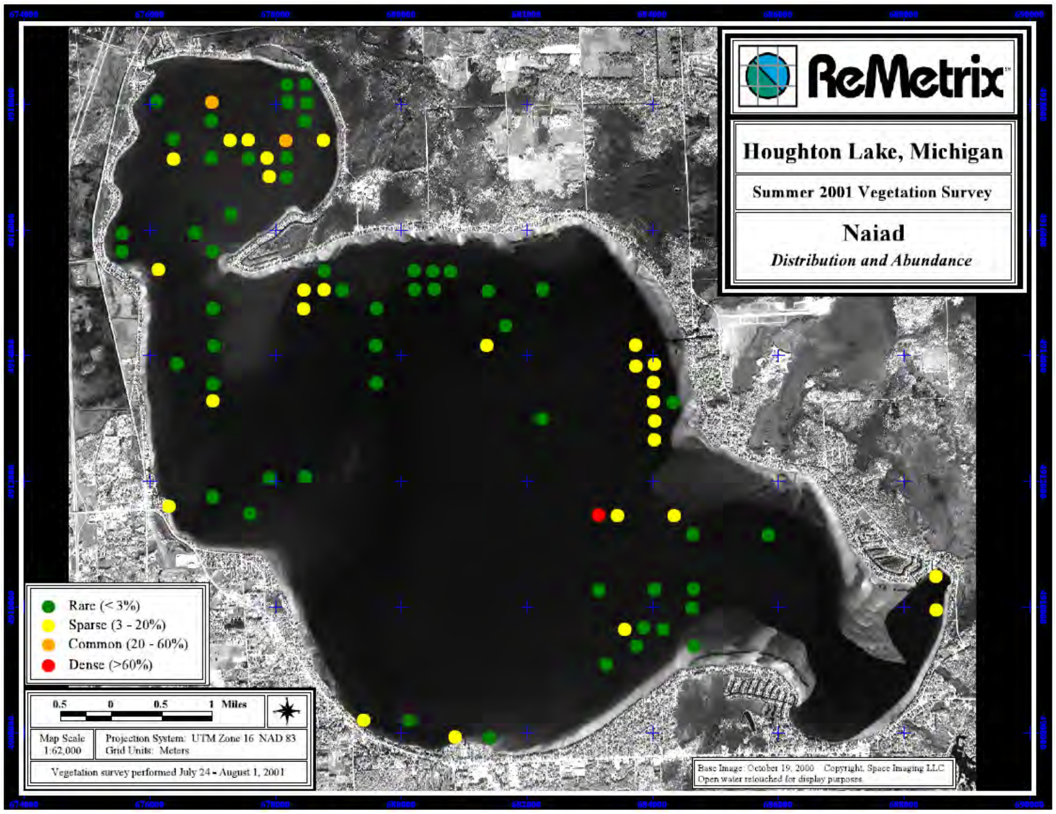
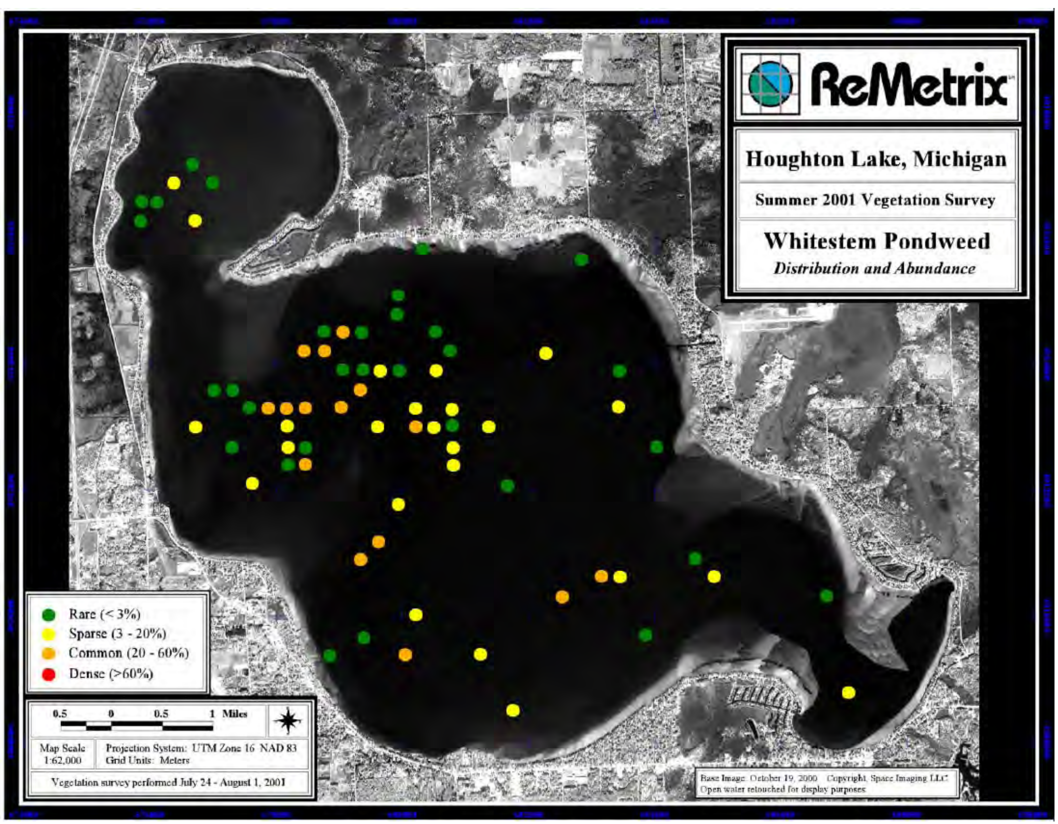
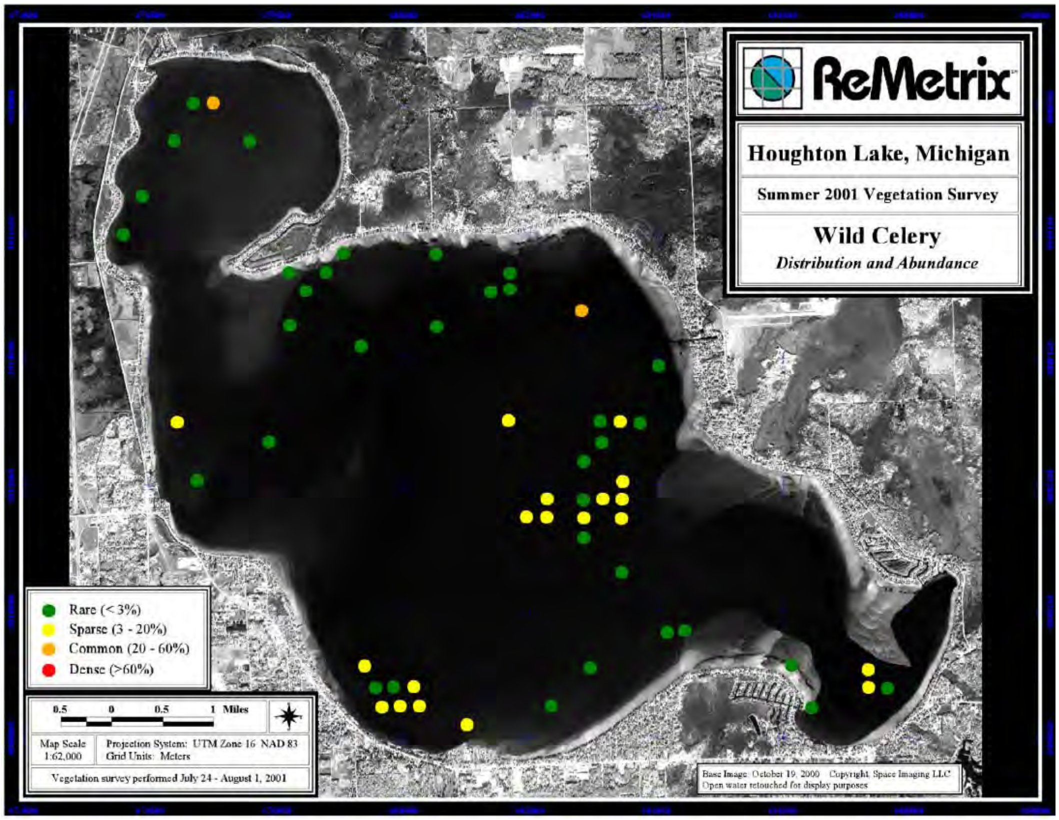
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

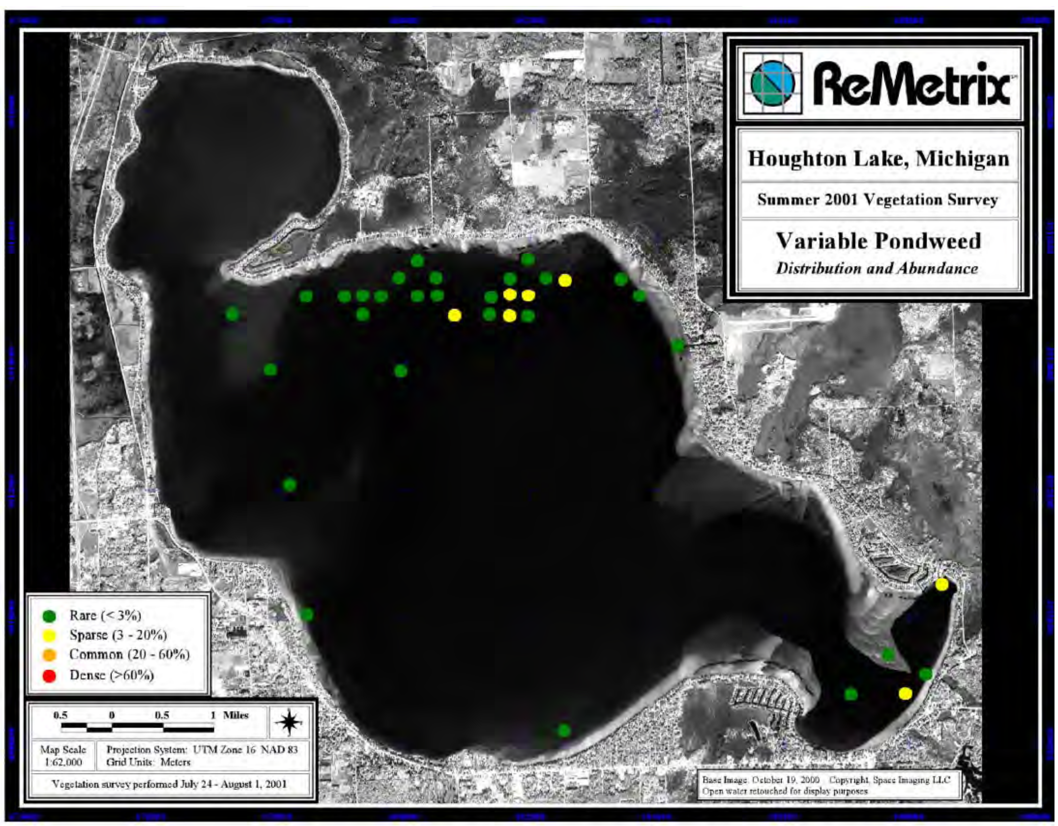

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Clasping-leaved Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

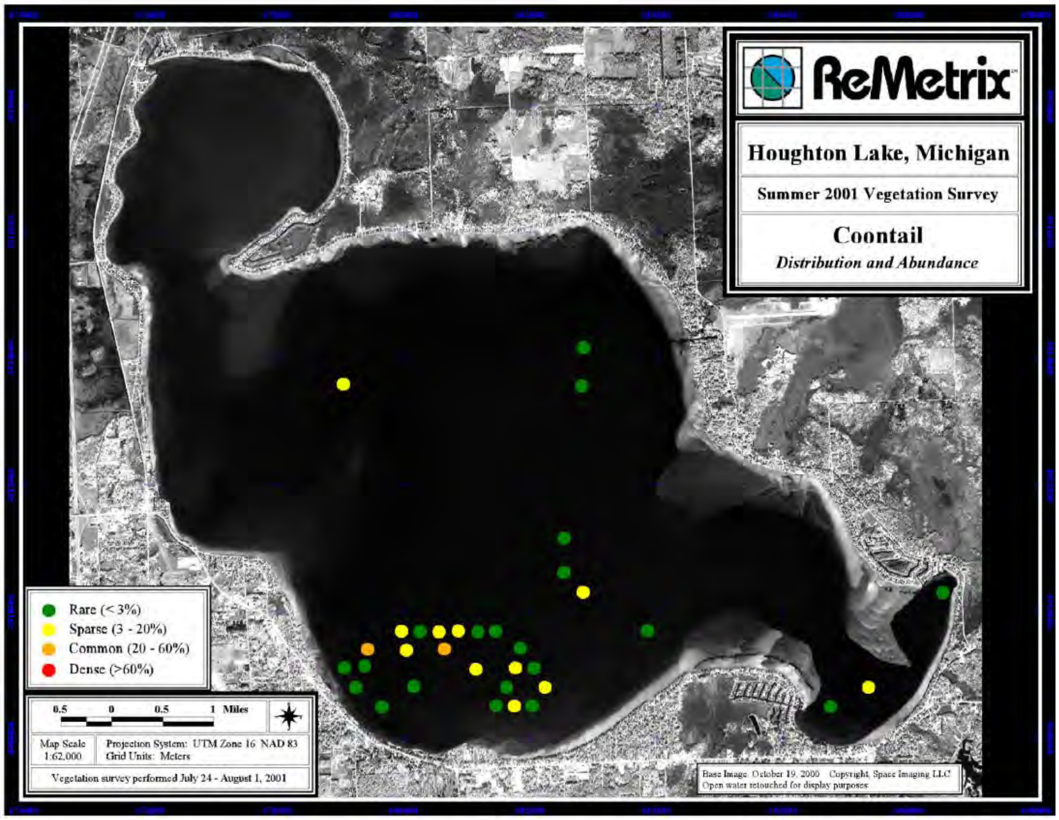

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Thin-leaved Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

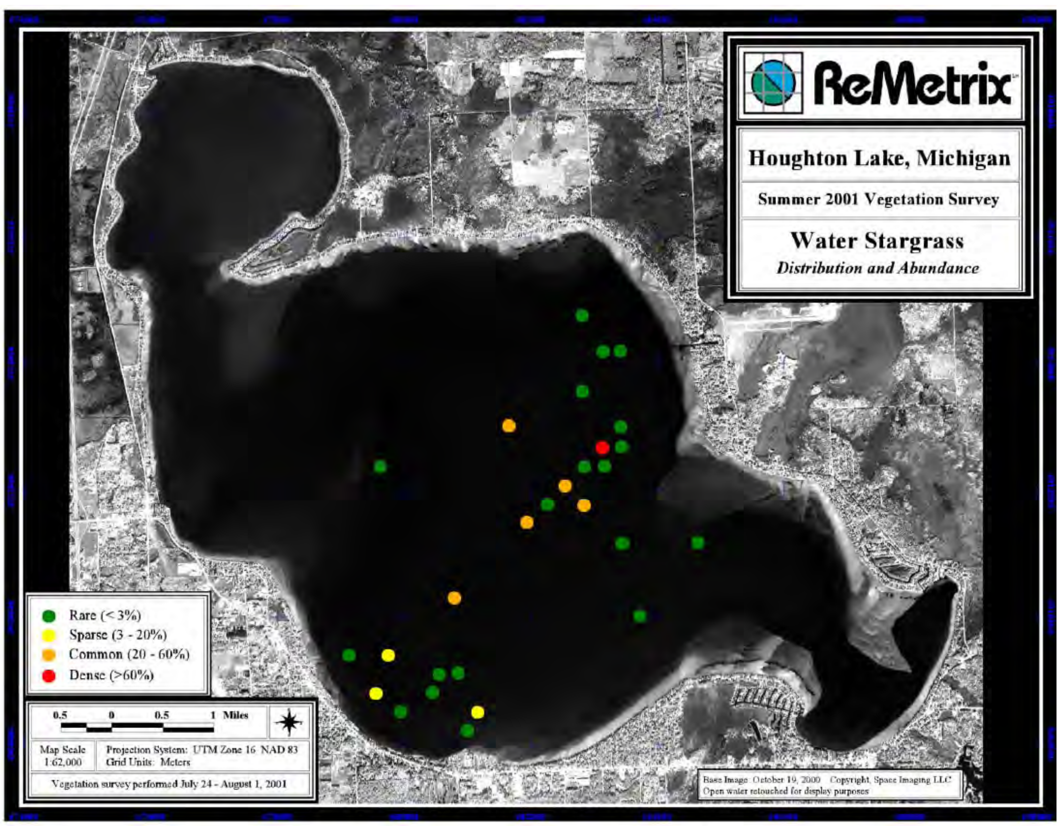

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Naiad
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes.

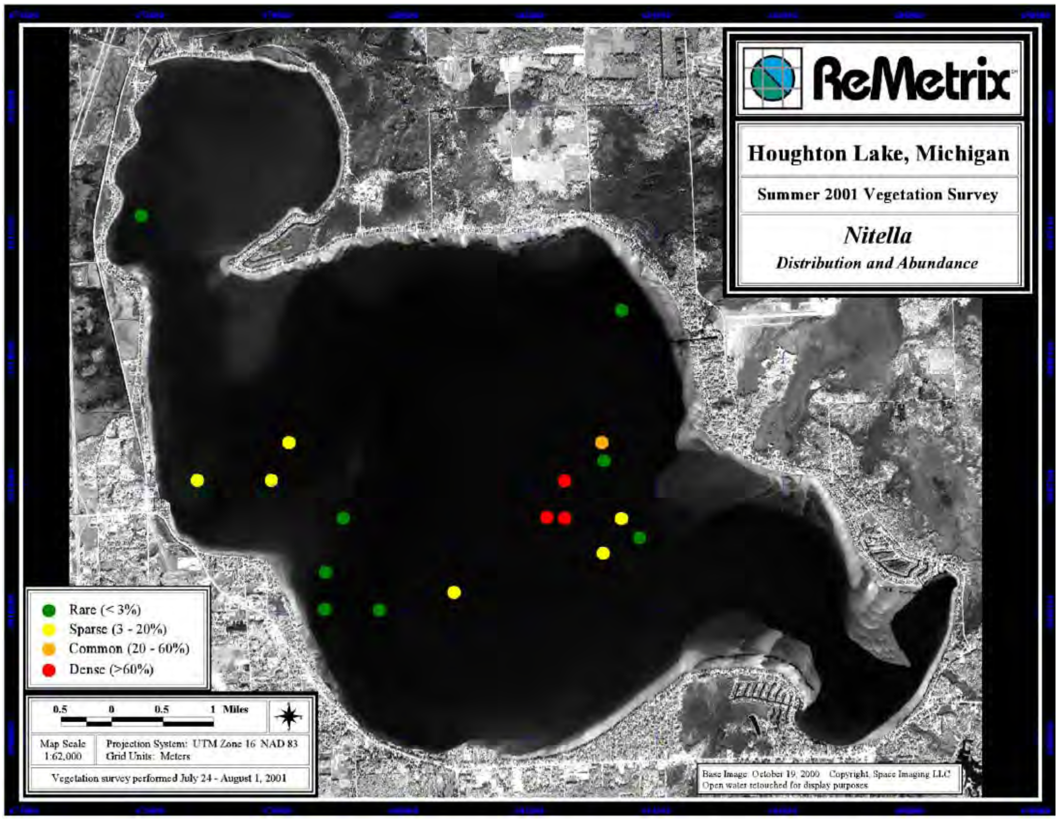

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Whitestem Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes.

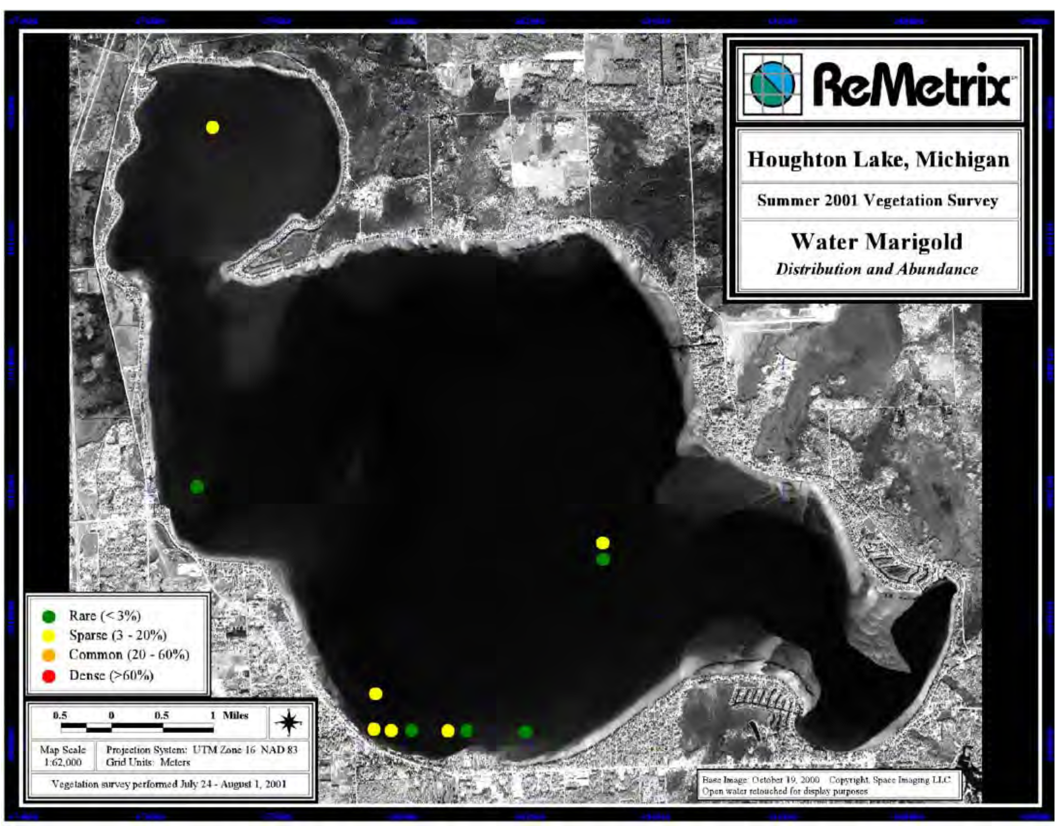

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Wild Celery
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

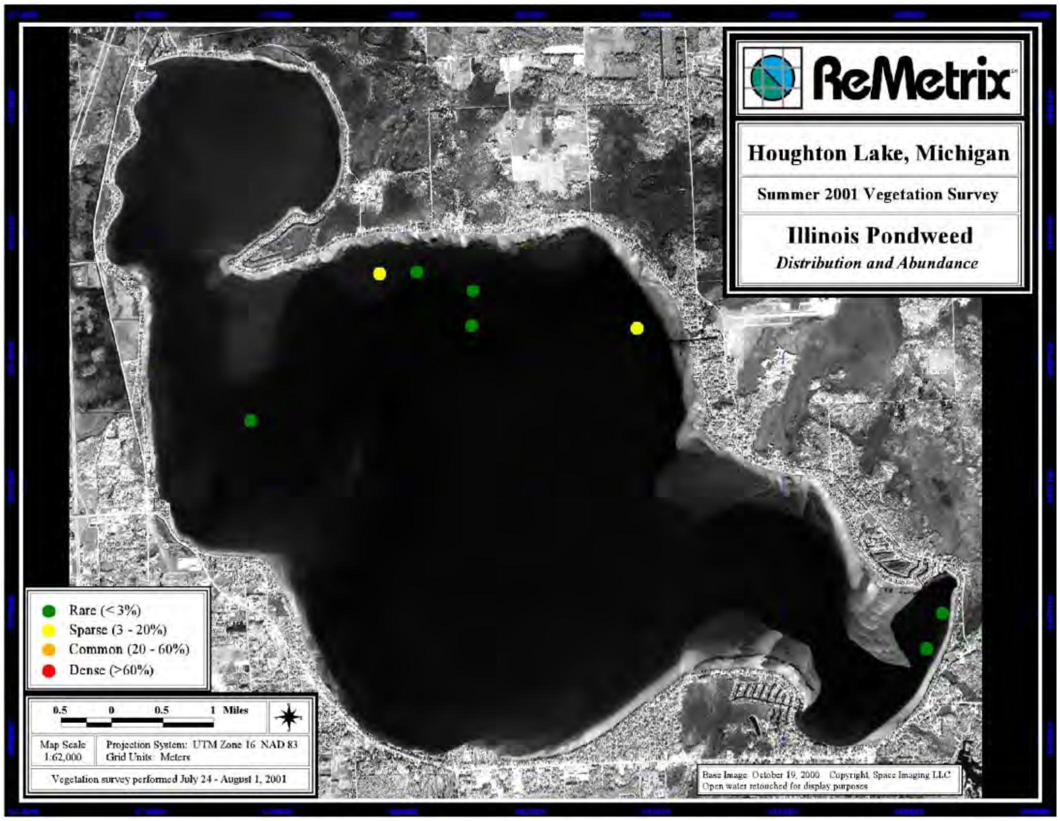

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Variable Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

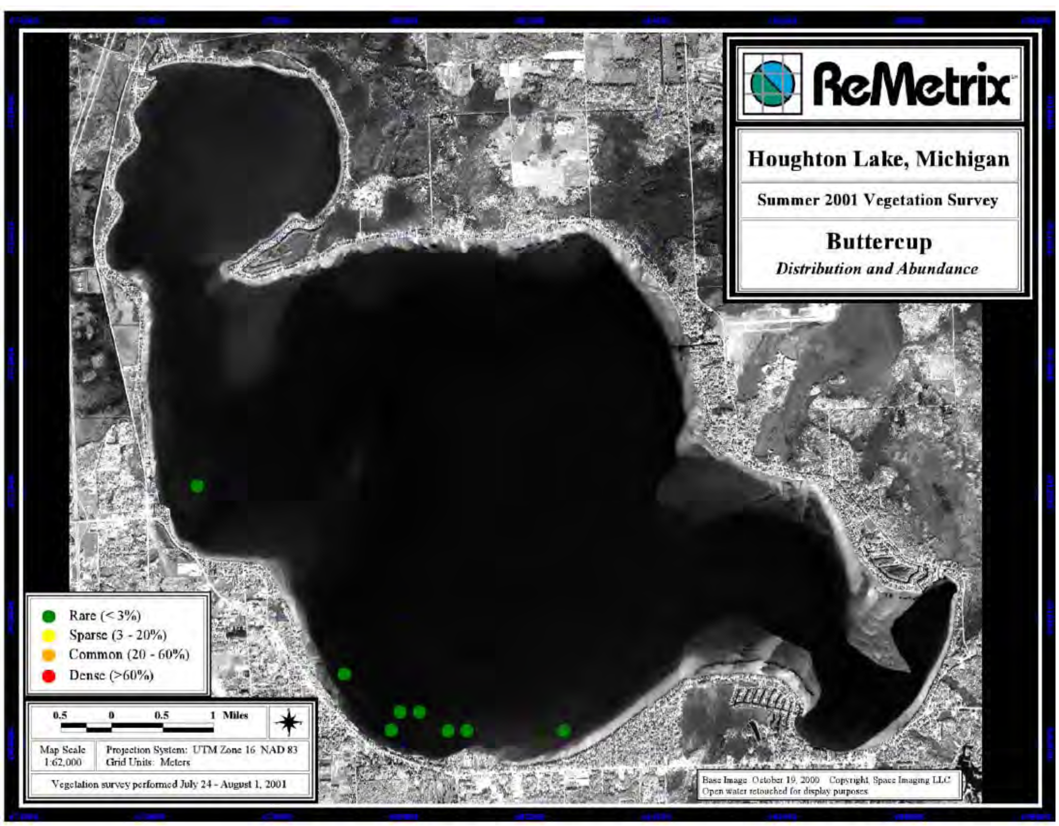

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Coontail
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

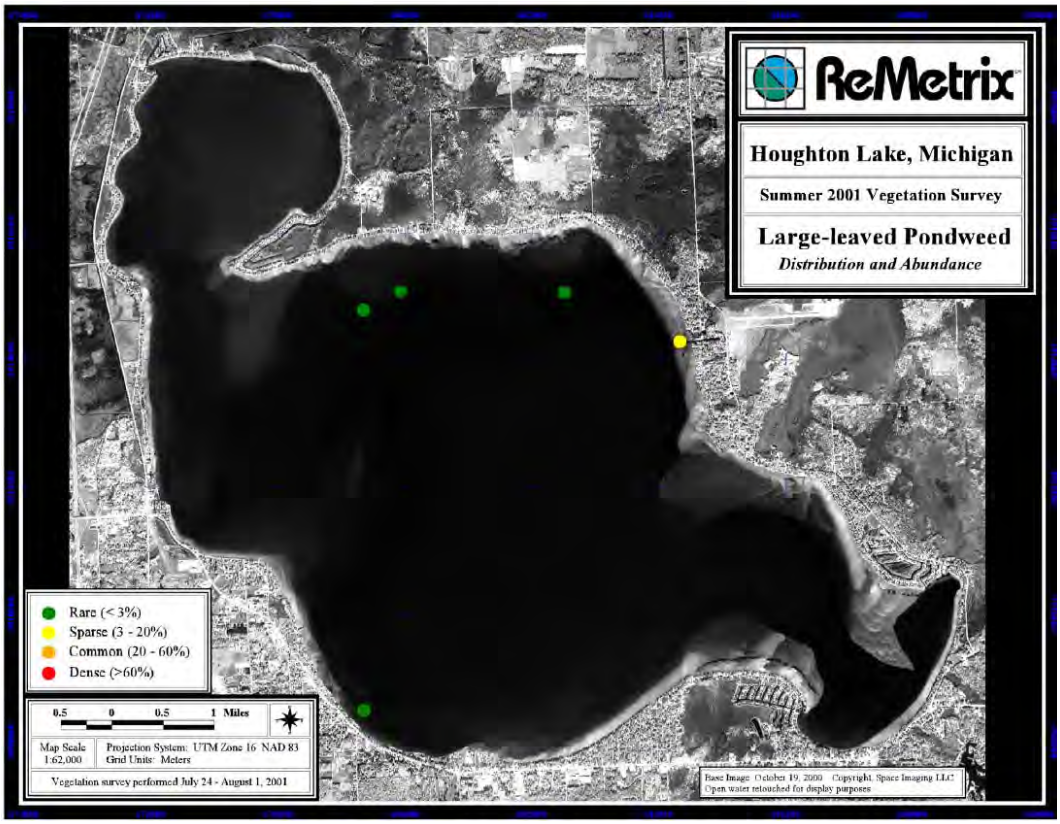

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Water Stargrass
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

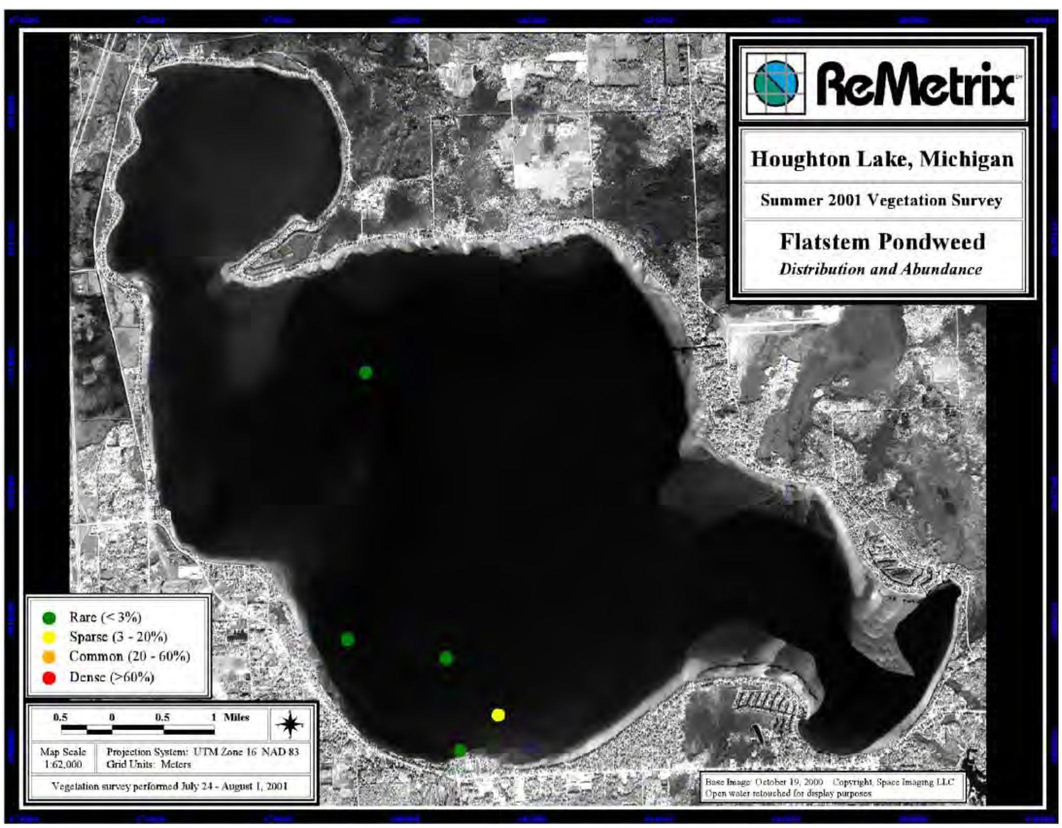

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Nitella
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

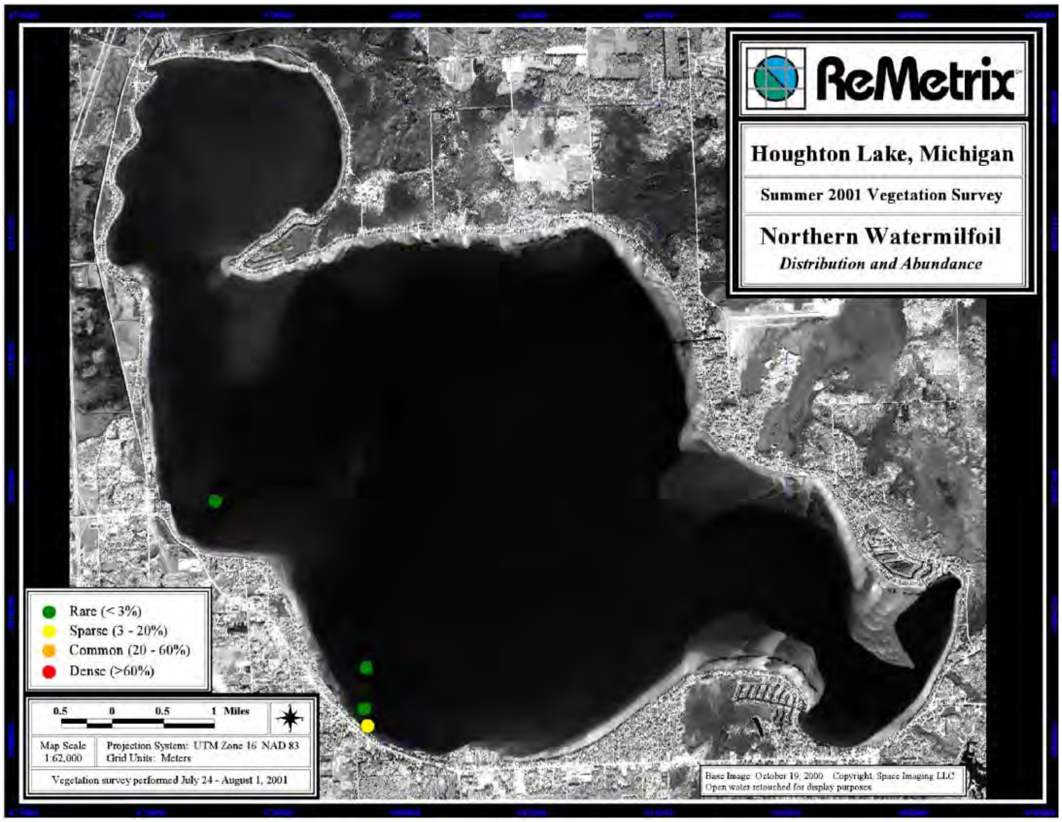

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Water Marigold
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Illinois Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

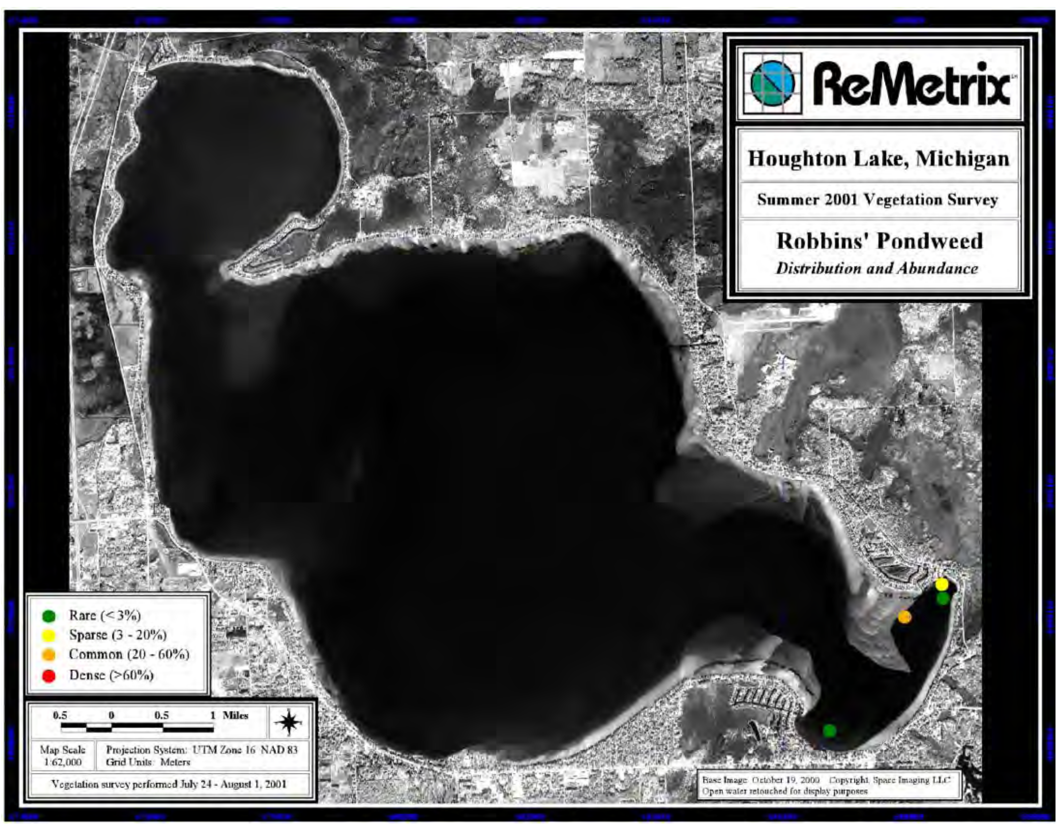

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Buttercup
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Large-leaved Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

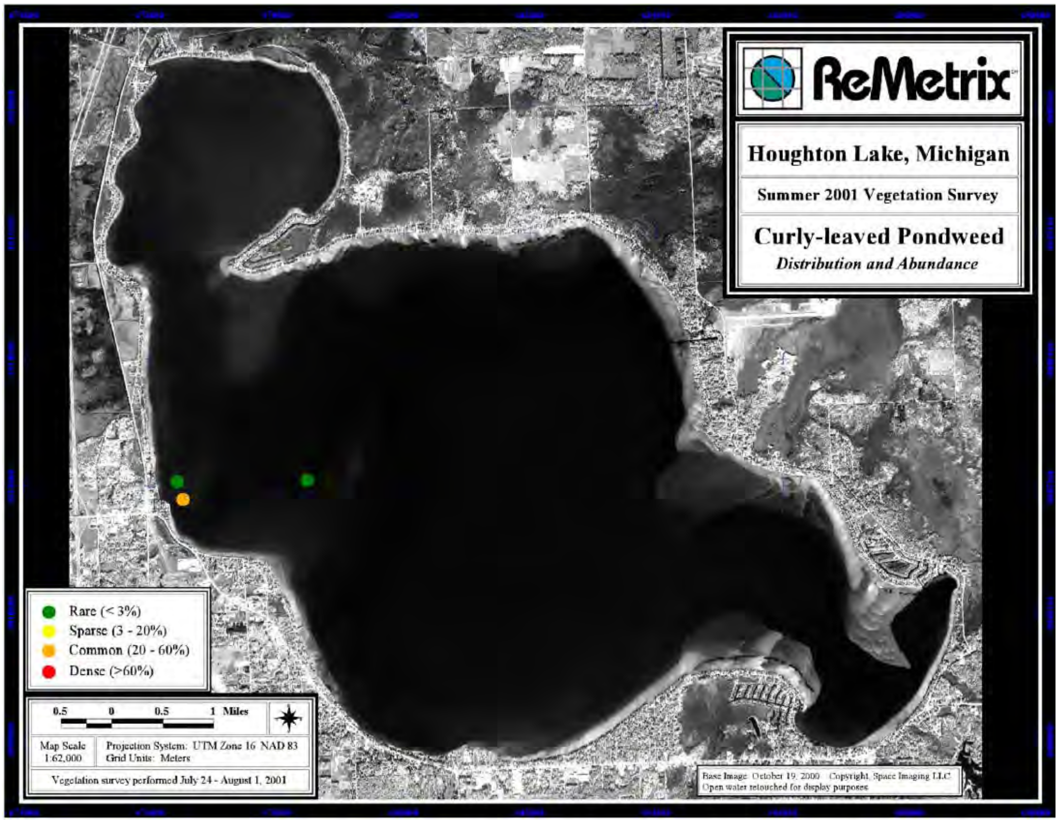

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Flatstem Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

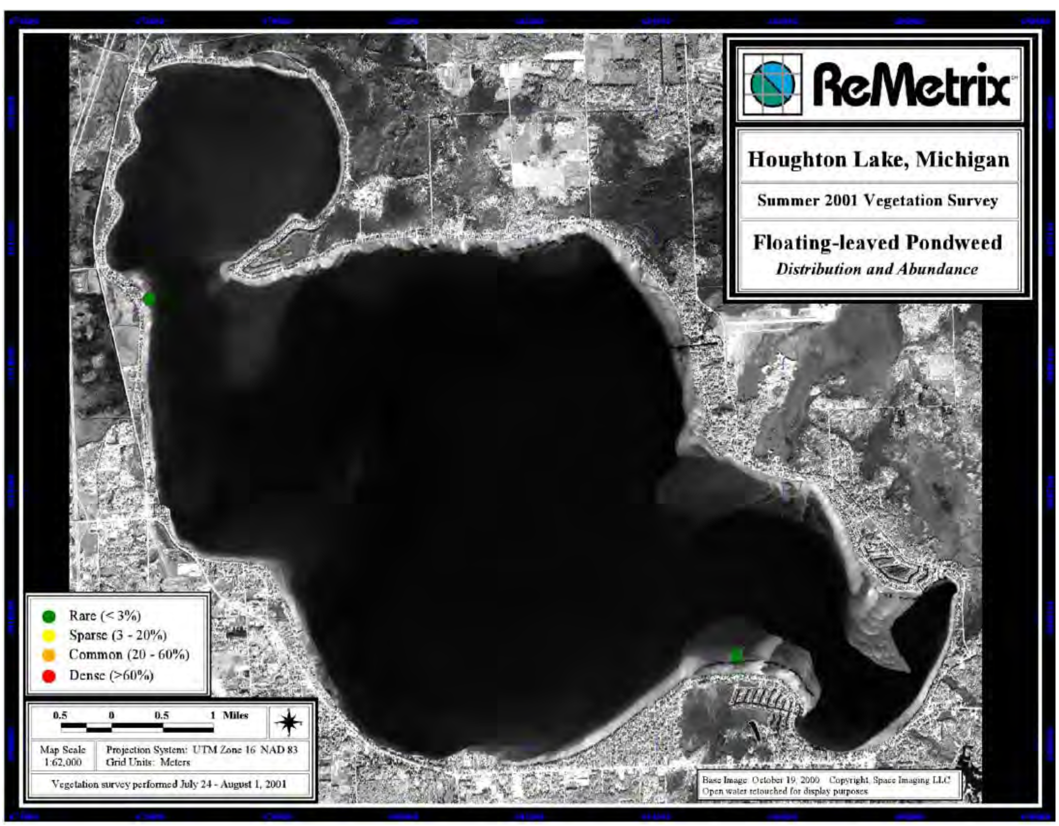


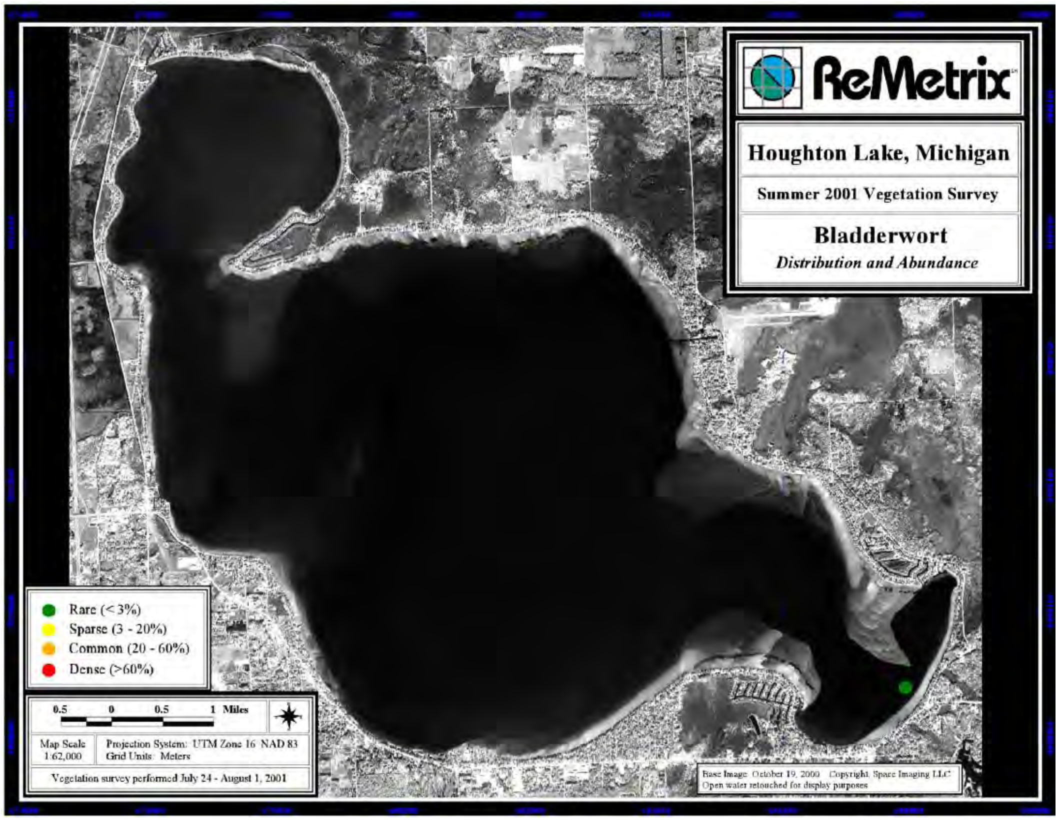
ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Northern Watermilfoil
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright Space Imaging LLC
Open water retouched for display purposes

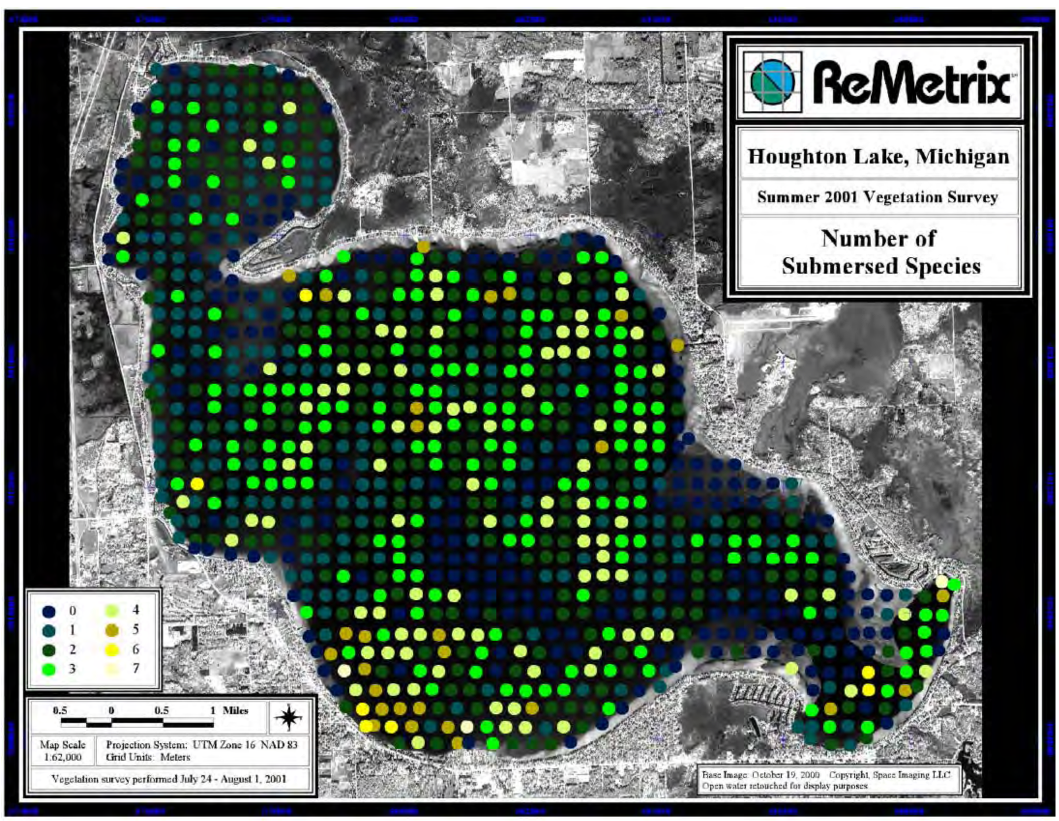


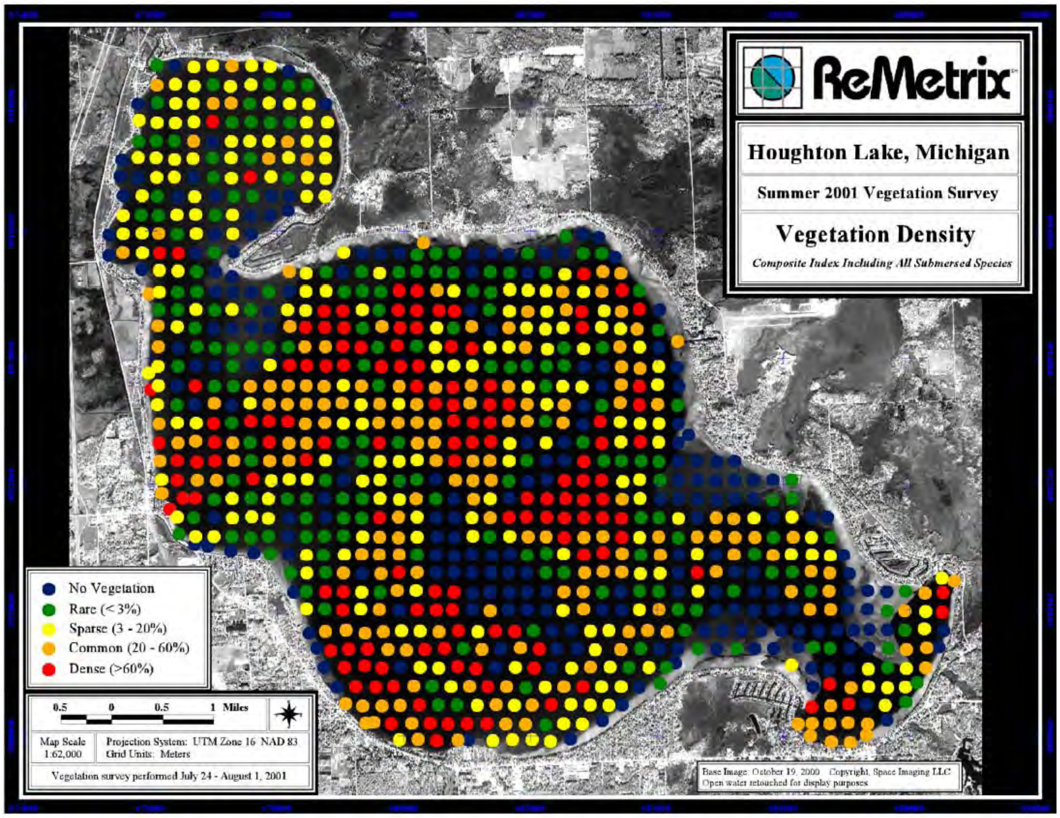
ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Robbins' Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright Space Imaging LLC
Open water retouched for display purposes

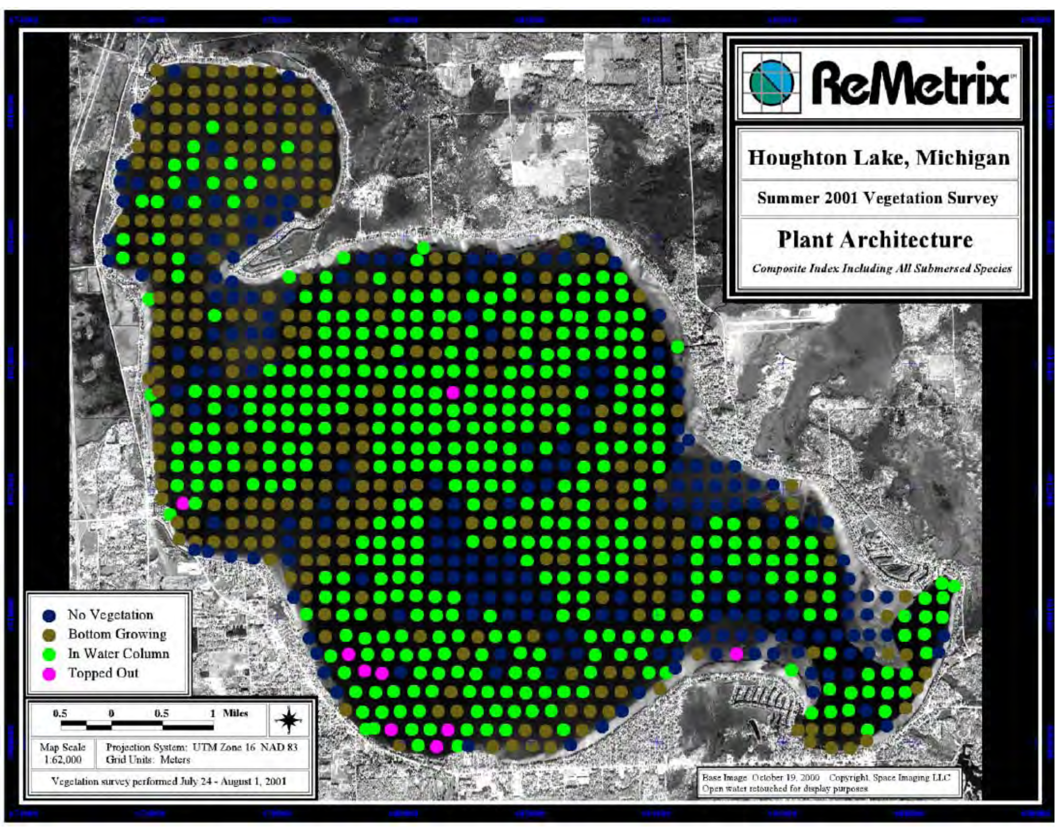

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Curly-leaved Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Floating-leaved Pondweed
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Bladderwort
Distribution and Abundance
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

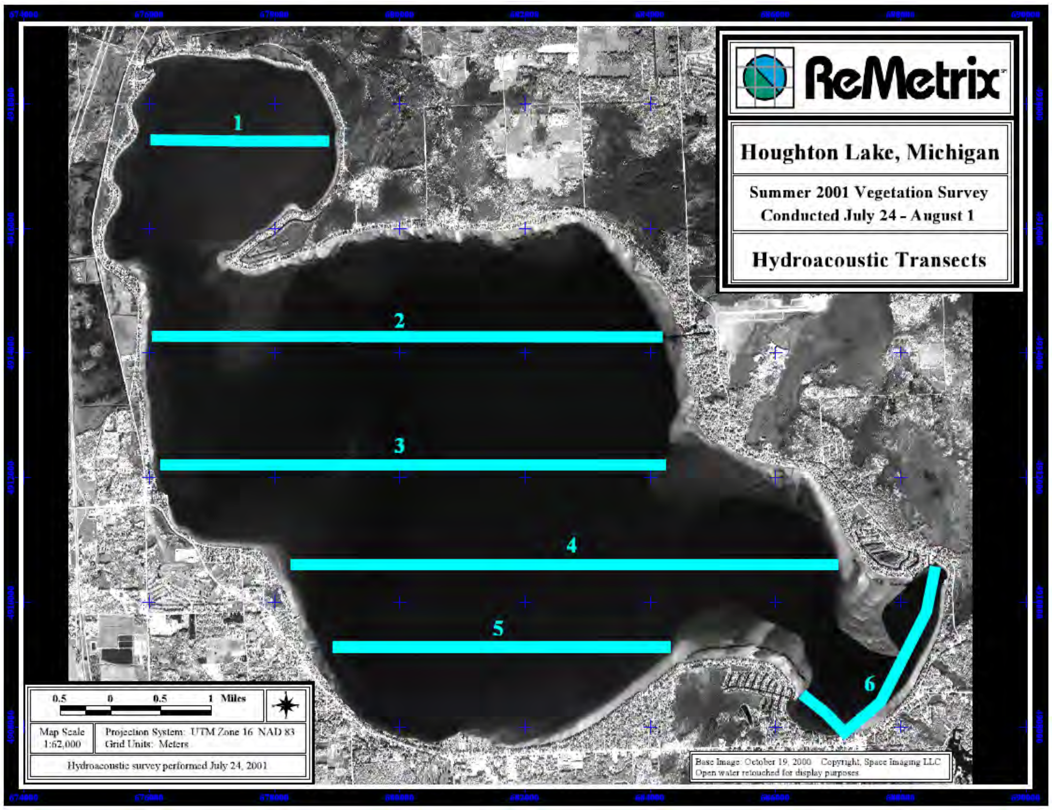

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Number of Submersed Species
0
1
2
3
4
5
6
7
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes


ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Vegetation Density
Composite Index Including All Submersed Species
No Vegetation
Rare (< 3%)
Sparse (3 - 20%)
Common (20 - 60%)
Dense (>60%)
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

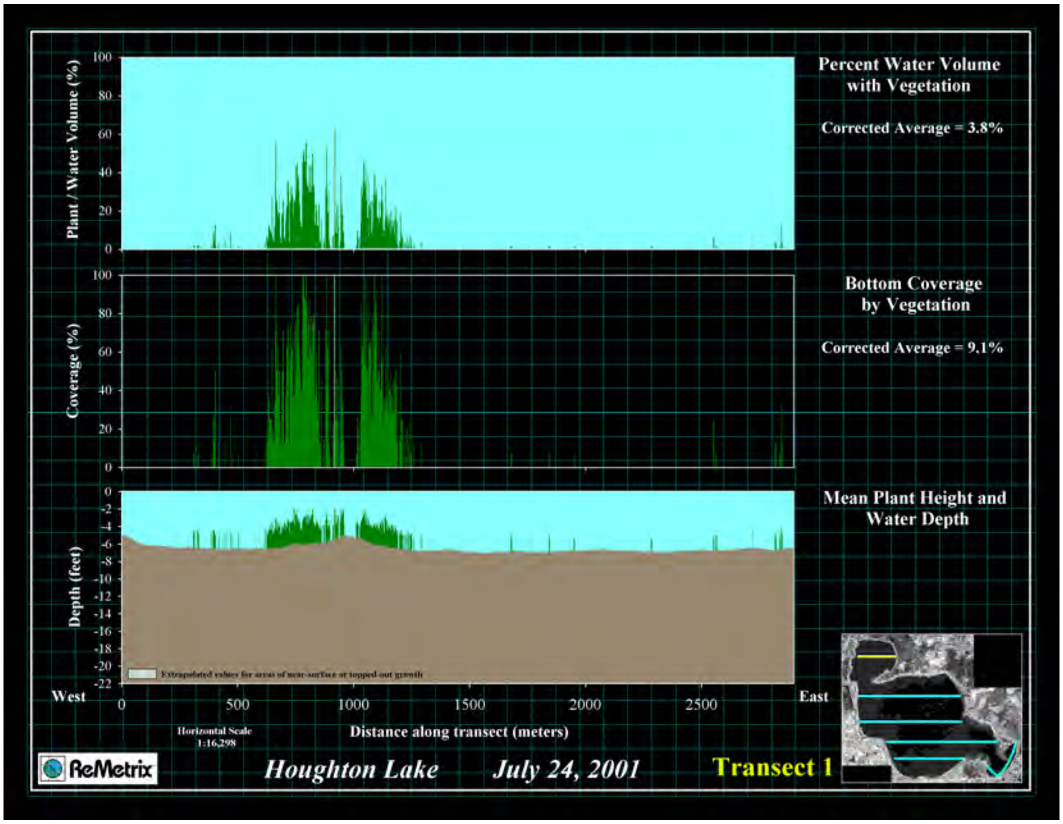

ReMetrix
Houghton Lake, Michigan
Summer 2001 Vegetation Survey
Plant Architecture
Composite Index Including All Submersed Species
No Vegetation
Bottom Growing
In Water Column
Topped Out
0.5 0 0.5 1 Miles
Map Scale 1:62,000
Projection System: UTM Zone 16 NAD 83
Grid Units: Meters
Vegetation survey performed July 24 - August 1, 2001
Base Image: October 19, 2000 Copyright, Space Imaging LLC
Open water retouched for display purposes

Hydroacoustic transects for vegetation assessment – July 24, 2001

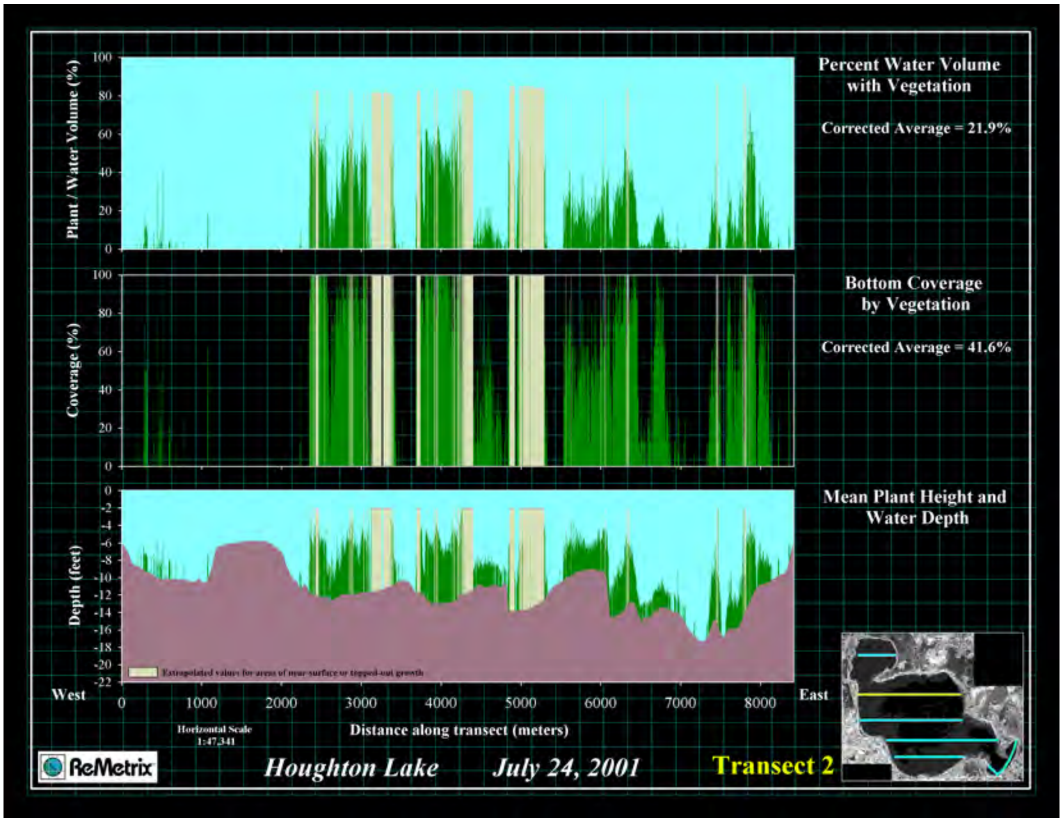
Map of positions of six hydroacoustic transects



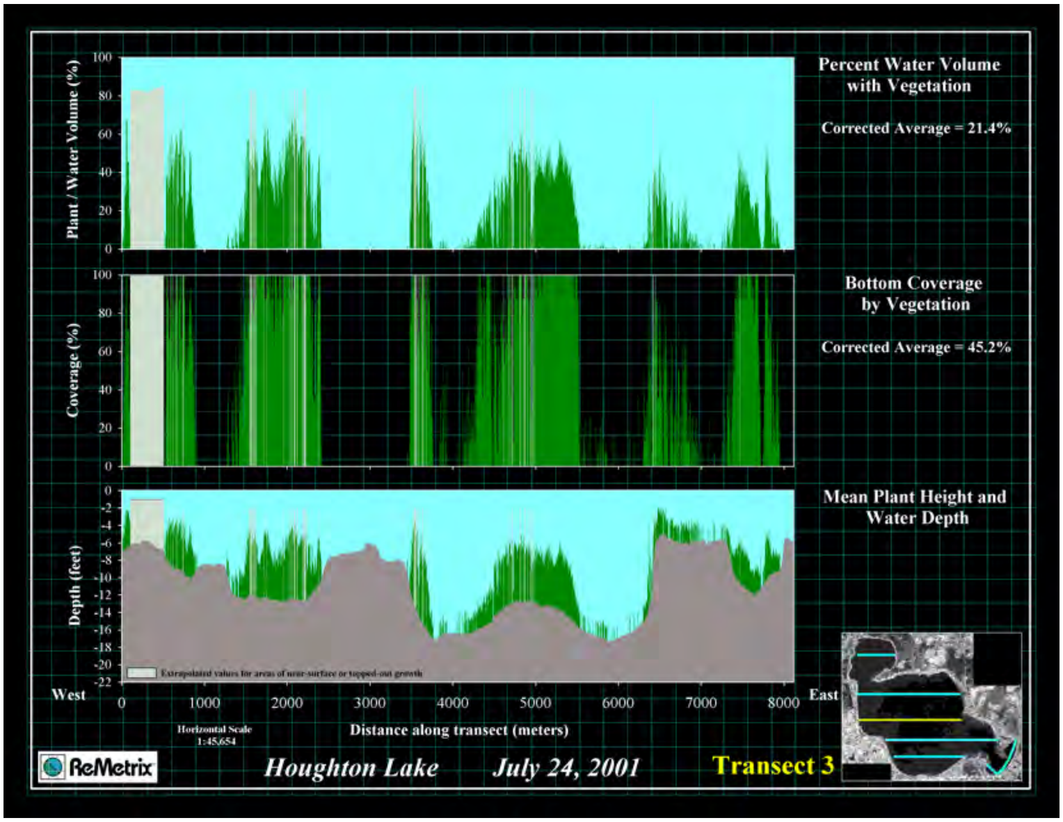
Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transect 1 (July 24, 2001)



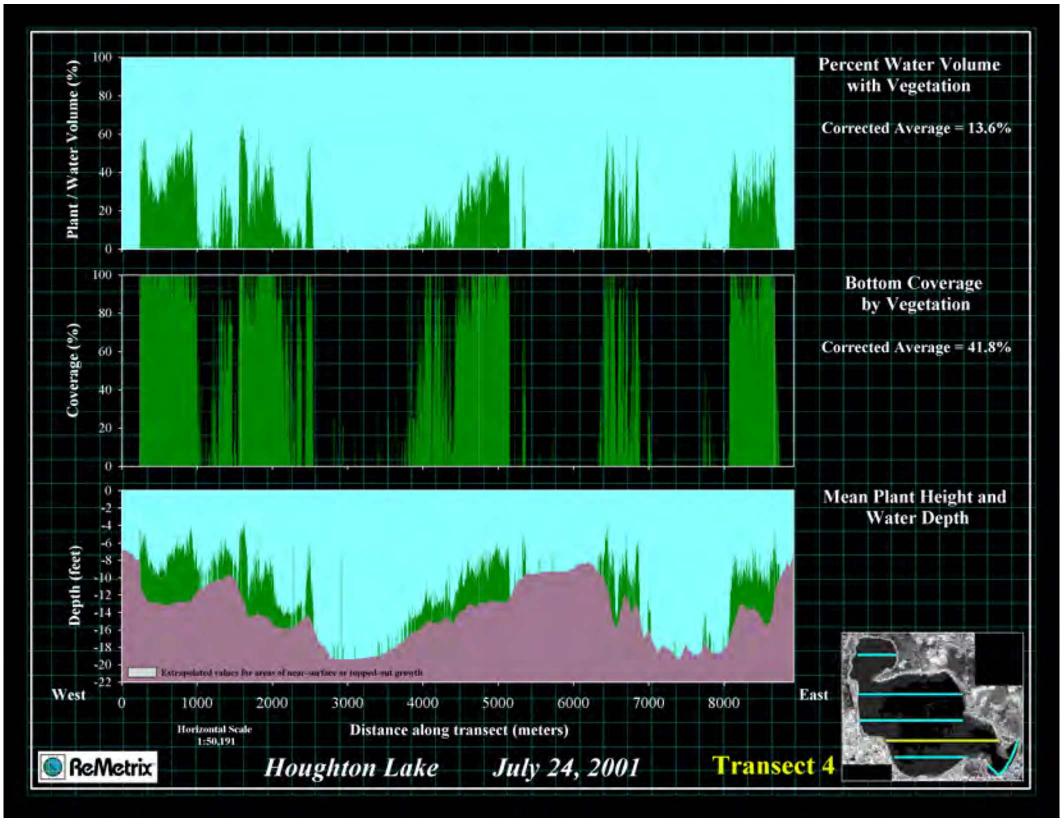
Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transect 2 (July 24, 2001)



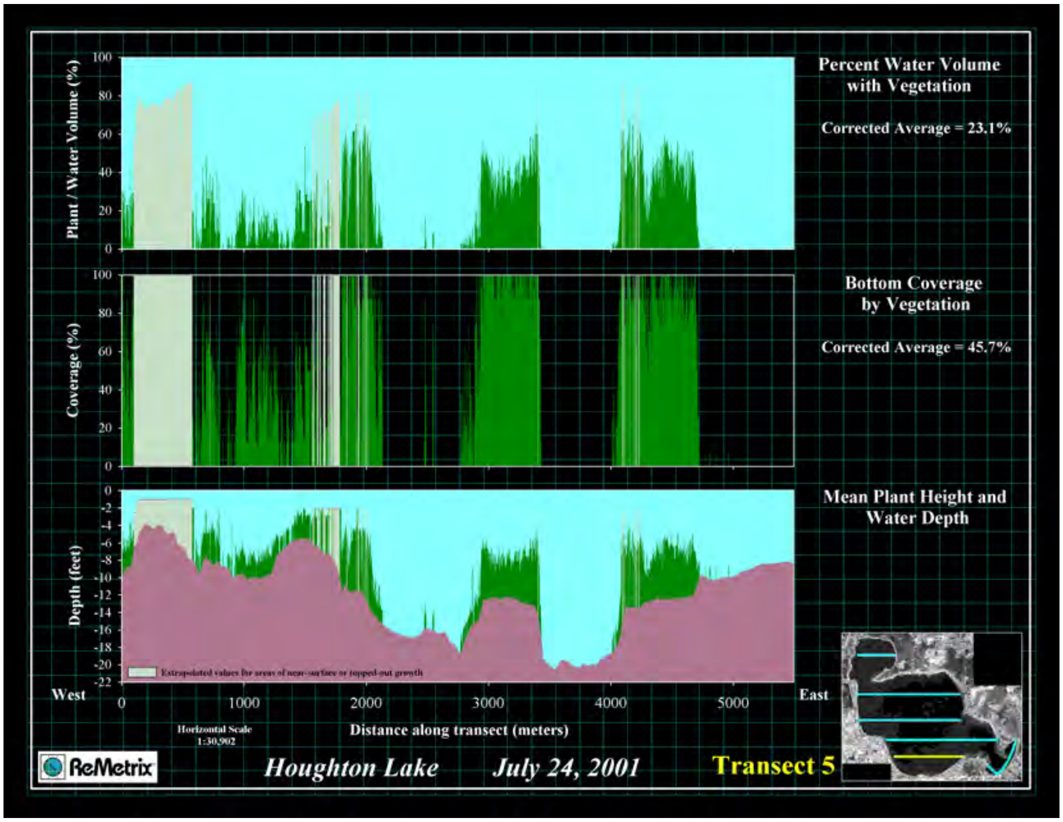
Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transect 3 (July 24, 2001)



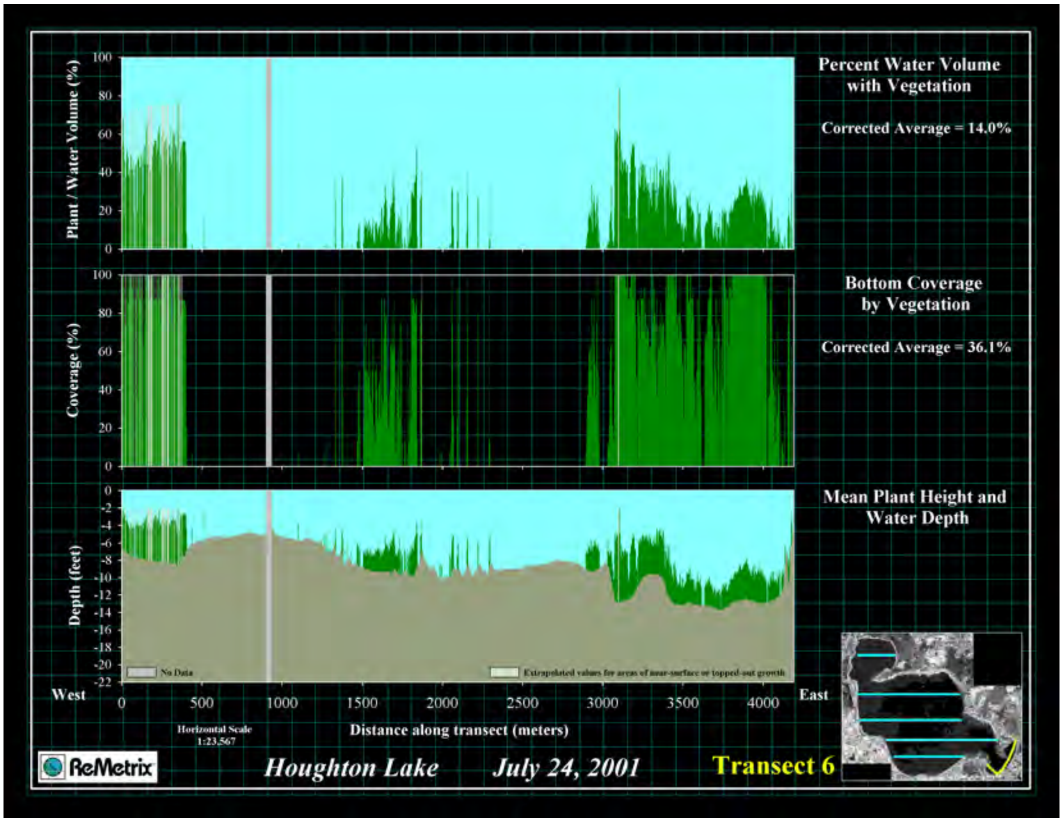
Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transect 4 (July 24, 2001)



Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transect 5 (July 24, 2001)

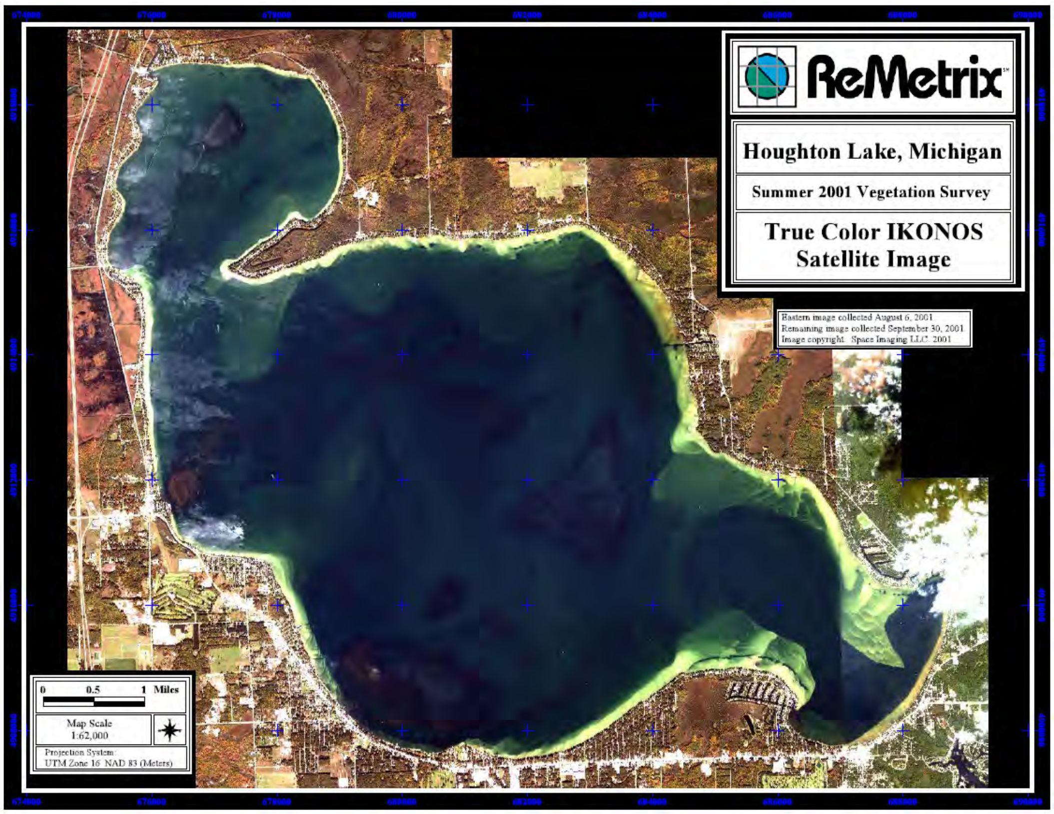


Graphs of vegetation biovolume, bottom coverage, mean plant height and water depth for transect 6 (July 24, 2001)

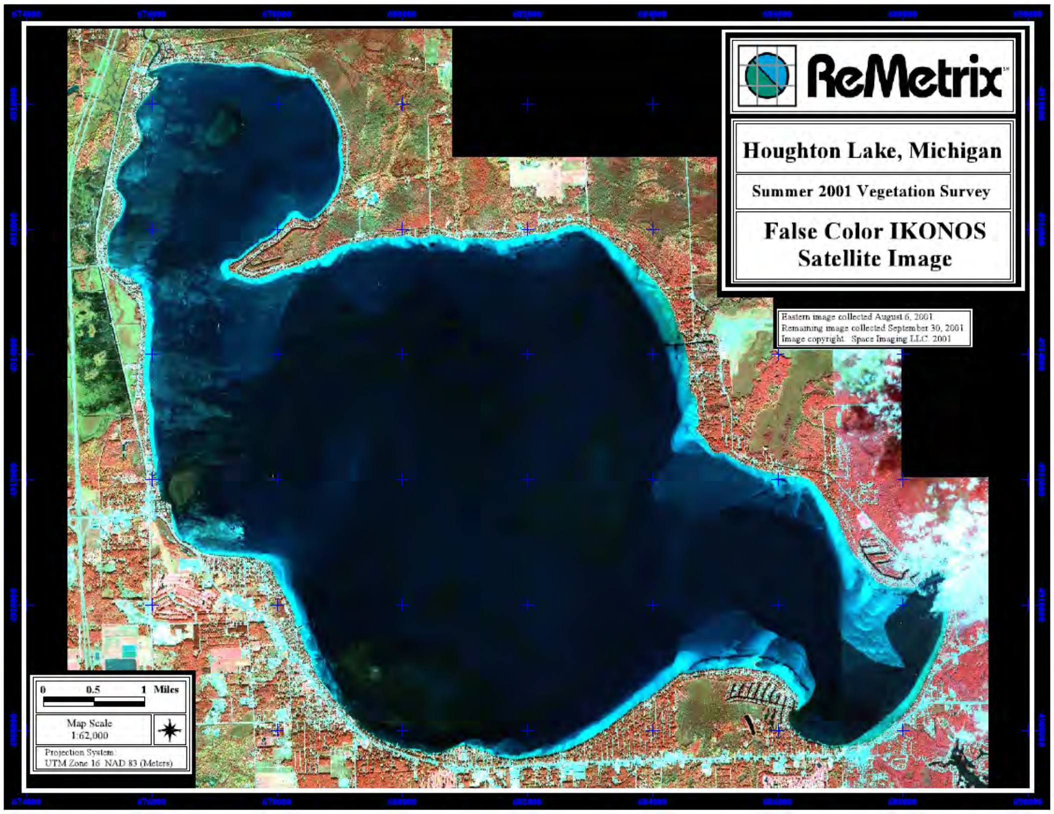


2001 Houghton Lake satellite base imagery and classification

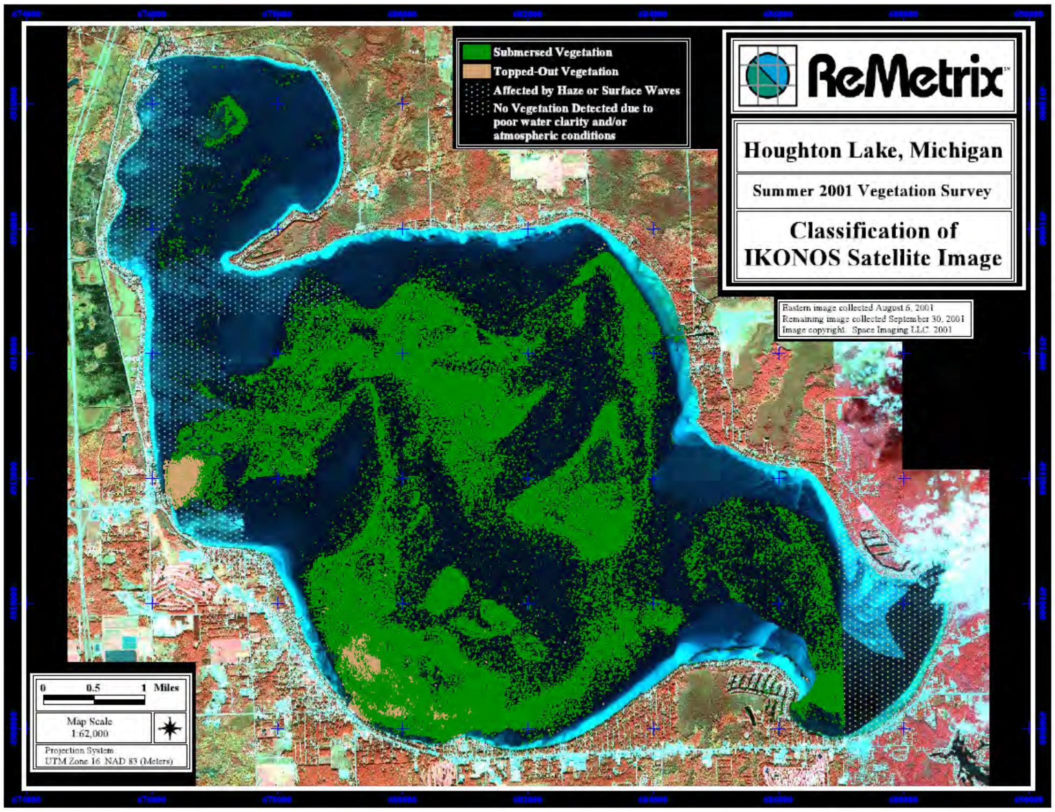
True color IKONOS satellite image of Houghton Lake, Michigan (Imagery Acquisition Dates: August 6 and September 30, 2001)



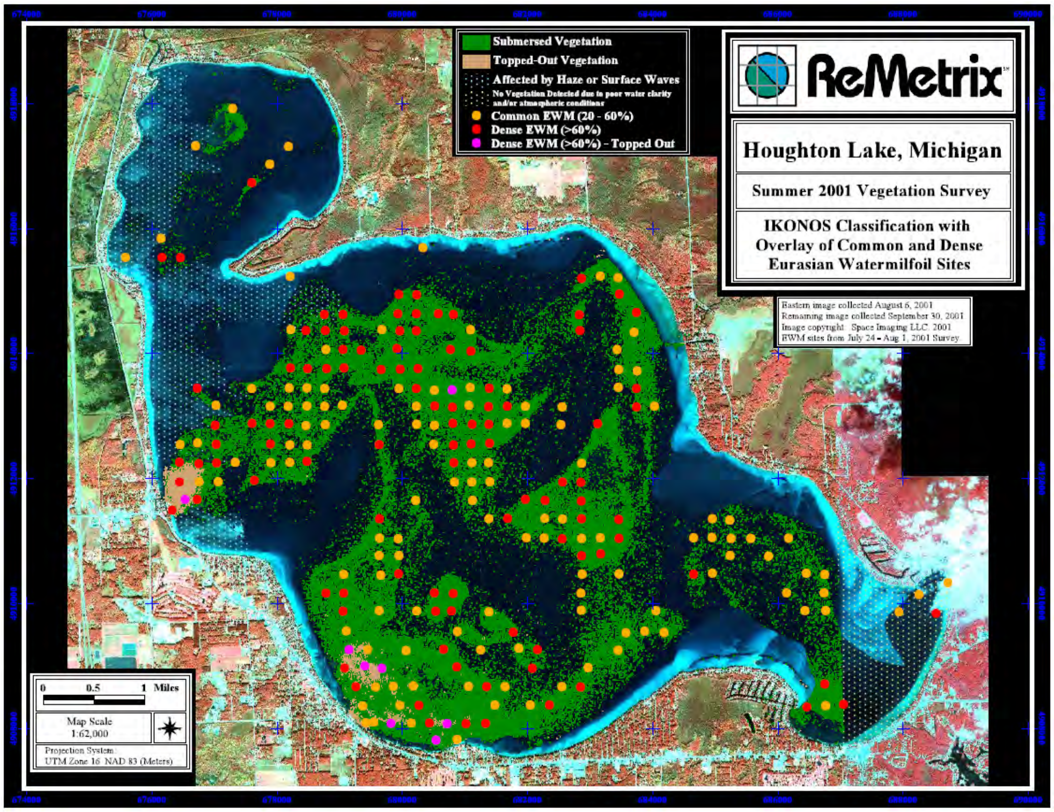
False color IKONOS satellite image of Houghton Lake, Michigan (Imagery Acquisition Dates: August 6 and September 30, 2001)



Classification of IKONOS satellite image of Houghton Lake, Michigan (Imagery Acquisition Dates: August 6 and September 30, 2001)



IKONOS Classification with overlay of common and dense Eurasian watermilfoil sites (Imagery Acquisition Dates: August 6 and September 30, 2001)



Appendix C: SCUBA Survey Transects

Locations and dimensions of SCUBA survey transects within eight of ten areas of special interest in 2002 monitoring of Houghton Lake Sonar (fluridone) treatment. These locations were again evaluated in 2004. Coordinates are provided in metric units per Universal Transverse Mercator (UTM) Zone 16N Projection (WGS 84 Coordinate System).

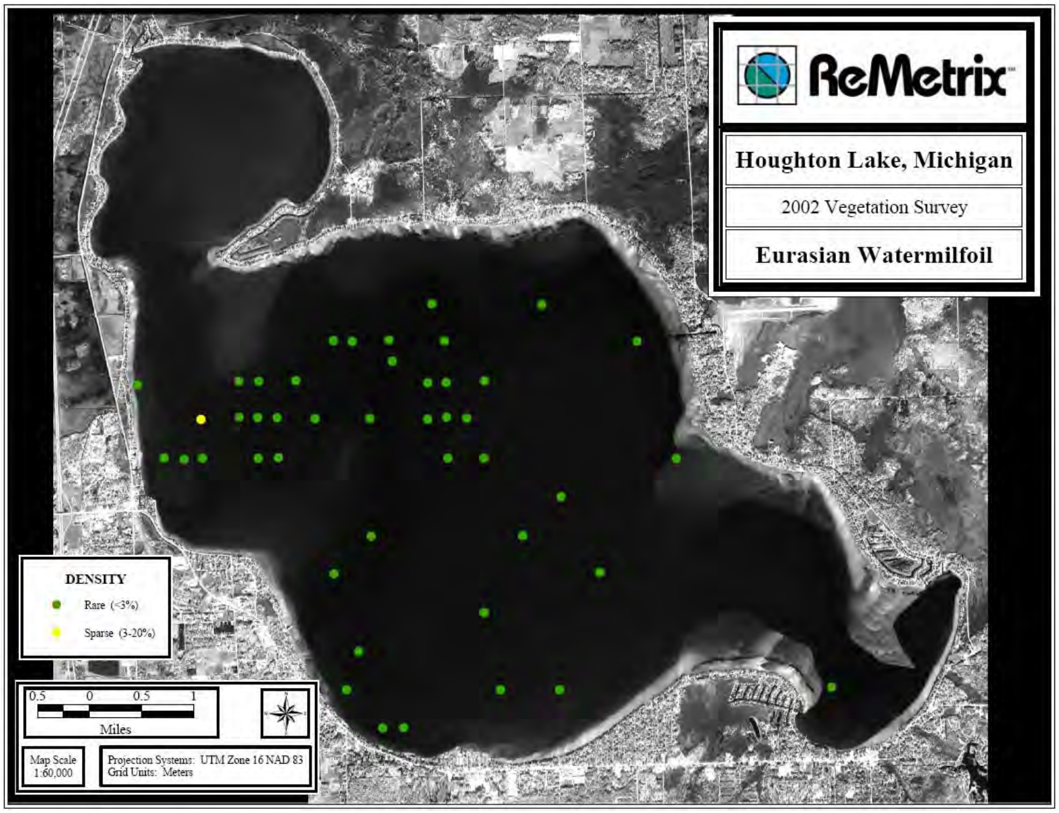
Transect No.	Beginning UTM Coordinates		Ending UTM Coordinates		Length (m)
	Easterly	Northerly	Easterly	Northerly	
1	676850	4912212	676950	4912212	100
2	679700	4914256	679800	4914256	100
4	681950	4909303	682050	4909303	100
5	681000	4912203	681100	4912203	100
6	682750	4912212	682850	4912212	100
8	686540	4908444	686601	4908365	100
9	676800	4917412	676900	4917412	100
10	688467	4910215	688438	4910120	100

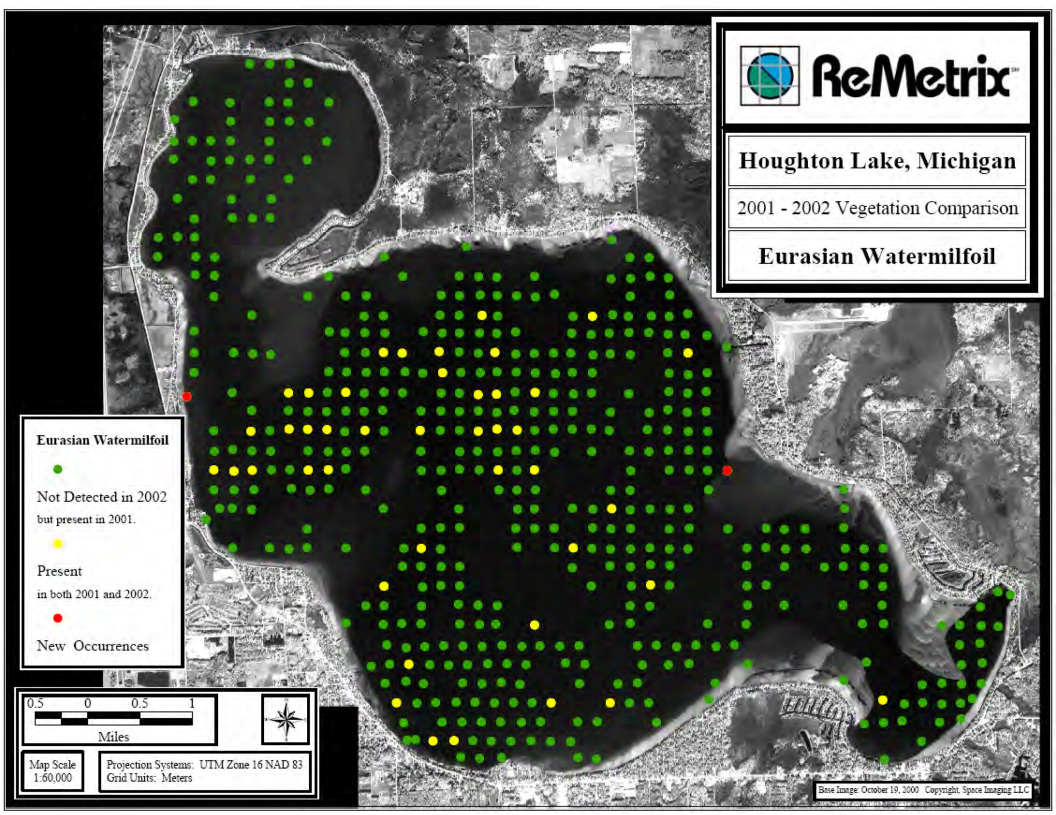
Transect No.	Beginning UTM Coordinates		Ending UTM Coordinates		Length, meters
	Easterly	Northerly	Easterly	Northerly	
1	676850	4912212	676950	4912212	100
2	679700	4914256	679800	4914256	100
4	681950	4909303	682050	4909303	100
5	681000	4912203	681100	4912203	100
6	682750	4912212	682850	4912212	100
8	686540	4908444	686601	4908365	100
9	676800	4917412	676900	4917412	100
10	688467	4910215	688438	4910120	100

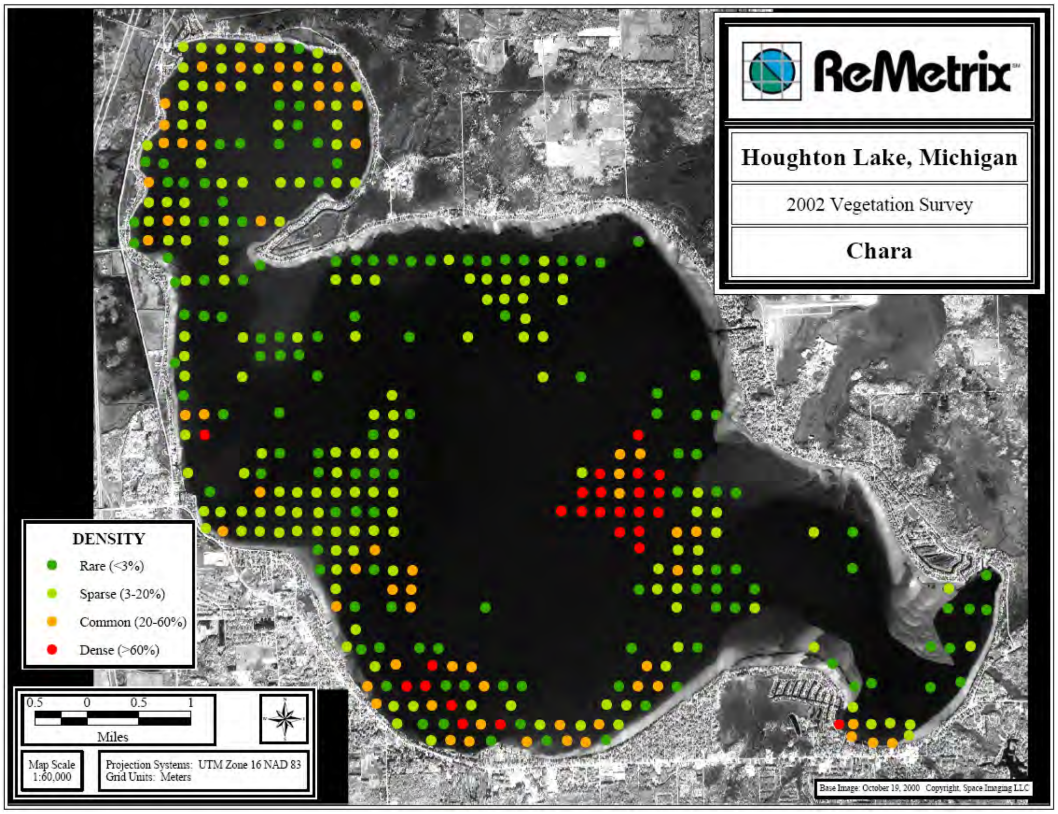
Appendix D: 2002 ReMetrix Vegetation Assessment

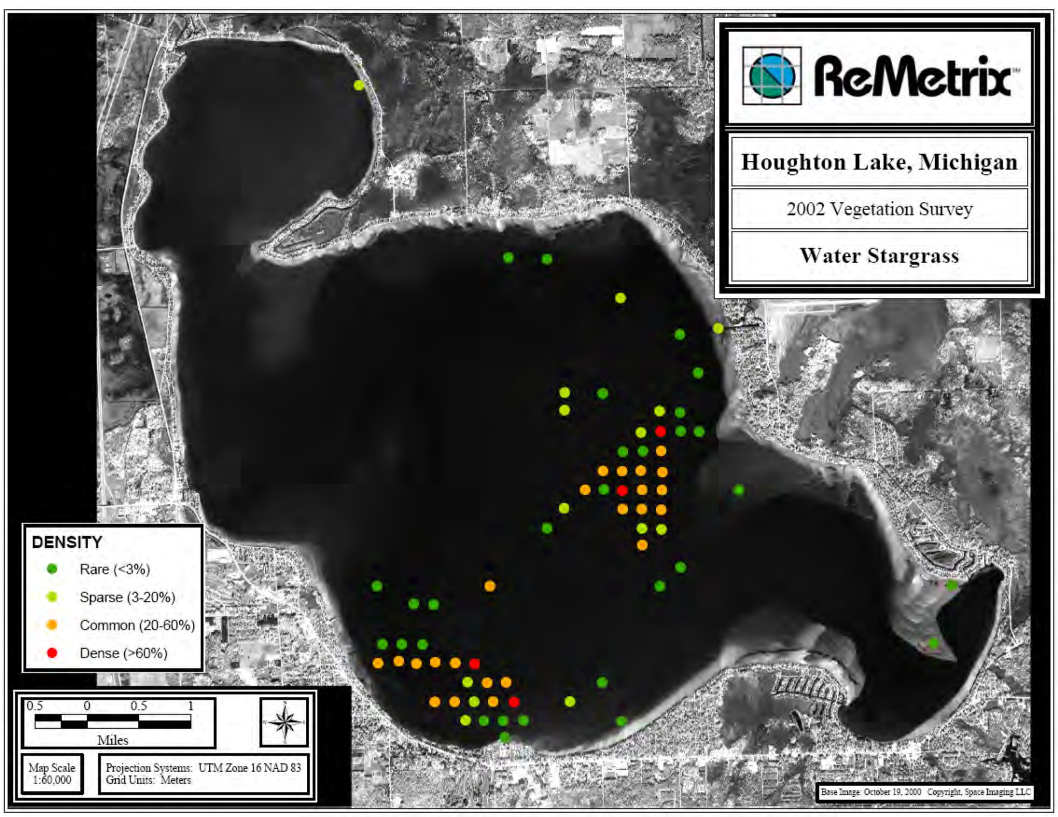
Final vegetation maps for various species and cumulative density maps

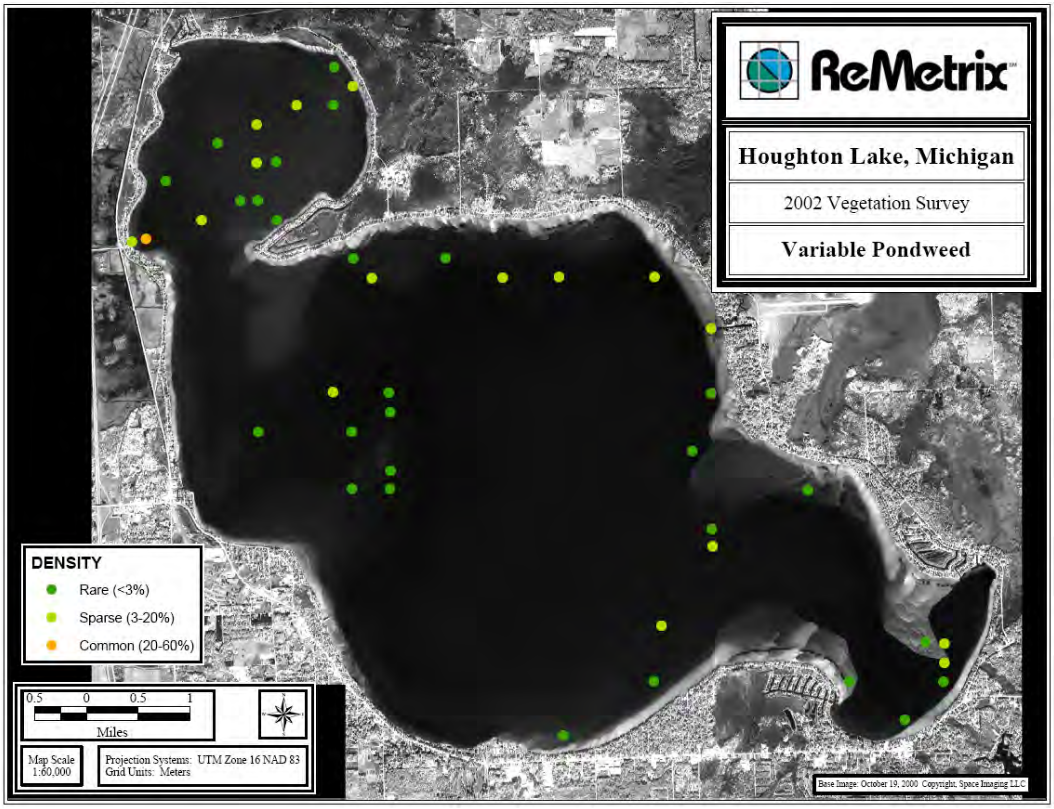
Species Diversity Per Sample Point
Eurasian Watermilfoil
Eurasian Watermilfoil: 2001 v. 2002
Chara
Water Stargrass
Variable-leaved Pondweed
Wild Celery
Coontail
Nitella
Large-leaved Pondweed
Elodea
Whitestem Pondweed
Thin-leaved Pondweed
Naiad
Richardson (Clasping-leaved) Pondweed
Flatstem Pondweed
Robbins' Pondweed
Crowfoot
Illinois Pondweed
Floating-leaved Pondweed
Northern Watermilfoil
Bladderwort
Sago Pondweed

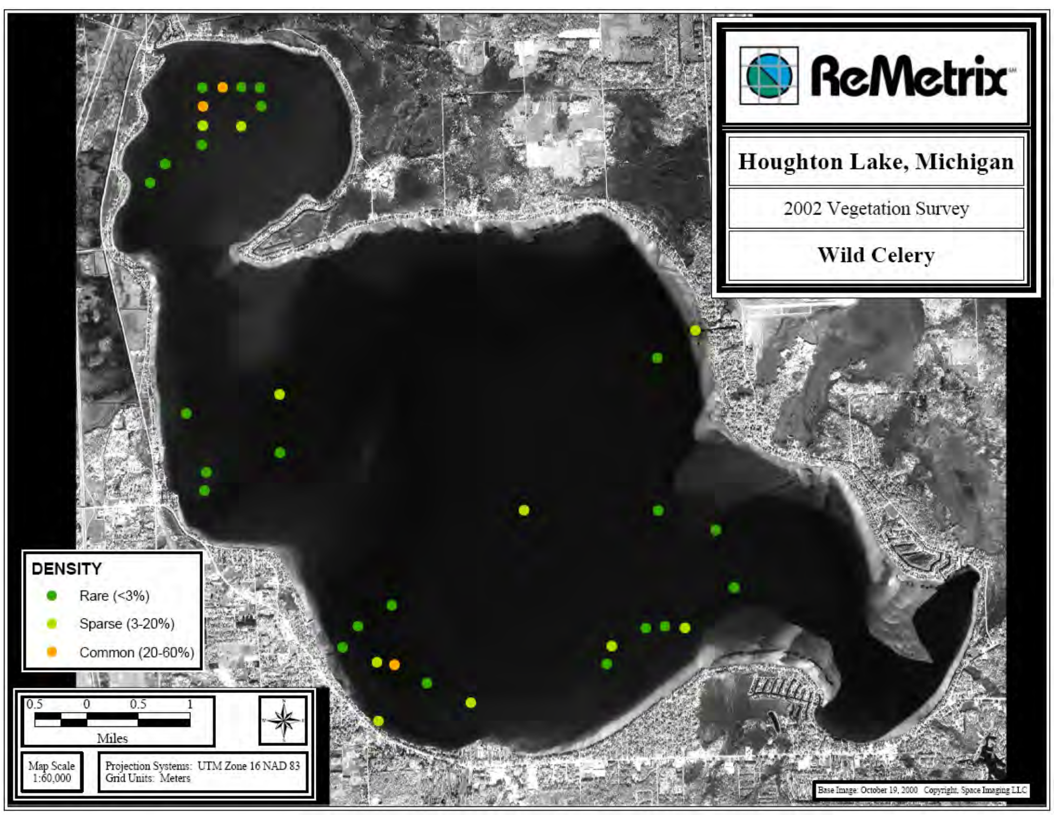

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Eurasian Watermilfoil
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters

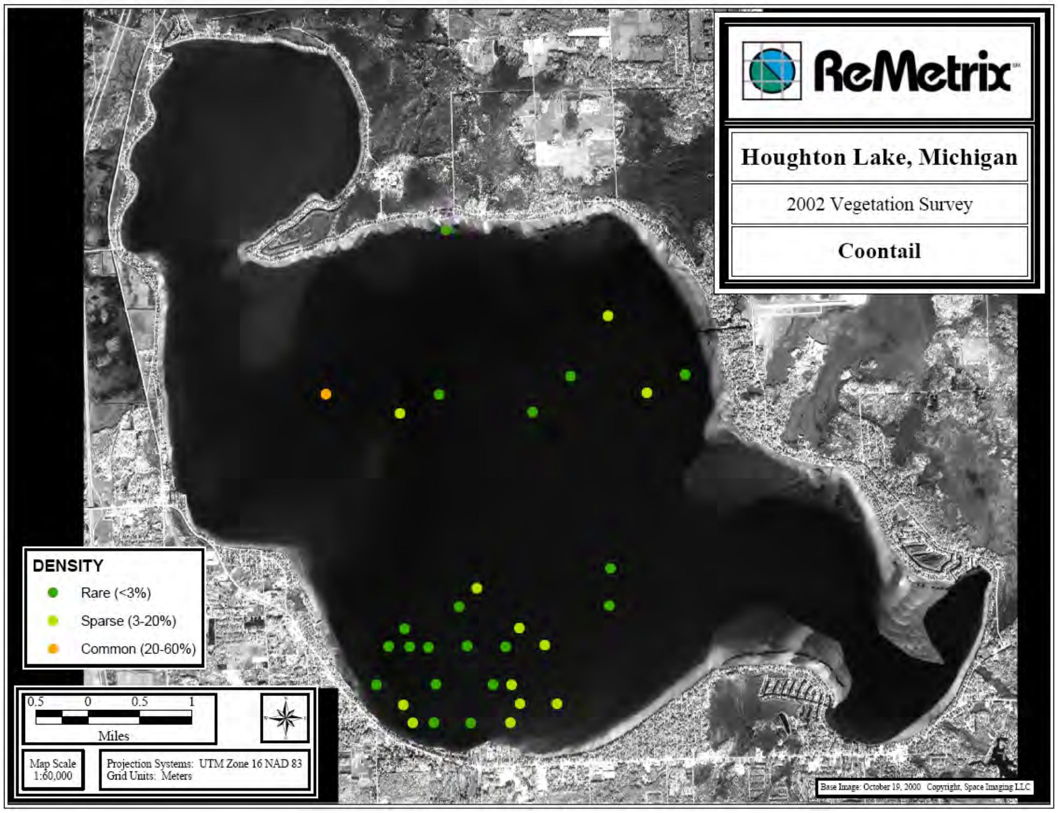

ReMetrix
Houghton Lake, Michigan
2001 - 2002 Vegetation Comparison
Eurasian Watermilfoil
Eurasian Watermilfoil
Not Detected in 2002
but present in 2001.
Present
in both 2001 and 2002.
New Occurrences
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

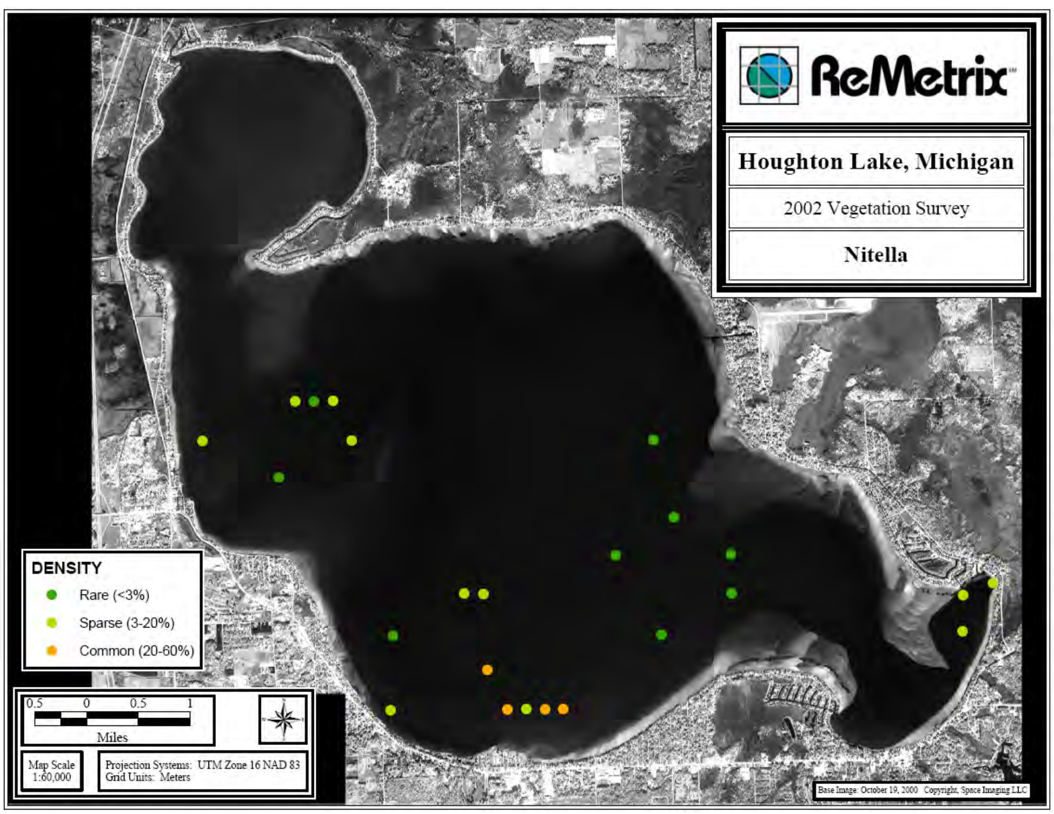

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Chara
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
Dense (>60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

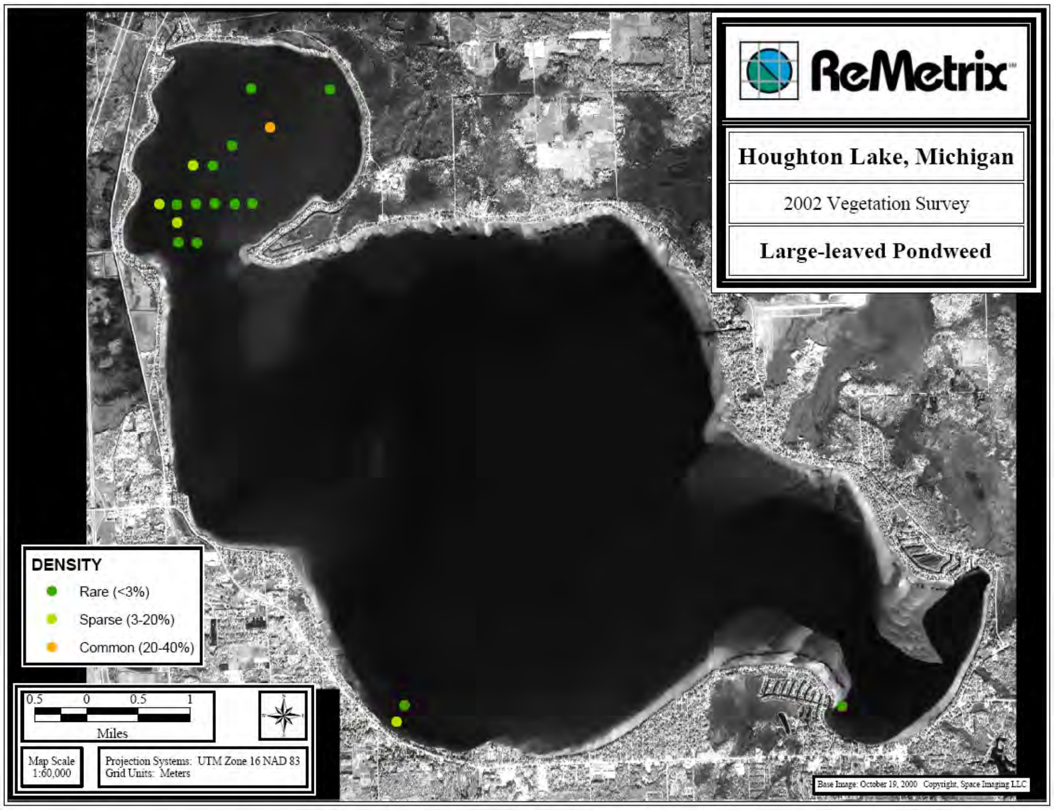

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Water Stargrass
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
Dense (>60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

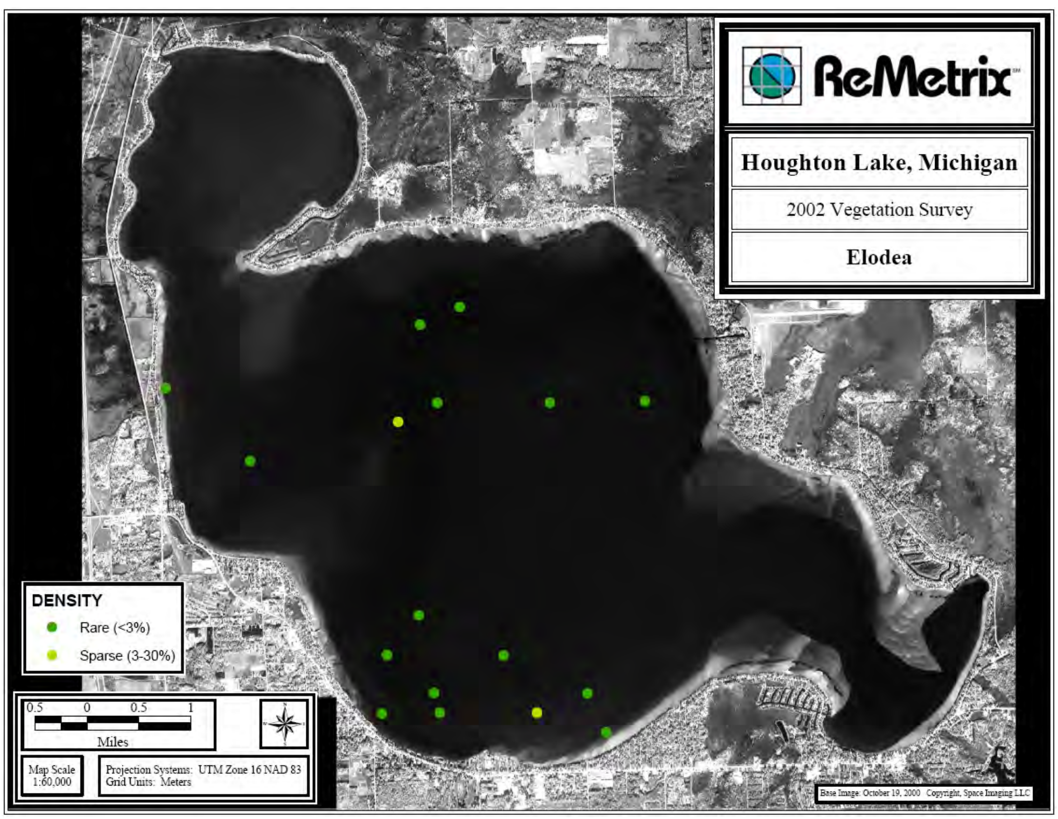

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Variable Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

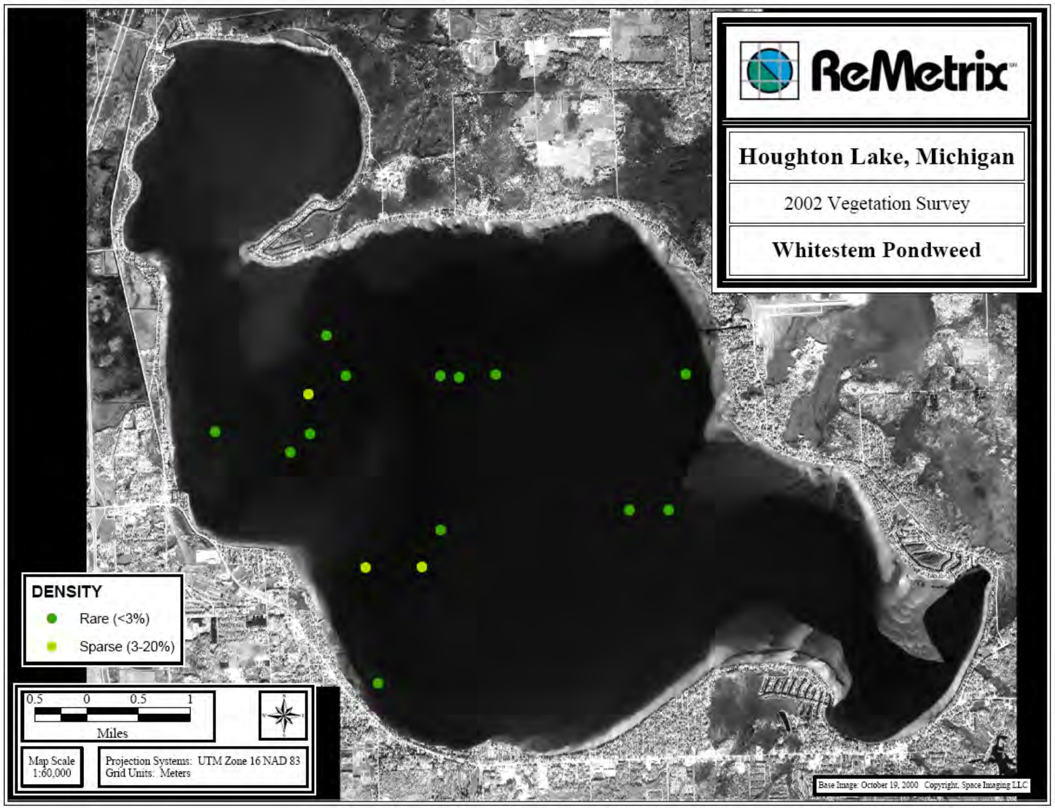

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Wild Celery
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

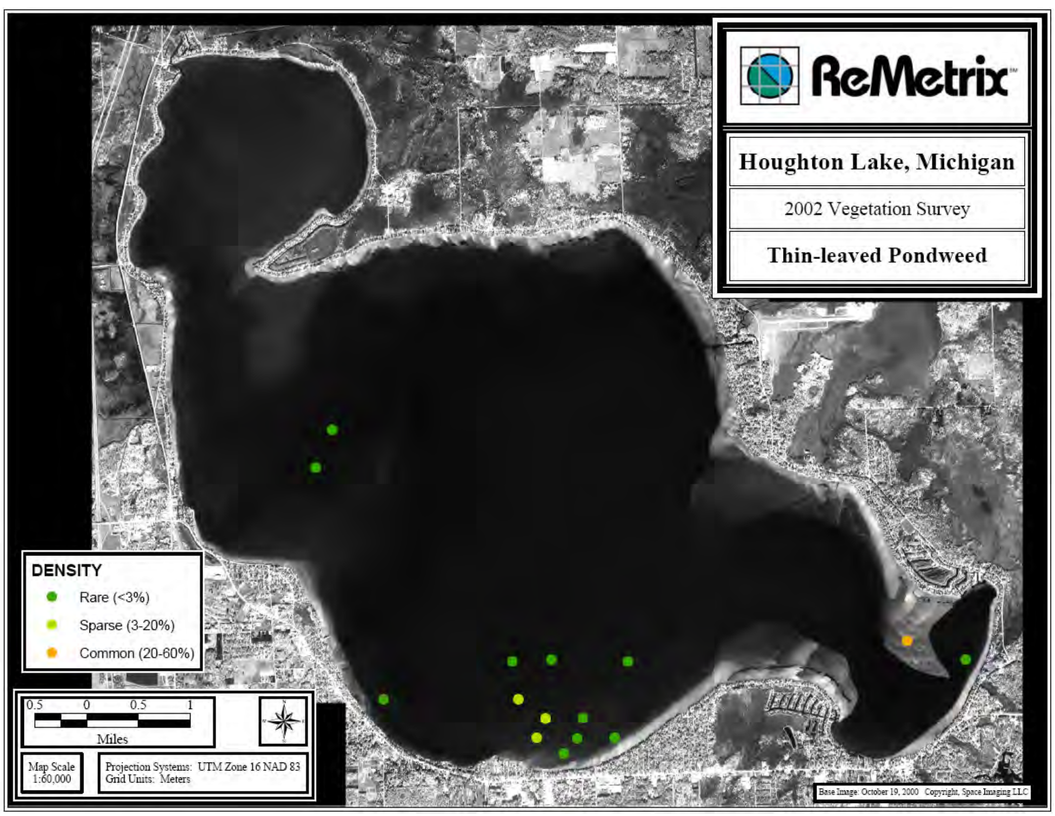

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Coontail
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

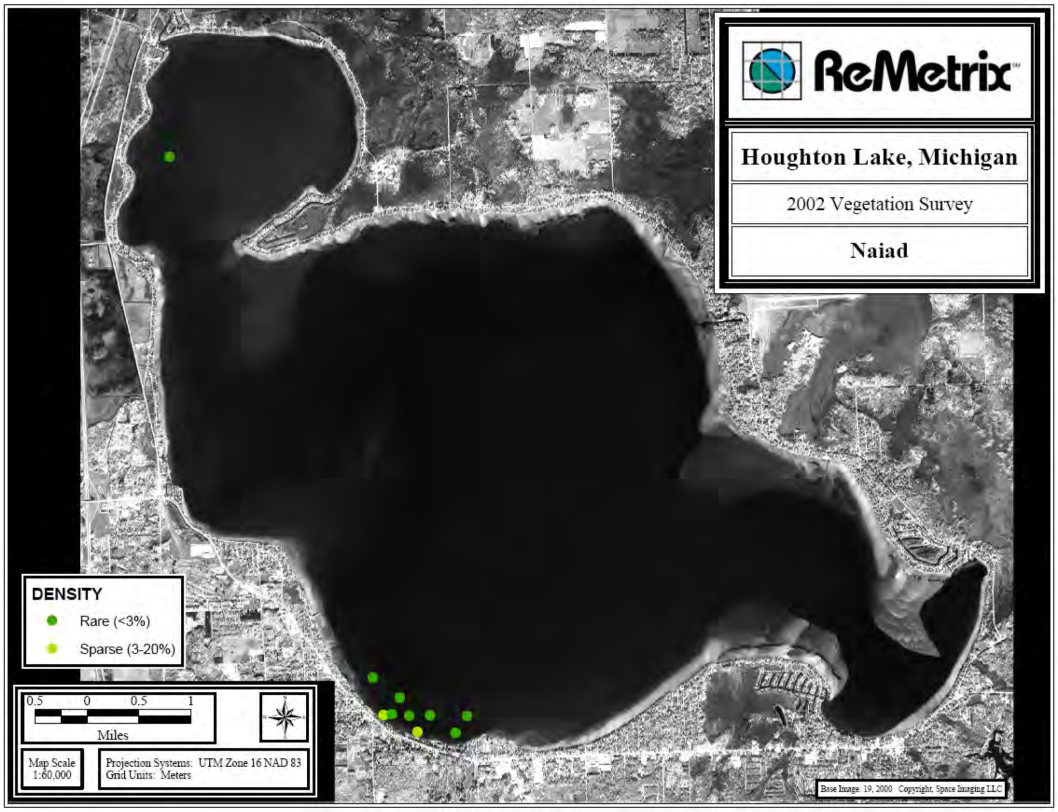

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Nitella
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

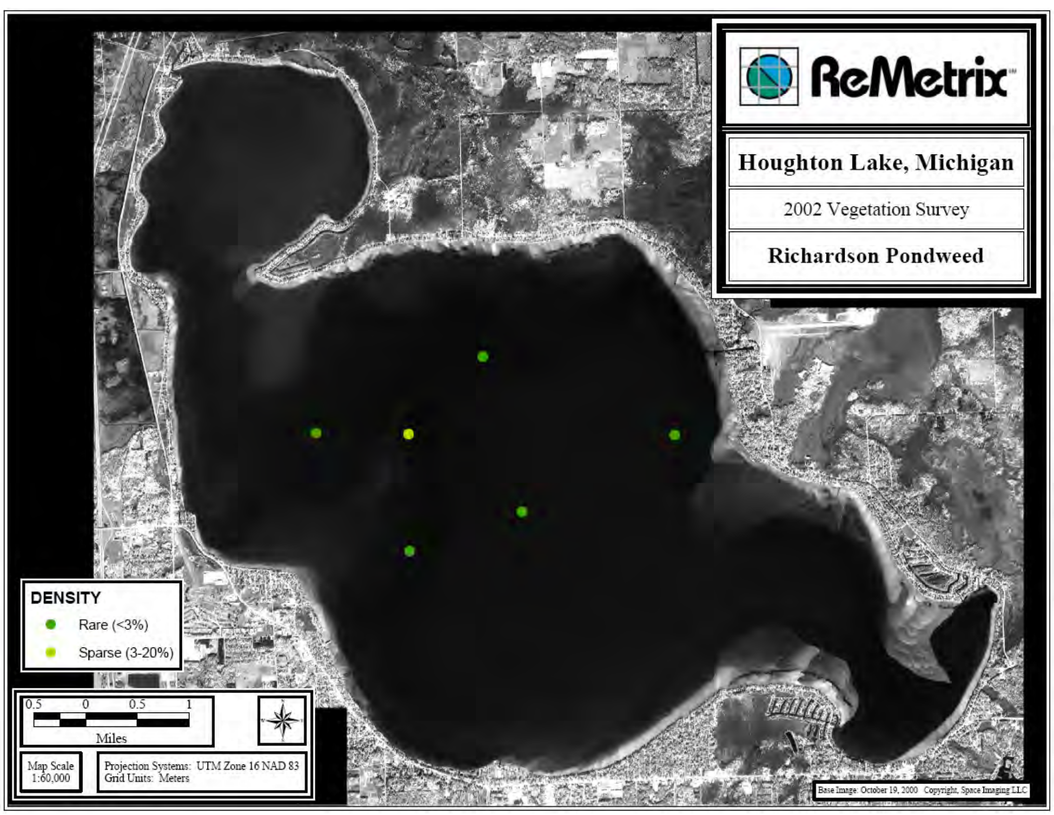

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Large-leaved Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-40%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

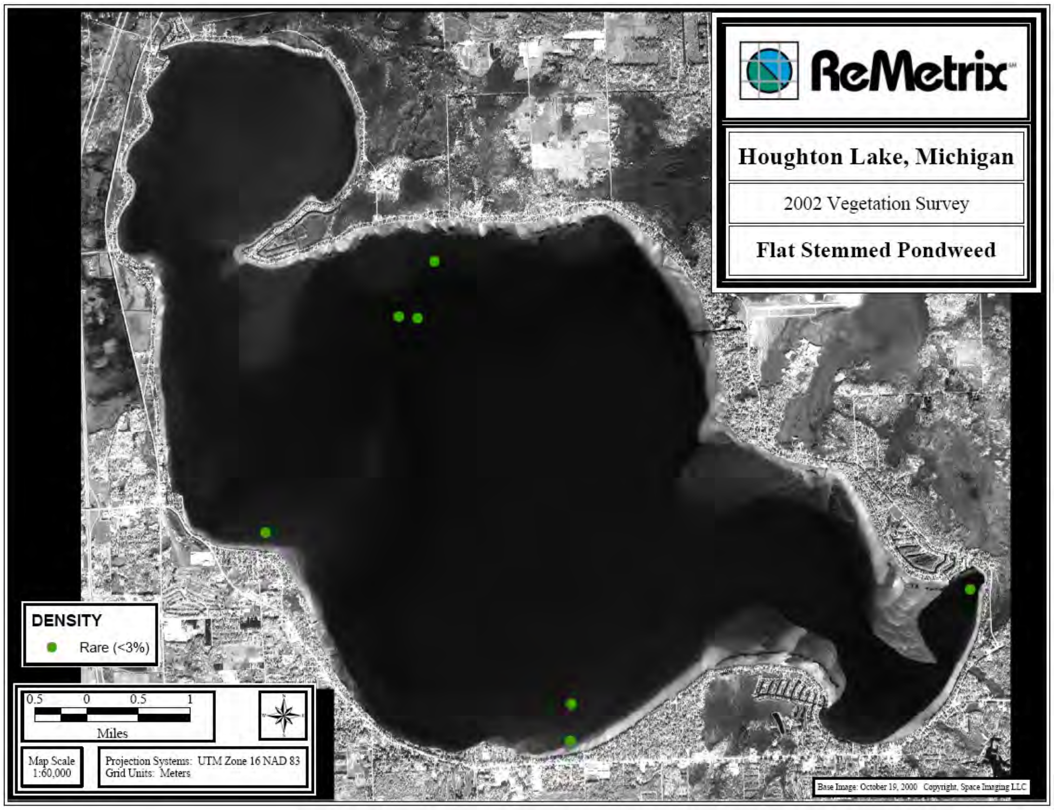

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Elodea
DENSITY
Rare (<3%)
Sparse (3-30%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

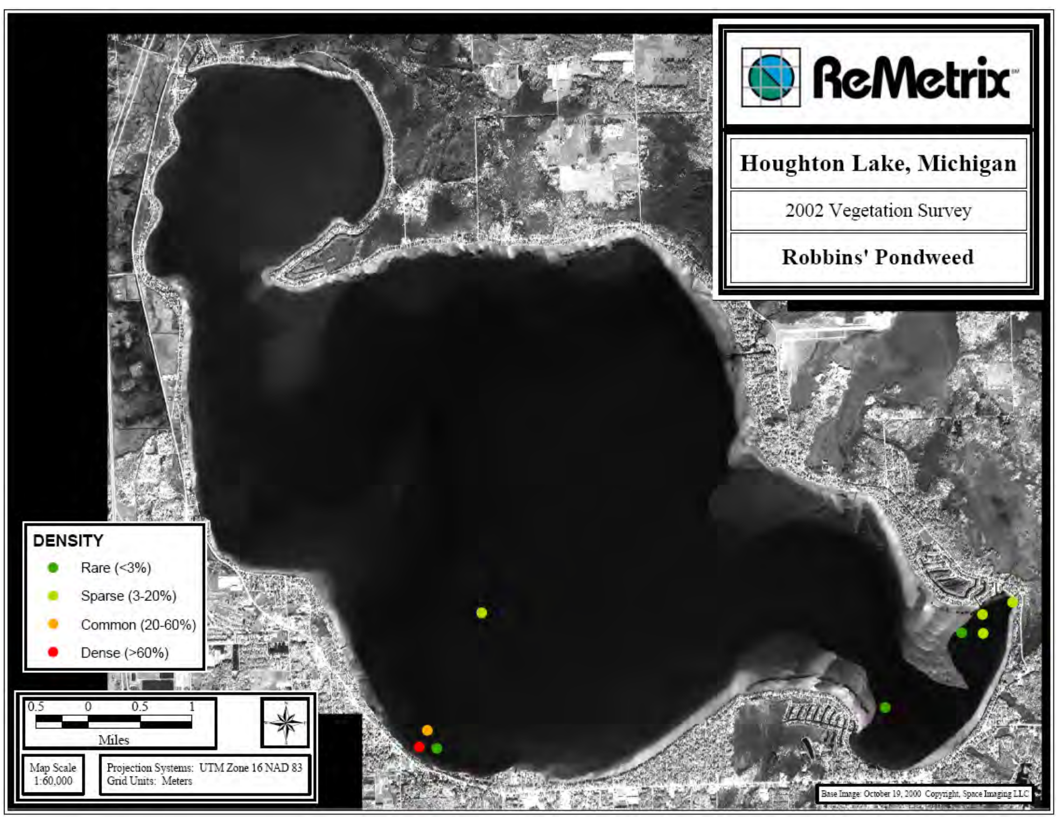

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Whitestem Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

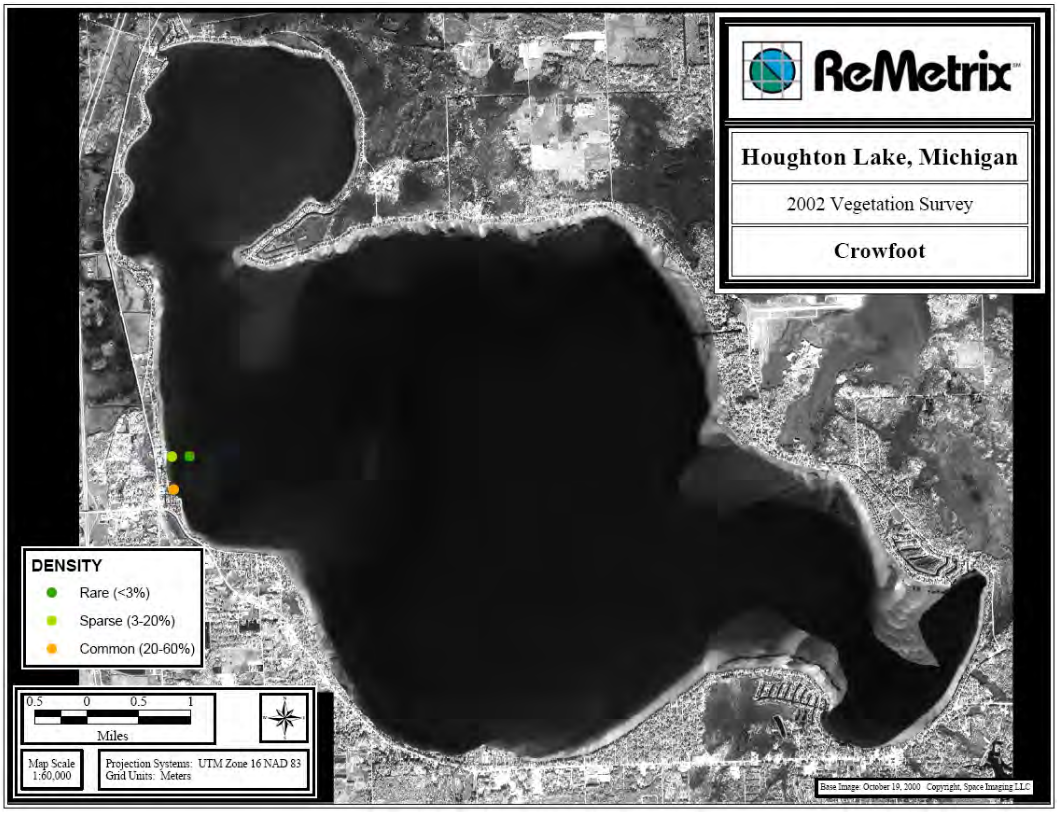

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Thin-leaved Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

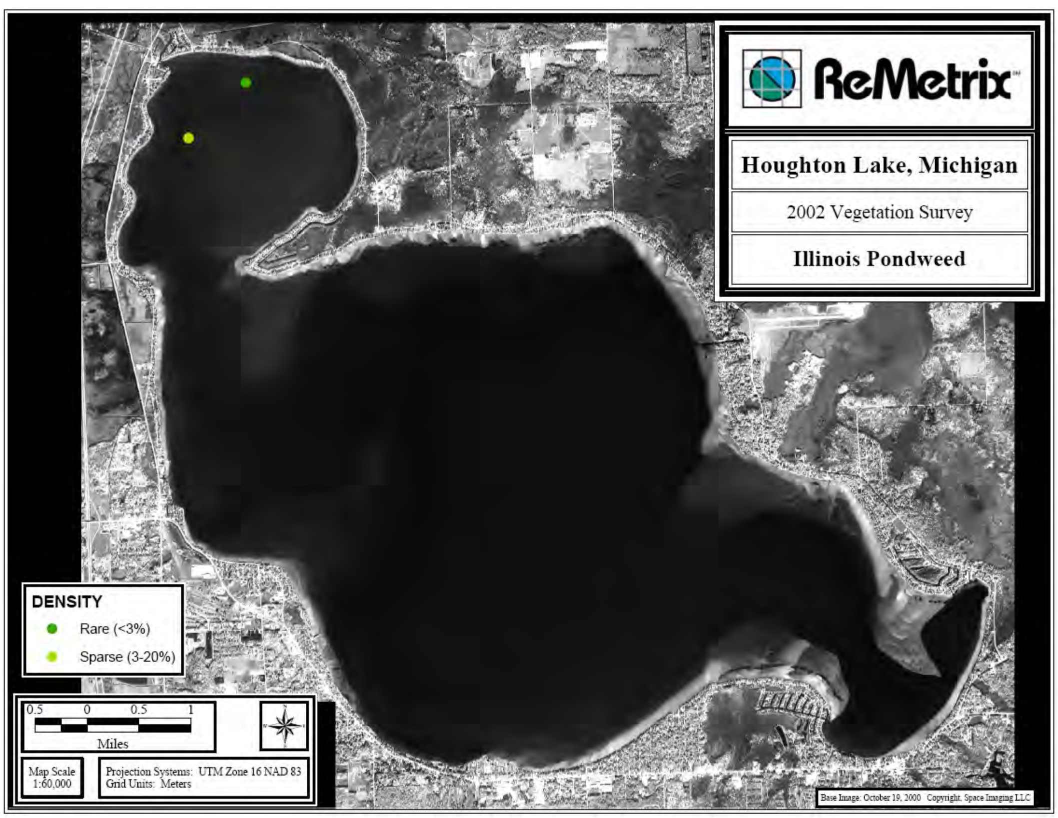

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Naiad
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters

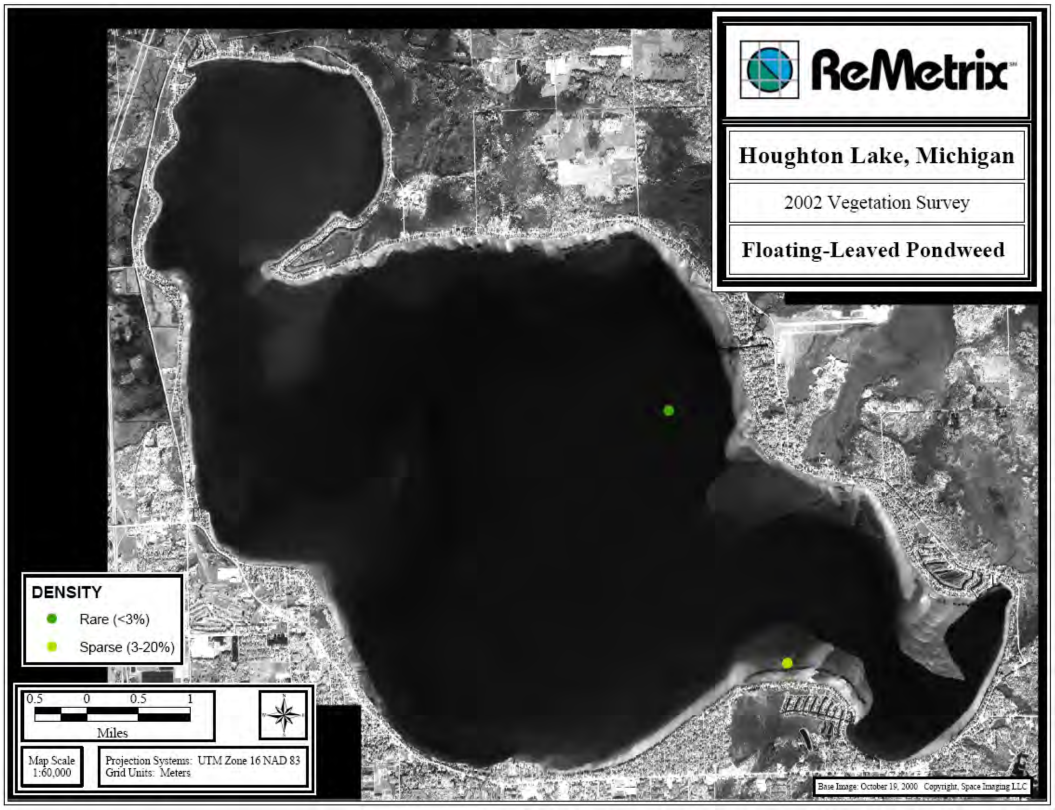

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Richardson Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

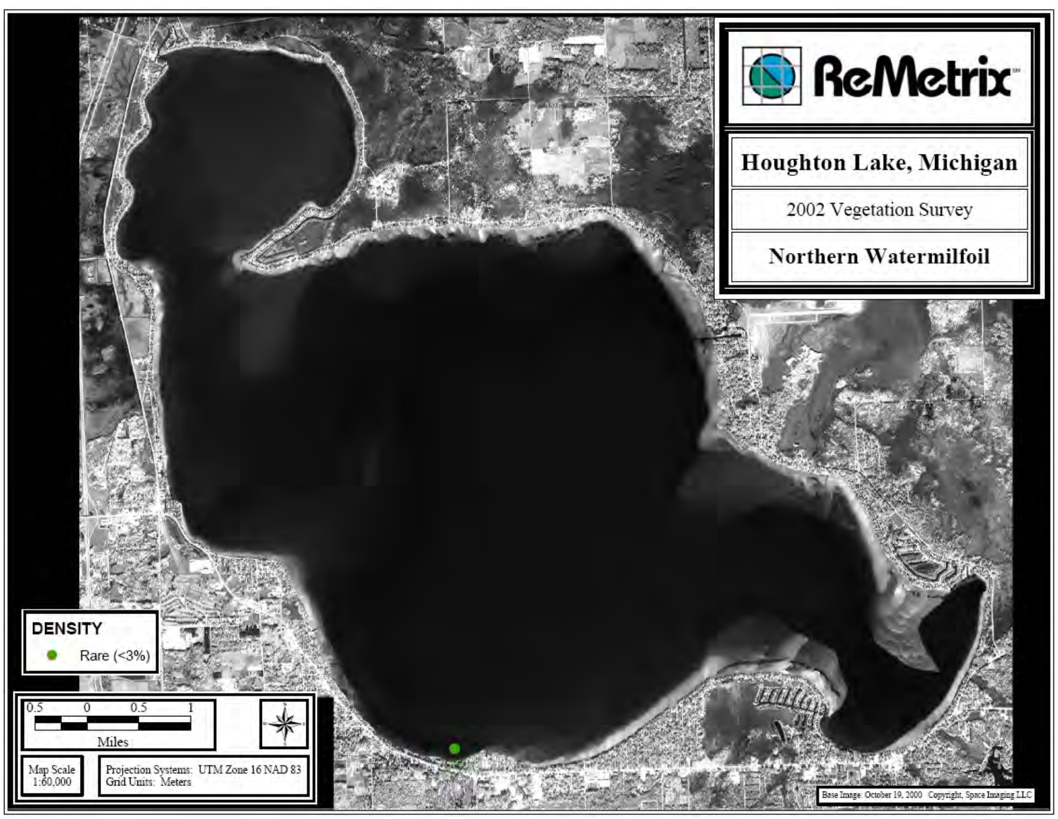

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Flat Stemmed Pondweed
DENSITY
Rare (<3%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

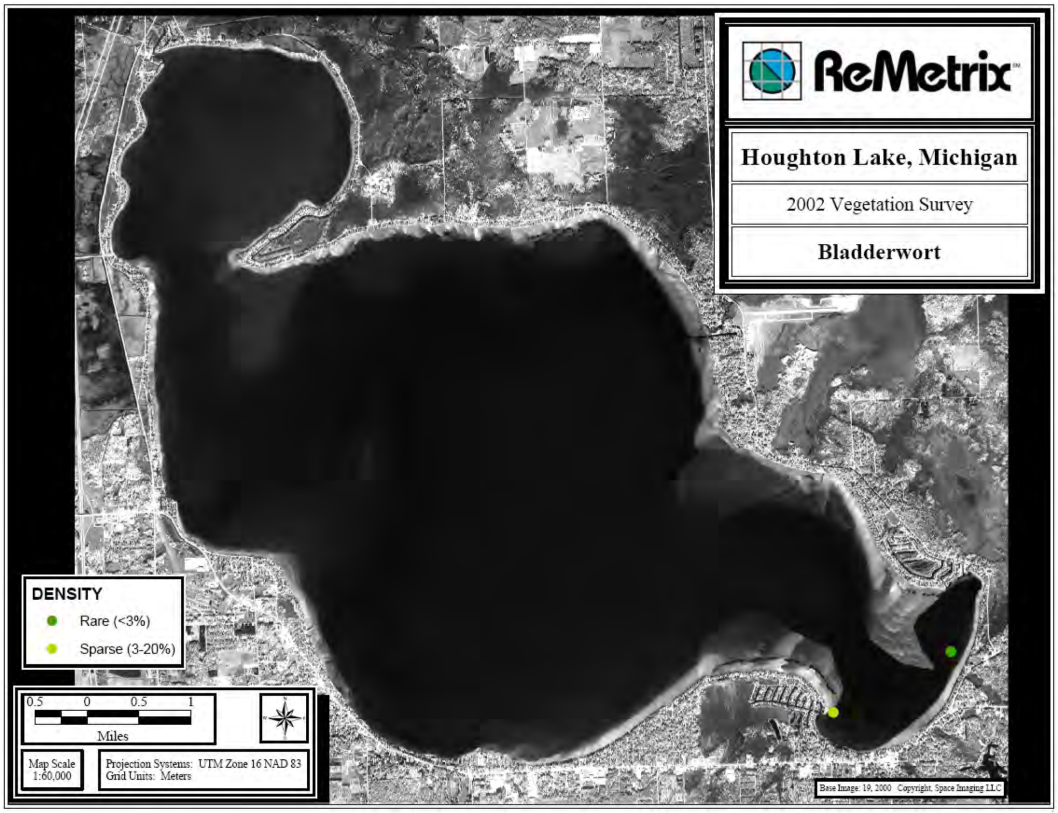

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Robbins' Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
Dense (>60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

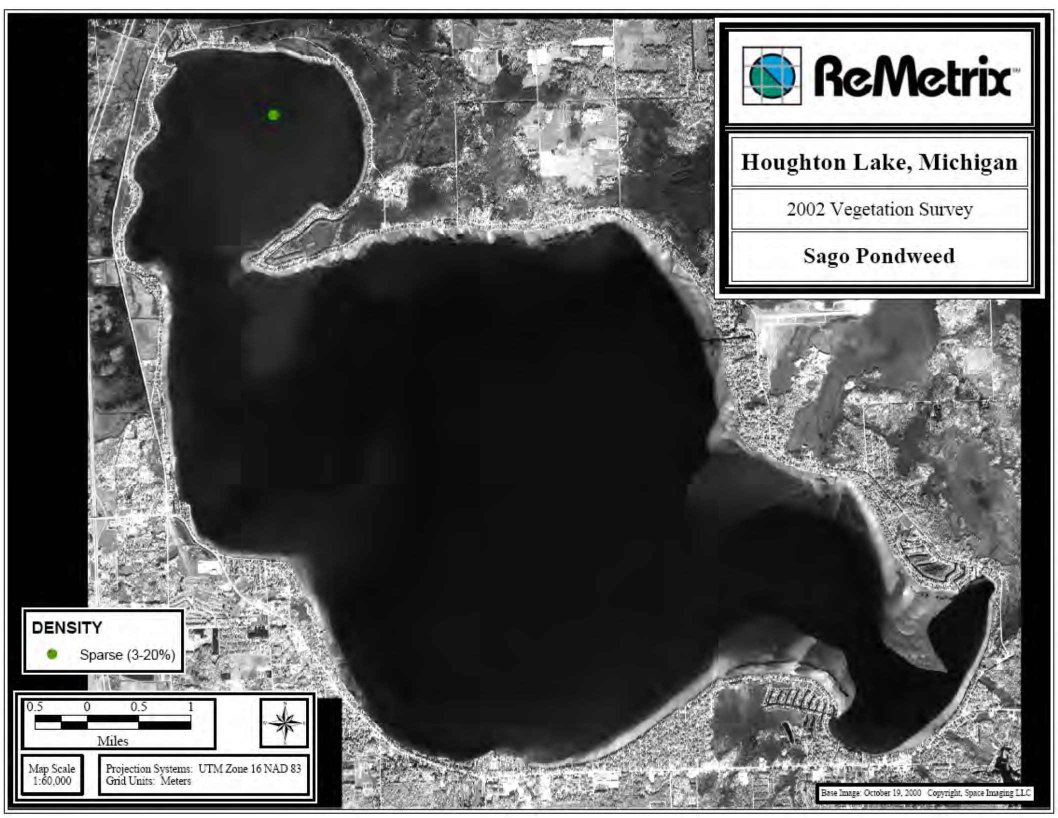

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Crowfoot
DENSITY
Rare (<3%)
Sparse (3-20%)
Common (20-60%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC


ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Illinois Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC


ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Floating-Leaved Pondweed
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

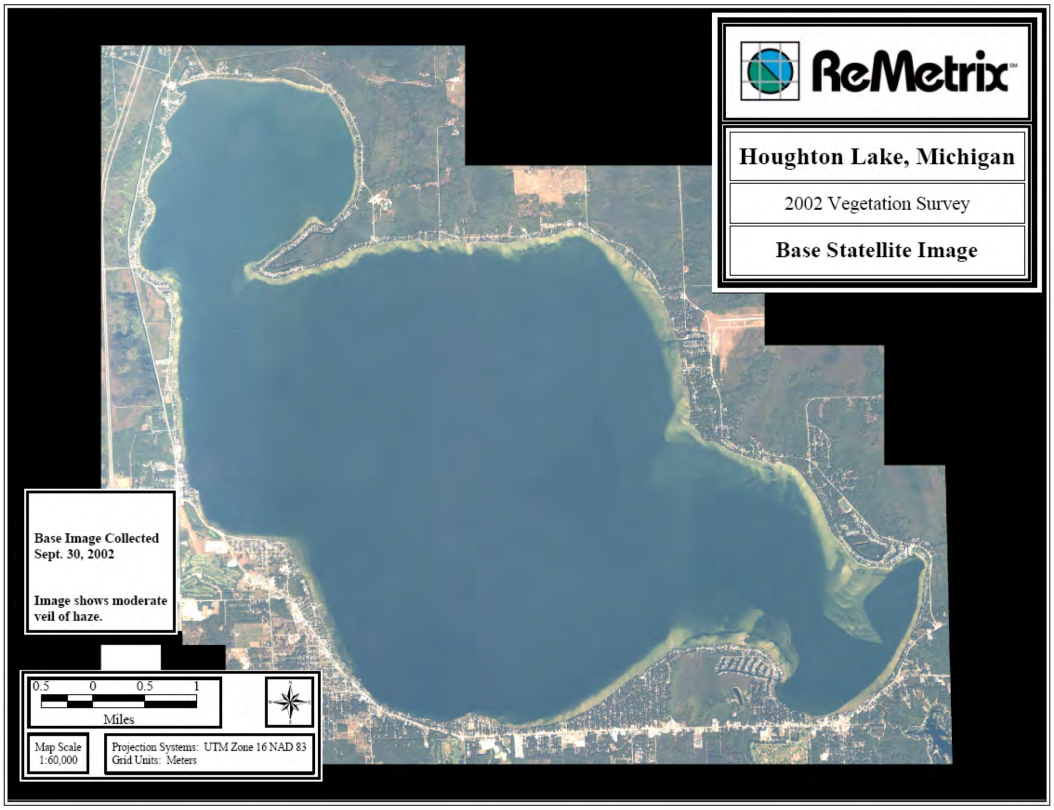

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Northern Watermilfoil
DENSITY
Rare (<3%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

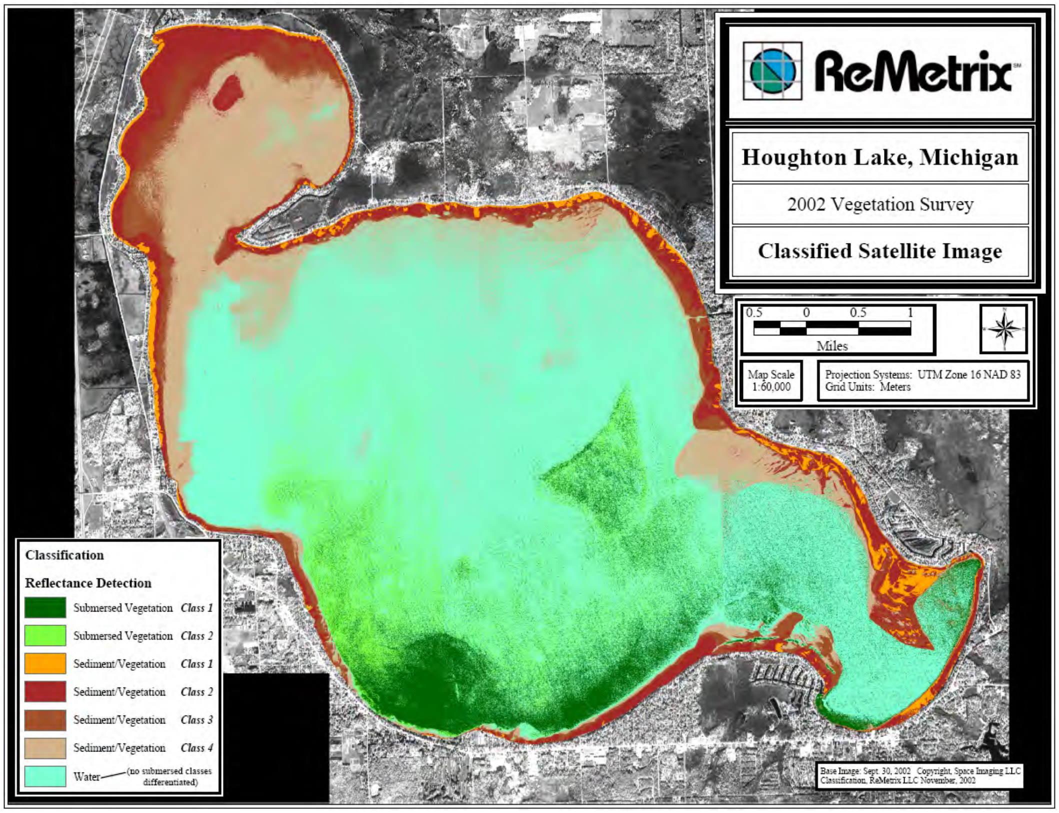

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Bladderwort
DENSITY
Rare (<3%)
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: 19, 2000 Copyright, Space Imaging LLC

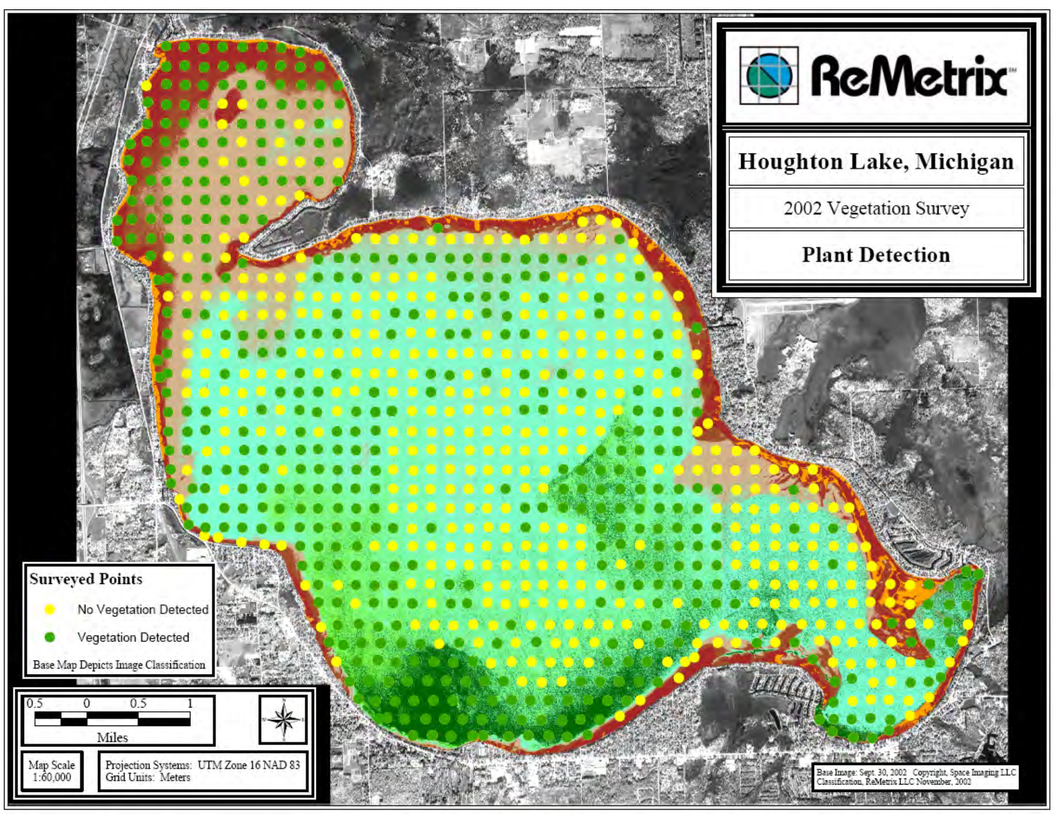

ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Sago Pondweed
DENSITY
Sparse (3-20%)
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: October 19, 2000 Copyright, Space Imaging LLC

2002 Houghton Lake satellite base imagery and classification

True Color IKONOS satellite image of Houghton Lake, Michigan (Imagery Acquisition Dates: September 30, 2002)




ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Classified Satellite Image
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Classification
Reflectance Detection
Submersed Vegetation Class 1
Submersed Vegetation Class 2
Sediment/Vegetation Class 1
Sediment/Vegetation Class 2
Sediment/Vegetation Class 3
Sediment/Vegetation Class 4
Water (no submersed classes differentiated)
Base Image: Sept. 30, 2002 Copyright, Space Imaging LLC
Classification, ReMetrix LLC November, 2002


ReMetrix
Houghton Lake, Michigan
2002 Vegetation Survey
Plant Detection
Surveyed Points
No Vegetation Detected
Vegetation Detected
Base Map Depicts Image Classification
0.5 0 0.5 1
Miles
Map Scale 1:60,000
Projection Systems: UTM Zone 16 NAD 83
Grid Units: Meters
Base Image: Sept. 30, 2002 Copyright, Space Imaging LLC
Classification, ReMetrix LLC November, 2002

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Houghton Lake is the largest inland water body in Michigan, covering a surface area of nearly 9,000 ha (22,000 acres). The lake is a major natural and recreational resource for the region with activities including sport fishing, boating, snowmobiling, and habitat for migratory water birds.

Problems resulting from the proliferation of the submersed invasive plant, Eurasian watermilfoil, in Houghton Lake led to the development and implementation of a plan for managing that invader and restoring the native vegetation of the lake. The Houghton Lake Management Plan offered several alternative strategies for managing Eurasian watermilfoil within the limits of available funding. The Houghton Lake Improvement Board adopted an integrated strategy for managing Eurasian watermilfoil in the lake. The first phase of the strategy occurred from 2002 to 2004. The selected strategy used a whole-lake application of the aquatic herbicide fluridone in the first year to selectively control Eurasian watermilfoil. A second phase (2004–2006) employed targeted, relatively small-scale treatments of systemic herbicides (i.e., 2,4-D and triclopyr). As Eurasian watermilfoil populations recovered in subsequent years, milfoil weevils were introduced to help maintain control. Native plants, particularly elodea, were to be replanted if the initial impact of the whole-lake fluridone application warranted such re-vegetation.
(Continued)

15. SUBJECT TERMS

Aquatic plants	Fluridone	Milfoil weevils
Eurasian watermilfoil	Herbicides	Native plants
	Houghton Lake, Michigan	Systemic herbicides

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14. ABSTRACT (Concluded).

In 2005, the diversity of aquatic plants was manifested by the occurrence of 23 species of aquatic plants in lake-wide surveys, while in 2006, 27 aquatic plant species were recorded. Overall, less than 3% of the total lake area was treated with herbicides for Eurasian watermilfoil control in 2006, indicating success of the maintenance control strategy. Because of the success of this management strategy, a second year of whole-lake fluridone applications was unnecessary.