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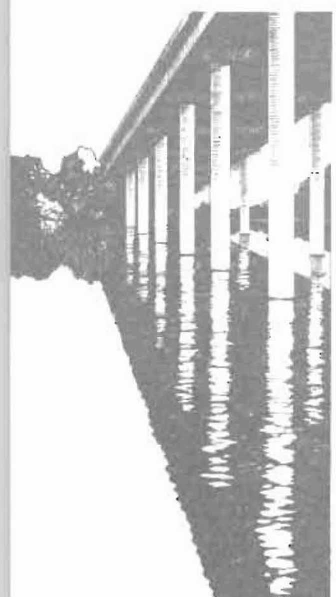

AQUATIC PLANT CONTROL RESEARCH PROGRAM

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ECOLOGICAL CONSIDERATIONS IN THE MANAGEMENT OF EURASIAN WATERMILFOIL IN LAKE MINNETONKA, MINNESOTA

by

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13. ABSTRACT *(Maximum 200 words)*

Eurasian watermilfoil (*Myriophyllum spicatum* L.) is a troublesome aquatic weed that has recently invaded Lake Minnetonka, Minnesota. Many factors influence invasion by Eurasian watermilfoil, including sediment fertility, water clarity, and the nature, extent, and frequency of disturbances to submersed plant beds. Replacement of established populations of native plant species by Eurasian watermilfoil is common, but not universal. Dense beds of the aggressive exotic watermilfoil interfere with recreation and can influence nutrient cycling and the quality of fish and invertebrate habitat.

Although Eurasian watermilfoil is new to Lake Minnetonka, aquatic plant and algal control has been practiced in the lake for many years. Until recently, herbicides were the predominant plant control technique used in the lake. Harvesting has increased dramatically in the last few years and will probably become the primary means of watermilfoil control.

A number of Eurasian watermilfoil management strategies are possible. Eradication of Eurasian watermilfoil from Lake Minnetonka is precluded by the large, well-established population of the species already present. Eradication of small, newly established populations in other nearby water bodies may be possible, although difficult. Selection of an appropriate watermilfoil management strategy will require the formulation of a detailed management plan for the lake.

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Contents

Preface

The work reported herein was sponsored by the US Army Engineer District, St. Paul, and by the Headquarters, US Army Corps of Engineers (HQUSACE), as part of the Aquatic Plant Control Research Program (APCRP). The APCRP is assigned to the US Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding for publication was provided under Department of the Army Appropriation No. 96X3122, Construction General. The APCRP is managed under the Environmental Resources Research and Assistance Programs, Mr. J. L. Decell, Manager. Mr. Robert C. Gunkel was Assistant Manager, ERRAP, for the APCRP. Technical Monitor during this study was Mr. James W. Wolcott, HQUSACE.

Principal Investigator for the study was Dr. John W. Barko, EL. The report was prepared by Dr. Craig S. Smith of the Aquatic Habitat Group (AHG), Environmental Resources Division (ERD), EL; Dr. Barko of the Aquatic Processes and Effects Group (APEG), Environmental Research and Simulation Division (ERSD), EL; and Ms. Dwilette G. McFarland of the APEG. Information on various aspects of the management and ecology of Eurasian watermilfoil in Lake Minnetonka was provided by Messrs. Edward L. McNally, Herbert Nelson, and John Shyne of the US Army Engineer District, St. Paul; Messrs. Wayne Barsted, Bruce Gilbertson, Howard F. Krosch, Robert Potocnik, Jack Skrypek, and Daniel Swanson of the Minnesota Department of Natural Resources; Mr. Bruce Wilson of the Minnesota Pollution Control Agency; Mr. Gene Strommen of the Lake Minnetonka Conservation District; Mr. Kevin Kretsch of Lake Restoration, Inc.; and Mr. Ronald Quanbeck of James M. Montgomery Consulting Engineers. The report was reviewed by Drs. Douglas Gunnison and William D. Taylor, EL. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

This investigation was performed under the general supervision of Dr. John Harrison, Chief, EL, Dr. Conrad J. Kirby, Chief, ERD, and Mr. Donald L. Robey, Chief, ERSD, and under the direct supervision of Mr. Edwin A. Theriot, Chief, AHG, and Dr. Thomas L. Hart, Chief, APEG.

Commander and Director of WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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1 Introduction

Background

Eurasian watermilfoil (*Myriophyllum spicatum* L.) is among the most troublesome submersed aquatic plants in North America. Nuisance growths of Eurasian watermilfoil have been reported from locations that include Lake George (Madsen et al. 1989), Saratoga Lake (Mikol 1985), and Cayuga Lake (Miller and Trout 1985), New York; the Chesapeake Bay (Bayley et al. 1978); Currituck Sound, North Carolina (Davis and Brinson 1983); Tennessee Valley Authority (TVA) reservoirs (Smith, Hall, and Stanley 1967); the Kawartha lakes, Ontario (Wile, Hitchin, and Beggs 1979); Devils Lake, Wisconsin (Lillie 1986); the Madison, WI, lakes (Andrews 1986); and the Okanagan and nearby lakes in British Columbia (Newroth 1985).

Excessive Eurasian watermilfoil growth primarily affects recreation, by interfering with swimming and boating, by reducing the quality of sport fisheries, and by reducing the aesthetic appeal of water bodies (see Newroth 1985). Other adverse effects of Eurasian watermilfoil growth include clogged industrial and power generation water intakes, seasonally lowered dissolved oxygen concentrations, and increased populations of permanent pool mosquitoes (Bates, Burns, and Webb 1985).

This report reviews information on the ecology of Eurasian watermilfoil, with specific reference to Lake Minnetonka, Minnesota, where this species has recently expanded its distribution to nuisance-level proportions (US Army Engineer District (USAED), St. Paul 1989). Factors influencing the distribution, productivity and growth form of Eurasian watermilfoil are discussed in the following sections of Chapter 1, as are effects on other aquatic organisms. In Chapter 2, Lake Minnetonka and its watershed are described within the context of its ability (both historically and at present) to support the growth of submersed aquatic plants, particularly Eurasian watermilfoil. In addition, Chapter 2 includes a historical account of disturbances to the lake, including plant control practices, with consideration for possible effects on the productivity and distribution of submersed aquatic plants. Chapter 3 provides recommendations to facilitate management efforts in Lake Minnetonka and elsewhere, by highlighting conditions that influence the severity of Eurasian watermilfoil problems and the resulting need for its control.

Ecology of Eurasian Watermilfoil

Biogeography

Eurasian watermilfoil belongs to the Haloragaceae, a large and diverse family of dicotyledonous plants. The genus *Myriophyllum* is found on every continent except Antarctica, but most of the 39 recognized species have very limited geographic distributions (Cook 1985). Eurasian watermilfoil is native to Europe, Asia, and northern Africa (Couch and Nelson 1985).

It is commonly ageed that Eurasian watermilfoil was introduced to North America, but the exact timing and location of its introduction(s) are disputed (cf., Reed 1977, Couch and Nelson 1985). Details of the introductions and expansion are particularly incomplete because *M. spicatum* was often confused with the native North American species *Myriophyllum sibiricum* Kom. (= *Myriophyllum exalbescens* Fern.). Herbarium records prior to 1950 show populations of Eurasian watermilfoil in several widely separated locations, including sites in the District of Columbia, Ohio, Arizona, and California (Couch and Nelson 1985). By 1985, Eurasian watermilfoil had been found in 33 states, the District of Columbia, and the Canadian provinces of British Columbia, Ontario, and Quebec (Couch and Nelson 1985). Since 1985 it has been discovered in Minnesota (C. Smith, personal observation). Eurasian watermilfoil has also been reported from several locations in northern Alaska (Holmquist 1971), but these plants may actually be *M. sibiricum*. At the edges of its present distribution, the species has probably not yet occupied all suitable habitats (Warrington 1985).

Biology

Eurasian watermilfoil is a submersed perennial with finely dissected leaves (see Aiken, Newroth, and Wile 1979 for a detailed description). The species is typically most abundant in 1 to 4 m of water (Nichols and Shaw 1986), although it can be found in water 1 to 10 m deep (Aiken, Newroth, and Wile 1979). Roots are adventitious and arise along lower, buried portions of the stem and, prior to fragmentation (see below), along upper portions of stems. Flowering occurs only when plants have reached the water surface. The inflorescence is a terminal spike and is borne above the water surface. Flowers are small and inconspicuous, and are probably wind-pollinated (Patten 1956).

Plants are essentially evergreen and form no specialized overwintering structures such as turions. Some shoots from the previous growing season persist through the winter, and new shoots are initiated in the fall. These do not elongate until spring. Carbohydrate storage occurs throughout overwintering shoots and roots, without being concentrated in any particular plant part (Titus and Adams 1979b, Perkins and Sytsma 1987).

Eurasian watermilfoil exhibits a characteristic annual pattern of growth. In the spring, shoots begin to grow rapidly as water temperatures approach about 15° C. As shoots grow, lower leaves drop off in response to shading (Adams, Titus, and McCracken 1974). When they reach the surface, shoots branch profusely, forming a dense canopy above leafless vertical stems. Typically, plants flower upon reaching the surface, although some populations rarely flower (Madsen and Boylen 1989). After flowering, plant biomass declines as the result of fragmentation of stems. Where flowering occurs early, plant biomass may increase again later in the growing season, and reach a second biomass peak associated with additional flowering and fragmentation (Adams and McCracken 1974).

Variations in this annual pattern result from differences in climate, water clarity, and rooting depth (see below). Plants growing in shallow water can reach the surface within a month or less of initiating growth, and are particularly likely to exhibit several biomass maxima and fragmentation periods. In deep clear water, plants typically grow continuously throughout the summer and reach the surface late in the growing season, if at all. Under such conditions, as in Lake George, New York, fragmentation does not occur until after the single, late-summer biomass peak (Madsen, Eichler, and Boylen 1988).

Propagation/spread

Eurasian watermilfoil can potentially spread by both sexual and vegetative means. However, vegetative spread of Eurasian watermilfoil by stem fragmentation and stolon formation is thought to be the major means of both intralake and interlake dispersal (Kimbel 1982; Nichols and Shaw 1986; Madsen, Eichler, and Boylen 1988). Stolons expand populations over distances of a few meters or less (Madsen, Eichler, and Boylen 1988). Fragments are the predominant means of dispersal over longer distances (Madsen, Eichler, and Boylen 1988), and are probably also the most important means by which Eurasian watermilfoil colonizes new habitats (Aiken, Newroth, and Wile 1979).

Within lakes and river systems, fragments are readily dispersed by water currents. The frequency of fragment transport between lakes by various mechanisms is not known, but human activities, such as recreational boat traffic, are believed to be one of the most important means of dispersal (Johnstone, Coffey, and Howard-Williams 1985). Other submersed plant species are known to have spread extensively by fragmentation (e.g., *Elodea canadensis* in Europe; Sculthorpe 1967). Vegetative reproduction alone probably accounts for the spread of Eurasian watermilfoil throughout North America.

Stem fragments are formed by mechanical damage and by autofragmentation; the latter occurs primarily after flowering (Gustafson and Adams 1973) and at the end of the growing season, just after maximum biomass is attained (Madsen, Eichler, and Boylen 1988). Human activities (e.g., harvesting) may increase the production of fragments or alter the timing of their production, but large numbers of fragments are produced without human intervention.

The importance of seeds as a means of dispersal has not been rigorously evaluated, but is generally considered to be minor. The relatively uniform appearance of North American Eurasian watermilfoil and the lack of any in situ observations of seedlings have been cited as evidence for the relative unimportance of seeds as a means of dispersal (Aiken, Newroth, and Wile 1979). Many populations flower and produce seeds, particularly in the first few years after establishment. Seeds are often viable, as shown by high rates of germination in the laboratory (Patten 1955, Coble and Vance 1987, Madsen and Boylen 1988). The environmental tolerances of young seedlings are probably much narrower than those of established plants, and the requirements of seedlings are seldom met in situ (Patten 1956).

Growth and morphology

Compared with other submersed plants of productive lakes, Eurasian watermilfoil is neither unusually productive nor does it attain unusually high levels of biomass (Grace and Wetzel 1978). Invasion of a lake by Eurasian watermilfoil does not necessarily lead to a major increase in aquatic plant productivity or biomass. In Lake Mendota, Wisconsin, for example, plant beds dominated by wild celery (*Vallisneria americana* Michx.), with a biomass of 289 g m^{-2} (dry weight) (Rickett 1921), were replaced by Eurasian watermilfoil, which averaged 130 g m^{-2} (Lind and Cottam 1969). When Eurasian watermilfoil invades relatively unproductive lakes, it may replace species that are less productive, but it does not usually become widespread in such lakes (see below).

Likewise, this species does not have unique photosynthetic characteristics, relative to other species. The similarity of photosynthetic responses reported by Van, Haller, and Bowes (1976) for a variety of species, including Eurasian watermilfoil, has been documented. Submersed aquatic plants in general possess extremely low rates of net photosynthesis compared to terrestrial vegetation, and their stature is related more to their ability to elongate and form a canopy at the water surface than to their production of biomass.

Table 1 summarizes the influence of environmental factors on the growth and morphology of Eurasian watermilfoil. Factors that influence morphology are particularly important because it is the morphology of Eurasian watermilfoil that imputes it as a nuisance species, rather than its productivity per se. Factors that affect growth are also important because of the influence of growth rate on propagation, spread, distribution, ecological impacts, etc.

Light intensity determines many aspects of the distribution and morphology of Eurasian watermilfoil. The species grows in lakes having a wide range in water clarity, but its morphology and depth distribution differ widely across the turbidity spectrum. Turbid water restricts Eurasian watermilfoil to shallow rooting depths, and the plant forms a canopy of horizontal stems at the surface, considered to be a near-optimal growth form (Titus and Adams 1979a). In relatively clear water, Eurasian watermilfoil grows at considerably greater rooting depths, from which it may not reach the surface (cf., Madsen et al. 1989). The highly plastic growth form of Eurasian watermilfoil enables it to overtop and shade potential competitors over a wide range of water levels and turbidity. Dominance by this species is often established early in the growing season, owing to a combination of high overwintering biomass and rapid spring growth (Nichols and Shaw 1986). Carbohydrate storage in overwintering tissues, by supporting shoot growth up to a depth where net photosynthesis is possible (Titus and Adams 1979b), contributes to the ability of Eurasian watermilfoil to persist at rooting depths where the light level at the sediment surface is below the compensation point.

Eurasian watermilfoil has a relatively high temperature optimum, but can photosynthesize and grow over a broad temperature range. Photosynthesis is maximal in the range of 30° to 35° C (Stanley and Naylor 1972; Van, Haller, and Bowes 1976; Titus and Adams 1979a), and growth increases with increasing water temperature up to at least 32° C (Barko and Smart 1981a). High water temperatures promote multiple biomass peaks and multiple periods of flowering and fragmentation (Grace and Tilly 1976). In contrast, the plant is capable of appreciable photosynthesis at 10° C (Stanley and Naylor 1972), corresponding with the reported lower limit for rapid growth (British Columbia Ministry of the Environment 1981).

The ability of this species to photosynthesize and grow at relatively low water temperatures contributes to its rapid growth to the surface in the spring and may increase its ability to compete with other species at relatively high latitudes (Barko, Hardin, and Matthews 1982). Eurasian watermilfoil is very susceptible to freezing temperatures (Stanley 1976), and short-term drawdown during freezing temperatures has been successfully used as a control technique in some TVA reservoirs (Bates, Burns, and Webb 1985).

Shoot elongation in this species is extremely sensitive to conditions of light and temperature (Barko and Smart 1981a). In general, conditions of low light and high water temperature, characteristics of many eutrophic environments, stimulate shoot elongation and canopy formation. Even though diminished light with depth in these systems ultimately limits depth distribution by negating net photosynthesis, low light conditions actually contribute to nuisance growth by promoting stem elongation and canopy formation at the surface.

Eurasian watermilfoil grows best on fine-textured, inorganic sediments with an intermediate density of about 0.8 to 1.0 g/ml (Barko and Smart 1986). It grows relatively poorly on highly organic sediments (organic content > 20 percent), which have an intrinsically low sediment density, and on coarse substrates (sand and gravel), which have a high sediment density. The response to sediment texture and organic matter content is largely related to mineral nutrient availability, which is highest in sediments of intermediate density (Barko and Smart 1986).

Over the spectrum of infertile to enriched aquatic systems, Eurasian watermilfoil appears to prefer an approximate midpoint (Figure 1; cf., Moss 1983). This species may be unable to compete with slower growing, nutritionally conservative species (e.g., isoetids) under infertile conditions, and it is potentially excluded due to shading by phytoplankton and attached algae under relatively enriched conditions (Jones, Walti, and Adams 1983). In less productive lakes, Eurasian watermilfoil typically does not

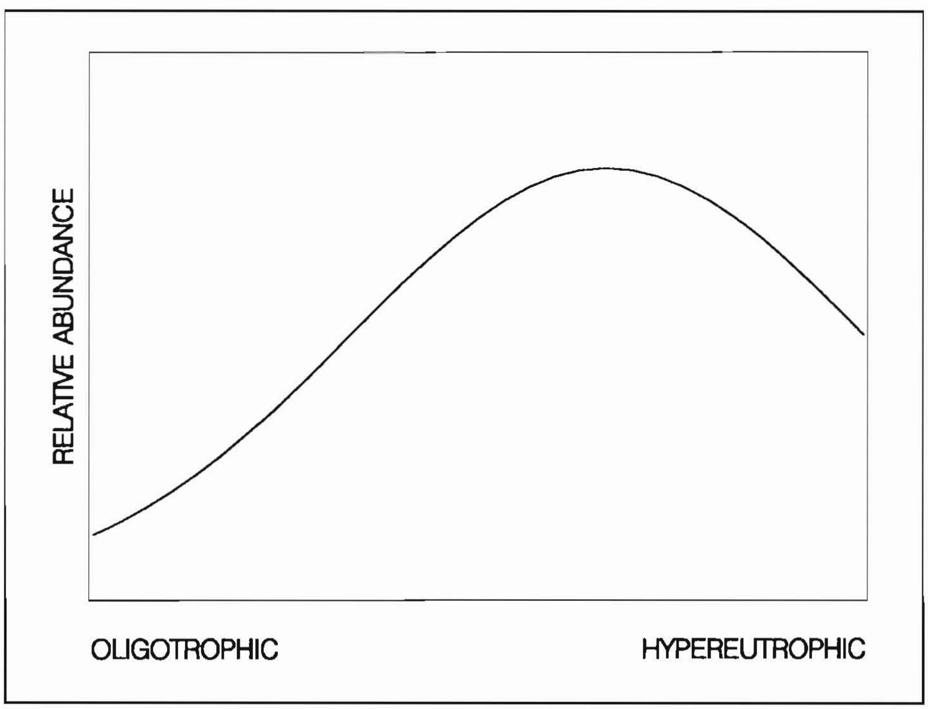

Figure 1. Influence of trophic status on Eurasian watermilfoil abundance

dominate a large fraction of the littoral zone, but instead is restricted to locations with nutrient-rich sediments. For example, the most oligotrophic of the Okanagan Basin lakes, Kalamalka Lake (Stockner and Northcote 1974), supports only relatively sparse, scattered Eurasian watermilfoil; most of the plant growth is concentrated in a few areas that receive heavy public use (Wallis 1986).

In the fundamentally oligotrophic Lake George, New York, the species is abundant primarily in locations where sedimentation rates are high, such as near the mouths of creeks (Madsen et al. 1989). In Devil's Lake, Wisconsin, the species is restricted to three discrete areas (Lillie 1986), and there is evidence that nutrient-rich groundwater enters the lake at these locations (Lillie and Barko, unpublished). Similar enhancement of submersed plant growth has been observed in areas of high groundwater flux in relatively unproductive Sparkling Lake, Wisconsin (Lodge, Krabbenhoft, and Striegl 1989).

Growth of Eurasian watermilfoil is poor in shallow water (less than 1 m deep), probably owing to a combination of such factors as wave action, large temperature fluctuations, seasonal variations in water level, high light intensity, coarse substrate, and enhanced epiphyte growth (British Columbia Ministry of the Environment 1981). In cold climates, ice scour may also limit the long-term establishment of Eurasian watermilfoil in shallow areas.

Mineral nutrition

The nutrition of a variety of submersed plants has been an area of active interest and considerable investigative attention during the last 15 to 20 years (Denny 1980; Agami and Waisel 1986; Barko, Adams, and Clesceri 1986). The nutrition of Eurasian watermilfoil has been perhaps the best investigated among all submersed plant species. Thus, rather than generalizing the results of studies involving other species, we consider below information obtained principally from studies of Eurasian watermilfoil.

It is generally agreed that uptake of phosphorus (P) from sediment by roots constitutes the primary mode of uptake for Eurasian watermilfoil in the majority of aquatic systems (Barko and Smart 1980, Carignan and Kalff 1980, Carignan 1982). Even in flowing-water systems where uptake from surrounding water might be expected to exceed uptake from sediment, submersed plants appear to obtain most of their P through root uptake (Chambers et al. 1989). Fine-textured lake sediments contain large pools of available P. Thus, in most lakes it is unlikely that the availability of this element would often limit the growth of Eurasian watermilfoil. Indeed, an experimental attempt to limit the growth of Eurasian watermilfoil in Lake Wingra, Wisconsin, by reducing P availability through aluminum sulfate application was unsuccessful (Mesner and Narf 1987).

For nitrogen (N), no firm consensus currently exists concerning sources of uptake by Eurasian watermilfoil, in part because N has been less extensively investigated than P. Nitrogen can be absorbed by Eurasian watermilfoil either as ammonium from sediment or as ammonium and/or nitrate from the overlying water (Nichols and Keeney 1976). However, the concentration of ammonium in sediment is much greater than in the overlying water of most aquatic systems. Furthermore, ammonium is preferred over nitrate by Eurasian watermilfoil (Nichols and Keeney 1976).

Investigations have indicated significant mobilization of N as ammonium from sediment (Best and Mantai 1978, Barko and Smart 1981b). Extensive reductions in sediment ammonium levels within Eurasian watermilfoil beds in conjunction with its seasonal growth (Carignan 1985) attest to the importance of roots in the N economy of this species. In situ fertilization of sediment by addition of ammonium-N has been demonstrated to significantly increase the growth of Eurasian watermilfoil (Anderson and Kalff 1986). Thus, unlike P, the availability of N may under some circumstances limit the growth of this species.

Other elements important to the growth of Eurasian watermilfoil include the cations Na, K, Ca, and Mg. Their influence in solution on the growth of Eurasian watermilfoil has been examined extensively by Smart and Barko (1986). In general, they concluded that these cations were unlikely to be growth limiting except under conditions of low inorganic carbon availability. Calcium, in particular, as a component of the carbonate system, has been recognized to play an important role in inorganic carbon uptake during photosynthesis by Eurasian watermilfoil (Lowenhaupt 1956, Stanley 1970, Smart and Barko 1986).

Numerous studies of photosynthesis in relation to water chemistry emphasize the importance of bicarbonate as an inorganic carbon source to Eurasian watermilfoil, and suggest that carbon availability may often limit its growth (e.g., Stanley 1970; Adams, Guilizzoni, and Adams 1978; Titus and Stone 1982; Smart and Barko 1986). Optimal growth of this species occurs in alkaline (hardwater) systems, with concomitantly high concentrations of dissolved inorganic carbon (Spence 1967, Hutchinson 1970, Stanley 1970). Thus, the alkalinity of water provides a simple, but useful, measure of the growth potential of Eurasian watermilfoil. Like many plants that "prefer" a hardwater condition, Eurasian watermilfoil can exist in softwater environments (Giesy and Tessier 1979), but it is not ideally suited to grow there.

Rooted aquatic plants, including Eurasian watermilfoil, can satisfy their requirements for micronutrients by uptake from sediment (Smart and Barko 1985). Since these elements tend to precipitate in the presence of oxygen, they are usually available in low concentrations in lake surface waters. Their availability to Eurasian watermilfoil growing in anaerobic sediments is much greater than in the overlying water. However, the relationship between growth and micronutrient supply for this and other submersed plant species has not been well investigated. In any event, it is unlikely that the growth of Eurasian watermilfoil would be limited by supply of micronutrients under most circumstances, because of its relatively minor requirements for these elements in tissues.

Mobilization of sediment nutrients

Substantial quantities of nutrients can be transferred from the sediments into the water as Eurasian watermilfoil takes up minerals from the sediment, translocates them to shoots, and releases them upon senescence and decomposition (Prentki et al. 1979, Barko and Smart 1980, Carpenter 1980b, Landers 1982, Smith and Adams 1986). However, this species and a variety of other submersed freshwater plant species investigated to date do not actively "pump" (i.e., excrete) nutrients directly into the water column (Denny 1980; Barko and Smart 1981b; Barko, Adams, and Clesceri 1986). The ability to mobilize sediment nutrients, and then release these nutrients to the water column upon tissue senescence, is certainly not unique to Eurasian watermilfoil.

As in other species, biomass turnover in Eurasian watermilfoil is affected by environmental conditions. Westlake (1982), based on information provided in Carpenter (1980b), indicated high biomass turnover in Eurasian watermilfoil. Nutrient release from this species during the growing season may be more prolonged than from other species, due to the relatively continuous sloughing of leaves and stems (Smith and Adams 1986). However, Carpenter (1980b) actually showed similar or somewhat higher tissue turnover (net production/peak biomass) in two native species than in Eurasian watermilfoil. Thus, there is no firm basis for suggesting that nutrient leaching or decay will be any faster in this species than in other species. Westlake (1982) stressed that environmental variables weigh heavily on tissue turnover (and associated nutrient release) in aquatic plants. Turnover in eutrophic systems, regardless of species composition, is usually greater than in oligotrophic systems, because of greater productivity in the former.

Habitat relationships

Both invertebrates and fish tend to be more abundant and diverse in aquatic plant beds than in adjacent open-water regions, presumably because of the shelter and substrate provided by plants (Wiley et al. 1984; Killgore, Morgan, and Rybicki 1989). Populations of benthic invertebrates beneath submersed vegetation can be more than 100 times larger than those in nonvegetated openings within plant beds (Miller, Beckett, and Bacon 1989). Eurasian watermilfoil has been shown to provide a better habitat for invertebrates (Pardue and Webb 1985) and for fish (Killgore, Morgan, and Rybicki 1989) than the open water of the littoral zone.

Production of forage fish and invertebrates appears to increase directly with increasing submersed plant biomass, while bass (*Micropterus salmoides* L.) production and their condition have been shown to be maximal at intermediate levels of plant biomass (Figure 2) (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 plant beds contributes to diminished bass production (Savino and Stein 1982, Engel 1987).

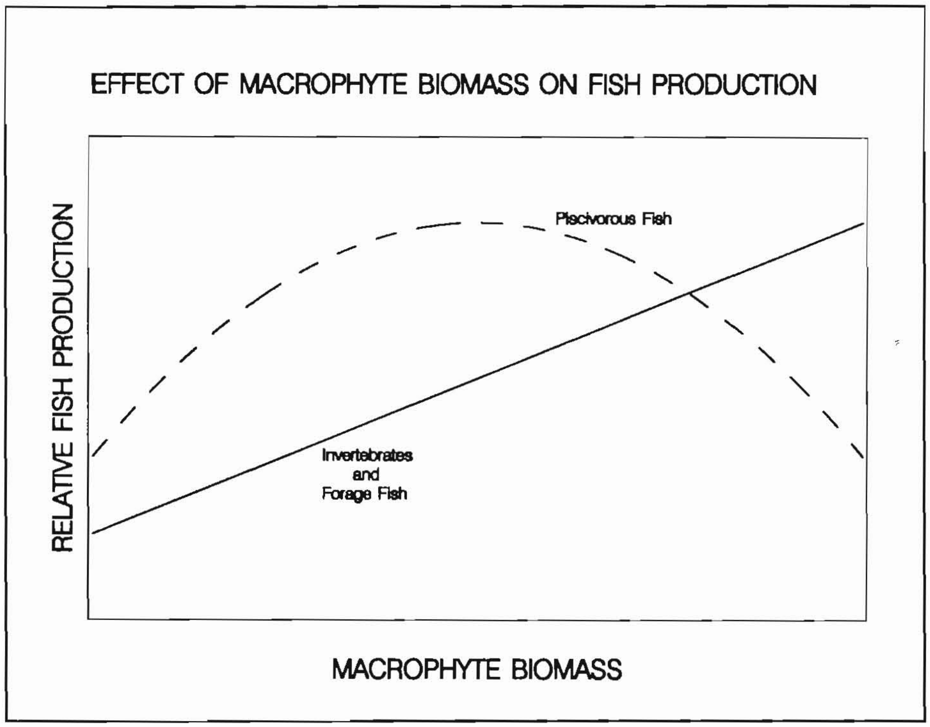

Figure 2. Influence of submersed plant biomass on production of invertebrates, forage fish, and piscivores (largemouth bass) (Wiley et al. 1984)

Invertebrate and fish communities in Eurasian watermilfoil beds differ from those associated with other submersed plants, but these differences are not particularly great. Dvorak and Best (1982) found that of eight morphologically distinct species, Eurasian watermilfoil had the poorest invertebrate fauna, although all plant species had a high number of macroinvertebrate species in common. In Lake Opinicon, Ontario, Eurasian watermilfoil beds supported significantly fewer benthic and foliar invertebrates per square meter than did mixed beds of pondweeds (*Potamogeton* spp.) and wild celery (Keast 1984), but much of the difference can be attributed to the threefold higher biomass of the pondweed-wild celery community. Likewise, fish abundance in the pondweed-wild celery community during daytime feeding periods was three to four times greater than in Eurasian watermilfoil beds.

The effect of Eurasian watermilfoil on salmonids is potentially much greater than for other fish species, because the plant reduces spawning success by covering spawning gravels (Newroth 1985). Thus, the greatest effects can be expected when invasion is associated with a large change in total plant biomass or when particularly sensitive species (e.g., salmonids) are affected. Except in these cases, invasion of native aquatic plant communities by Eurasian watermilfoil will probably not prompt major changes in fish or invertebrate populations.

Invasions/declines

Eurasian watermilfoil is often described as an invasive species, and it is loosely accepted that invasions are followed by rapid growth and concomitant displacement of native species. Certainly this species has a history of rapidly obtaining dominance in many eutrophic systems, but this pattern is by no means universal. In the Great Lakes, for example, this species, although present for some time, has not been reported to be a common or a nuisance component of the submersed plant community (Schloesser and Manny 1984). At present, this species does not appear to be significantly expanding its distribution in Lake George, New York (Madsen et al. 1989).

The extent to which Eurasian watermilfoil replaces native species differs from location to location. Native species were nearly completely displaced in Lake Mendota (Lind and Cottam 1969) and Lake Wingra (Nichols and Mori 1971), Wisconsin, while in TVA systems the plant almost exclusively invaded new habitat.[1] In Devils Lake, Wisconsin, Eurasian watermilfoil took over areas that had been dominated by elodea (*Elodea canadensis*); however, it appears to have had little effect on the distribution of other species (Lillie 1986). In Lake Opinicon, Ontario, Eurasian watermilfoil invaded areas that had for the most part been unvegetated (Keast 1984).

Specific factors contributing to successful invasion by Eurasian watermilfoil are unknown, and there is equally little information available to explain its explosive growth in some systems, but not in others, following invasion. In a unique review of information on plant invasions, Johnstone (1986) suggested that invasions are caused by the removal of barriers that previously exclude a plant species from a particular area. Barriers appear to be removed in association with disturbance (change). Indeed, the near complete dominance of Eurasian watermilfoil in Lake Wingra, Wisconsin, for about a decade (Carpenter 1980a) followed a long history of disturbance for this system (Baumann et al. 1974). For invasion to be successful, the timing of barrier relief by disturbance or directional change

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[1] Personal Communication, 1990, A. Leon Bates, Tennessee Valley Authority, Muscle Shoals, AL.

(succession) must coincide with incursion by the invading species. Thus, invasions appear to be rather stochastic events.

Several characteristics of Eurasian watermilfoil enable it to rapidly colonize disturbed areas and to remain in place once established. The ability to spread rapidly by fragmentation allows Eurasian watermilfoil to quickly colonize new habitat whenever it is made available, such as by sediment deposition, water-level changes, or decline/removal of populations of other species. Characteristics of Eurasian watermilfoil that make it an effective competitor for light are probably extremely important with regard to its ability to replace other species and to persist once established, as light is probably the most critical factor for submersed plant growth in the aquatic environment.

The kinds of disturbances that can lead to invasion by Eurasian watermilfoil are probably the same as those influencing submersed plant succession (Sheldon 1986). These may include, for example, sedimentation; ice scouring; wave action; bioturbation; herbivory; changes in water level, water clarity, temperature, nutrient loading, or climate; and a variety of possible anthropogenic factors. Disturbance resulting from Tropical Storm Agnes led to an increase in Eurasian watermilfoil abundance that nearly excluded other previously abundant species at the south end of Cayuga Lake, New York (Oglesby and Vogel 1976). Eutrophication or reversal of eutrophication, both constituting a disturbance, can effect pronounced changes in the composition of aquatic plant communities (Moss 1983, Osborne and Polunin 1986). Invasion windows for this species apparently open in close association with marked changes (either an increase or decrease) in trophic state.

Composite environmental changes simultaneously alter several facets of the environment. In drought years, for example, lowered runoff typically results in reduced sediment and nutrient loading, higher than normal temperatures, reduced turbidity and, in some cases, lowered water levels. The resulting conditions are ideal for expansion of Eurasian watermilfoil populations.

Lowered nutrient inputs reduce phytoplankton growth, thereby further increasing water clarity. Increased water clarity and lowered water levels mean that areas that were formerly too poorly illuminated to sustain the growth of rooted plants are now accessible. High light intensities and warm water temperatures promote abundant growth of Eurasian watermilfoil. Nutrient availability for the growth of rooted plants is relatively unaffected, since Eurasian watermilfoil plants obtain mineral nutrients primarily from the sediments. Thus, Eurasian watermilfoil problems are likely to be worse in (and following) drought years than in nondrought years.

Some evidence for this is provided by the observation that Eurasian watermilfoil problems were particularly severe in the Madison, WI, lakes (C. Smith, personal observation), and in TVA reservoirs[1] during the summer of 1988, when eastern/midwestern North America was experiencing a drought.

Major declines in populations of Eurasian watermilfoil have been reported and evaluated (Carpenter 1980a, Nichols and Shaw 1986, Painter and McCabe 1988). Hypotheses tendered as to the cause of these declines include nutrient depletion, shading by phytoplankton and attached algae, attack by parasites or pathogens, long-term effects of harvesting and/or herbicides, accumulation of a toxin, climatic fluctuations, competition from another plant (Carpenter 1980a), and insect herbivory (Painter and McCabe 1988), but none of the declines has been adequately explained. In many locations, Eurasian watermilfoil populations increased to a high level of dominance, maintained dominance for a few years, and then declined.

To date, Eurasian watermilfoil has declined in the Chesapeake Bay area (Bayley, Rabin, and Southwick 1968); in the Madison, WI, area lakes (Carpenter 1980a); in several southern Ontario lakes (Wile, Hitchin, and Beggs 1979; Painter and McCabe 1988); in Devils Lake, Wisconsin;[2] and in a few localized areas within the Okanagan Valley lakes of British Columbia (British Columbia Ministry of the Environment 1981). In these locations, the period of peak milfoil abundance ranged from approximately 5 to 10 years, with 10 years being typical (Carpenter 1980a). When milfoil declined, the rate and amount of decline varied from location to location. Typically, postdecline populations of Eurasian watermilfoil are less likely than predecline populations to reach the water surface or to flower.

Recovery of native species has not been studied, but in Lake Wingra, Wisconsin, wild celery and several pondweeds (*Potamogeton* spp.) increased following the milfoil decline (C. Smith, personal observation).

As pointed out by Carpenter (1980a), the potential transience of Eurasian watermilfoil abundance needs to be considered in the development of aquatic plant management programs. Some control techniques may actually promote expansion of plant populations or delay declines. For example, Carpenter (1980a) reported that frequently harvested areas in Lake Wingra continued to support robust plant growth after the species had declined in other parts of the lake. Techniques such as derooting, shallow dredging, and drawdown, and others which create favorable habitat, may perpetuate high Eurasian watermilfoil populations. Two exemplary

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[1] Personal Communication, 1990, A. Leon Bates, Tennessee Valley Authority, Muscle Shoals, AL.

[2] Personal Communication, 1990, R. A. Lillie, Wisconsin Department of Natural Resources, Fitchburg, WI.

locations where robust Eurasian watermilfoil populations are reported to have persisted for more than 10 to 15 years, Guntersville Reservoir, in Alabama, and the Okanagan area lakes in British Columbia, are more intensely managed than locations where the plant has declined (Table 2). In view of the apparent relationship between disturbance and invasion (see above), it would be useful to have better information than is presently available on the effects of specific control measures on longevity of Eurasian watermilfoil abundance.

2 Description of Lake Minnetonka and Its Watershed

Lake Minnetonka is a complex of 15 morphologically distinct basins spanning 5,801 ha in east-central Minnesota (Figure 3). It is an irregularly shaped, dimictic lake, with over 25 named arms and bays. At normal full-pool elevation (283.4 m NGVD), the lake has mean and maximum depths of 6.9 and 30.8 m, respectively, and a total volume of 400.6×10^6 m^3. The three largest basins, Lower Lake (2,481 ha), Upper Lake (1,732 ha), and Crystal Bay (336 ha), are also the deepest (25.6 to 30.8 m), and together comprise nearly 90 percent of the total lake volume. The smaller basins have mean depths ranging from 2.0 to 4.3 m, and vary in surface area from 8.1 to 334 ha. Major physical characteristics of the lake are summarized in Table 3.

Grays Bay Dam was constructed primarily for flood control and regulation of water supply during periods of low inflow. Lake levels and discharge are controlled both by an overflow spillway (maximum elevation, 283.4 m NGVD) and three vertically sliding tainter gates with an invert elevation of 282.2 m NGVD. The dam is operated to provide periodic drawdowns in fall and early spring to create storage for spring snowmelt. Maximum water-level fluctuations for any month generally do not exceed 0.4 m.

Drainage

The watershed of Lake Minnetonka covers a roughly oval-shaped (30,500-ha) area in Hennepin and Carver Counties, Minnesota (Figure 4). This area is drained by five major streams into Lake Minnetonka: Six Mile Creek, which enters the lake from the west, and Painter Creek, Lake Classen Creek, Long Lake Creek, and Lake Gleason Creek, which enter mainly from the north. Additional drainage is received via direct surface runoff, groundwater seepage, and numerous minor creeks and ditches.

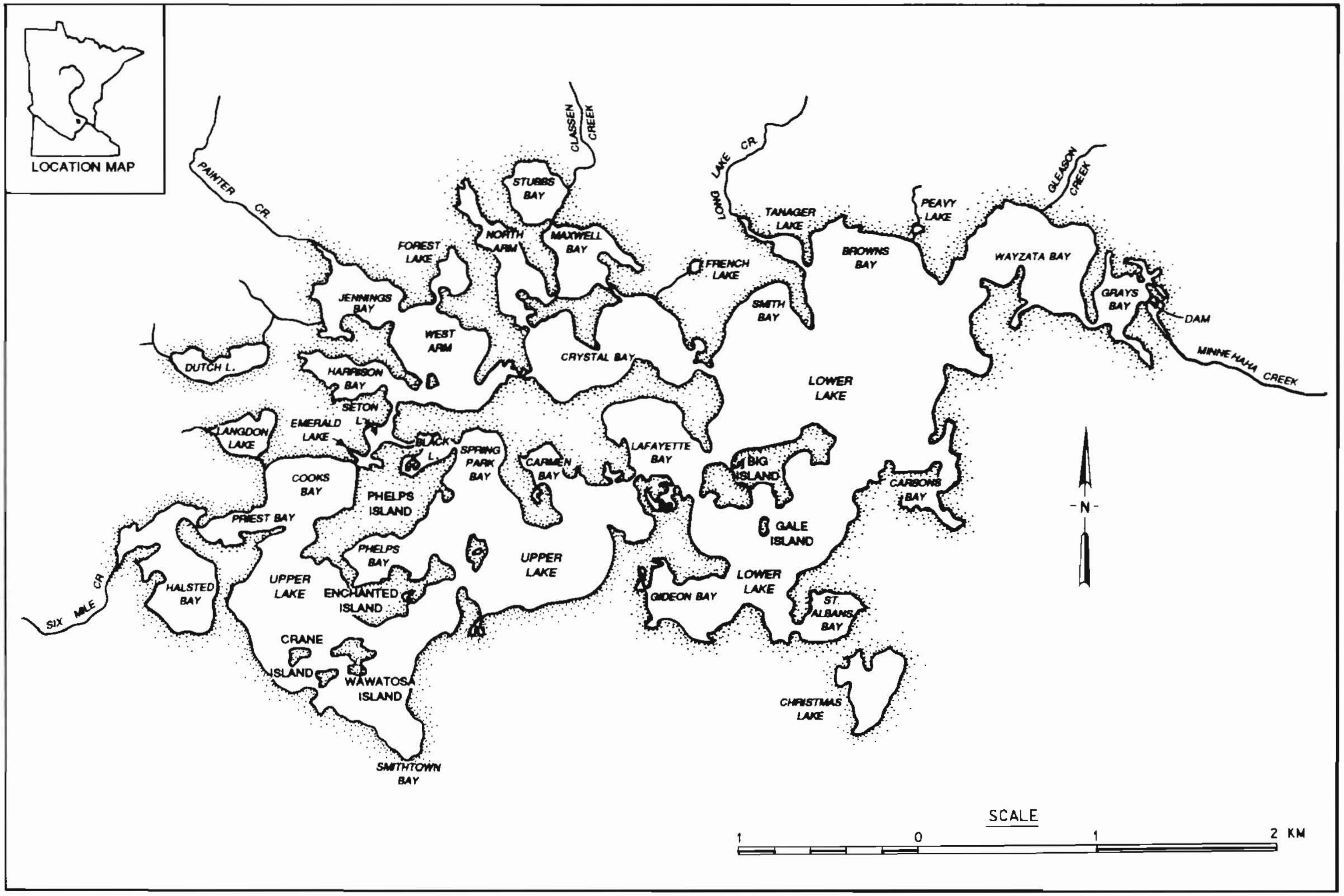

Figure 3. Map of Lake Minnetonka

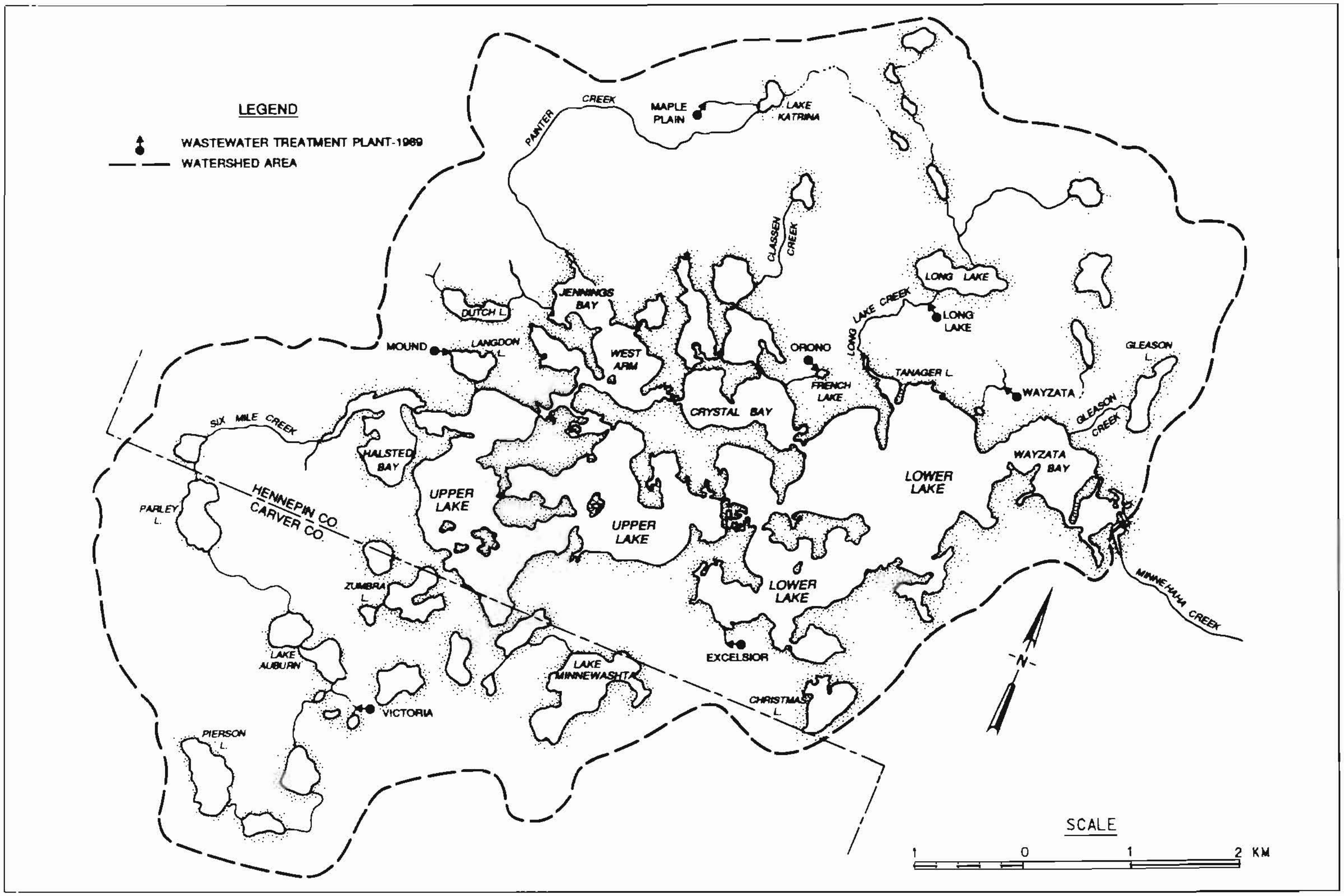

Figure 4. Location of sewage treatment facilities formerly discharging effluent into Lake Minnetonka

External hydraulic and nutrient loadings are highest during rapid snow thaws of spring. During the remainder of the year inflow is diminished, reaching an overall seasonal minimum in late summer or fall.

The main outlet stream, Minnehaha Creek, originates at Grays Bay Dam (at the east end of the lake) and flows approximately 26 km southeasterly to its confluence with the Mississippi River in Minneapolis. En route to the Mississippi River, the creek passes through Lake Nokomis and Lake Hiawatha and connects with channels to Lake Harriet, Lake Calhoun, Lake of the Isles, and Cedar Lake. The estimated hydraulic residence time in Lake Minnetonka is 15 years (Schoell 1967).

Land Use

Lake Minnetonka lies approximately 19.3 km west of the center of the Minneapolis-St. Paul metropolitan area. The recreational and aesthetic amenities of the lake, along with its proximity to the Twin Cities, have prompted extensive urbanization of its 175-km shoreline. Of the 23 municipalities contained in the watershed, 13 are situated adjacent to the lake. Shoreline areas reflect an attractively wooded suburban setting, characterized by single-family housing with some commercial and industrial development along major transportation routes.

Areas approaching the periphery of the watershed are used primarily for agricultural purposes including cultivated croplands (corn, soybeans, hay, and small grains), pastures, and open fields. While agricultural land presently occupies a major portion of the watershed, the demand for residential property in the vicinity of Lake Minnetonka has continued to rise. It is expected that over the next 15 years, agricultural practices will taper significantly to accommodate low- to medium-density residential development. Table 4 lists the areas of land in major land use categories as documented by the Minnehaha Watershed Creek District (Hickok and Associates, Inc. 1987).

Consequent to the rapid urbanization of the watershed, seven sewage treatment facilities were constructed (between 1927 and 1963) with ultimate release of treated effluent either into the lake or its tributaries (Figure 4). Sewage effluent from these facilities was estimated to have contributed 20.8 percent of the water, 31.5 percent of the nitrogen, and 80.6 percent of the phosphorus that entered the lake by its tributaries from June 1966 to May 1967 (Orr 1968). Although sewage facility discharge was phased out between 1971 and 1986, the chemical quality of Lake Minnetonka continues to be suppressed by diffuse nonpoint runoff from urban and agricultural lands (Hickok and Associates, Inc. 1987).

Prior to 1949, the development of shoreline real estate and renovations of Grays Bay Dam necessitated extensive dredging in Lake Minnetonka. Many of these operations were geared to accommodate road construction paralleling the shore, clearing and filling of beach areas, and harbor and lagoon construction (Moyle 1950). While such large-scale operations appear to have dissipated since that time, the lake is still dredged periodically in small areas to enhance access to boat landings and improve navigation in narrow channels between bays.

At present, no quantitative information exists from which to estimate the total area in Lake Minnetonka that has been dredged in recent years. However, permits granted by the MDNR since 1988 suggest that dredged areas comprise only a minor portion of the littoral zone of the lake. Relative to aquatic plant dispersal, dredging operations are recognized to provide an effective means of disseminating propagules and exposing sediments for colonization, particularly by rhizomatous and fragmenting species (e.g., Eurasian watermilfoil) of submersed plants (cf., Sheldon 1986).

Geology

Glacial drifts forming the morainic hills and basins in the watershed of Lake Minnetonka were deposited during the "Wisconsin Age" of the Pleistocene Epoch (ca. 20,000 years ago). Beneath the lake lies a sandy noncalcareous (Patrician) red drift, consisting mainly of crystalline igneous and metamorphic rock. The drift was deposited by a glacial lobe that flowed southwest 240 km from the basin of Lake Superior.

In the western portion of the watershed, the red drift was buried by a moraine of gray, claylike (Kewatin) drift, deposited by a Grantsburg sublobe that moved from the west through the area as an offshoot of the Des Moines glacial lobe (ca. 14,000 years ago). This gray drift is highly calcareous and contains fragments of limestone and shale, rock types typically found in northwest Minnesota and Manitoba. The two drift types each vary in thickness from approximately 40 to 100 m, and can be separated in the lake by a line running generally northwest from Excelsior Bay through Minnetonka Beach, Maxwell, and Stubbs Bays.

Recreation

For over a century, Lake Minnetonka has been famous for the year-round recreational opportunities it affords. Swimming, boating, fishing, and water-skiing are among the numerous water-based sports for which the lake is widely used. Good angling is provided by the lake in both winter and summer; however, in recent years, while winter fishing has gained in popularity, fishing in summer has leveled off, in part due to the rise in other open-water activities such as yachting, cruising, speedboating, and water-skiing.

Recreational boating and associated wave action in Lake Minnetonka are potentially important mechanisms for both intralake and interlake dispersal of propagules of submersed aquatic plants. The potential role of these physical disturbances in the propagation and spread of Eurasian watermilfoil in Lake Minnetonka needs to be stressed, since the periods of peak biomass production and autofragment formation by this species (i.e., summer and early fall) occur when recreational boat traffic abounds in the lake.

Water Quality

Recent water quality assessments by the Minnehaha Creek Watershed District (MCWD) and the Minnesota Pollution Control Agency (MPCA) have classified Lake Minnetonka as eutrophic (Hickok and Associates, Inc. 1987; Heiskary and Wilson 1988; MPCA 1988). By definition, eutrophic or "well-nourished" lakes receive high nutrient inputs and support high levels of organic matter production (Wetzel 1983, Reynolds 1984). Until 1986, seven municipal sewage treatment plants were major point sources of nutrient loading into Lake Minnetonka (Moyle 1950; Megard 1970a, 1970b, 1977; Affeldt and Davis 1984; Affeldt 1985). Nutrient inputs from these facilities have been associated with excessive phytoplankton and aquatic plant production, decreased water clarity, and low dissolved oxygen concentrations.

At present, adverse water quality effects are most apparent in Tanager Lake, Halsteds Bay, West Arm, and Jennings Bay—all shallow basins that were formerly receiving bodies for wastewater effluents (Megard 1970a, 1970b, 1977; US Environmental Protection Agency 1975; Affeldt and Davis 1984; Affeldt 1985).

In May 1968, the MPCA adopted a resolution for the diversion (between 1971 and 1986) of untreated wastewaters from the Lake Minnetonka watershed to the Metropolitan Waste Control Commission's Blue Lake facility for disinfection and release into the Minnesota River. The implementation of this policy resulted in the discontinuance of average annual inflows of approximately 51.6 tons of nitrogen and 30.4 tons of phosphorus into the lake (Orr 1968). Yet, despite the termination of these tremendous nutrient inputs, nitrogen and phosphorus concentrations in the lake have remained relatively high (Affeldt 1985; Hickok and Associates, Inc. 1987; MPCA, unpublished).

Elevated nutrient concentrations are thought to have continued due to a combination of factors, e.g., the lengthy retention time of water in the lake, internal nutrient loading, and land use practices that promote runoff and erosion. Of these, the release of nutrients from lake bed sediments is considered to be the dominant cause (Hickok and Associates, Inc. 1987).

The most comprehensive monitoring of water quality in Lake Minnetonka was conducted by the MPCA during water years 1981 and 1982, following the phaseout of six of the seven wastewater treatment plants (Affeldt 1985). Although the facility in Maple Plain was still in operation at that time, data collected since its closure (in 1986) indicate little if any improvement in the nutritional status of Jennings Bay and West Arm, the ultimate receiving waters for the discharge.

The water quality data summarized in Tables 5-8 of this report were obtained during the 1982 MPCA survey (Affeldt 1985). Eighteen sampling stations were established in the lake (Figure 5), and data were collected at 2-week intervals (from 29 June to 21 September) for each of six parameters: Secchi disk (SD) transparency, chlorophyll *a* (chl *a*), temperature (temp), total phosphorus (TP), total Kjeldahl nitrogen (TKN), and dissolved oxygen (DO). The chl *a* and nutrient concentrations in the epilimnion were determined from single samples integrated over a 0- to 2-m water depth. Vertical profiles of temperature and DO were based on measurements at the surface, proceeding at 1-m intervals to a depth of 10 m, then increasing to 2-m increments thereafter. It should be noted that although alkalinity determinations were not included in this survey, data from other sources indicate the lake to be moderately alkaline (Moyle 1950; Megard 1970a,b).

Water clarity

Overall, SD transparencies in Lake Minnetonka declined from an average of 2.5 m in 1949 to 1.72 m in 1982 (Minnesota Department of Natural Resources (MDNR) unpublished, 1982). Historically, water clarity has been greatest in the main Lower and Upper Lake basins (Moyle 1950; Megard 1970a,b; MDNR unpublished, 1982; MPCA unpublished, 1990). Conditions of lesser water clarity have persisted in the shallower northern and western bays, including Tanager Lake, a small embayment north of the Lower Lake. In general, seasonal reductions in transparency occur in early spring and late summer, coinciding with the introduction of sediment loads in runoff (spring) and peaks in algal productivity (spring and summer) (Moyle 1950; Megard 1970a,b; Hickok and Associates, Inc. 1987; MPCA unpublished, 1990).

Mean SD determinations for the summer of 1982 (Table 5) were lowest in Halsteds Bay (0.66 m), West Arm (0.63 m), Jennings Bay (0.58 m), and Tanager Lake (0.55 m). The low SD values for these locations coincide with elevated chl *a* concentrations (Table 5), reflecting high phytoplankton productivity. Chlorophyll maxima in excess of 100 µg/L were observed at each of these embayments, the highest of which was reported for Halsteds Bay (153 µg/L). Secchi disk means were greatest in the Lower Lake at Browns Bay (2.43 m), Wayzata Bay (2.42 m), and Gale Island (2.23 m). These stations exhibited the lowest chl *a* concentrations, with maxima of 23.1, 25.0, and 30.2 µg/L, respectively.

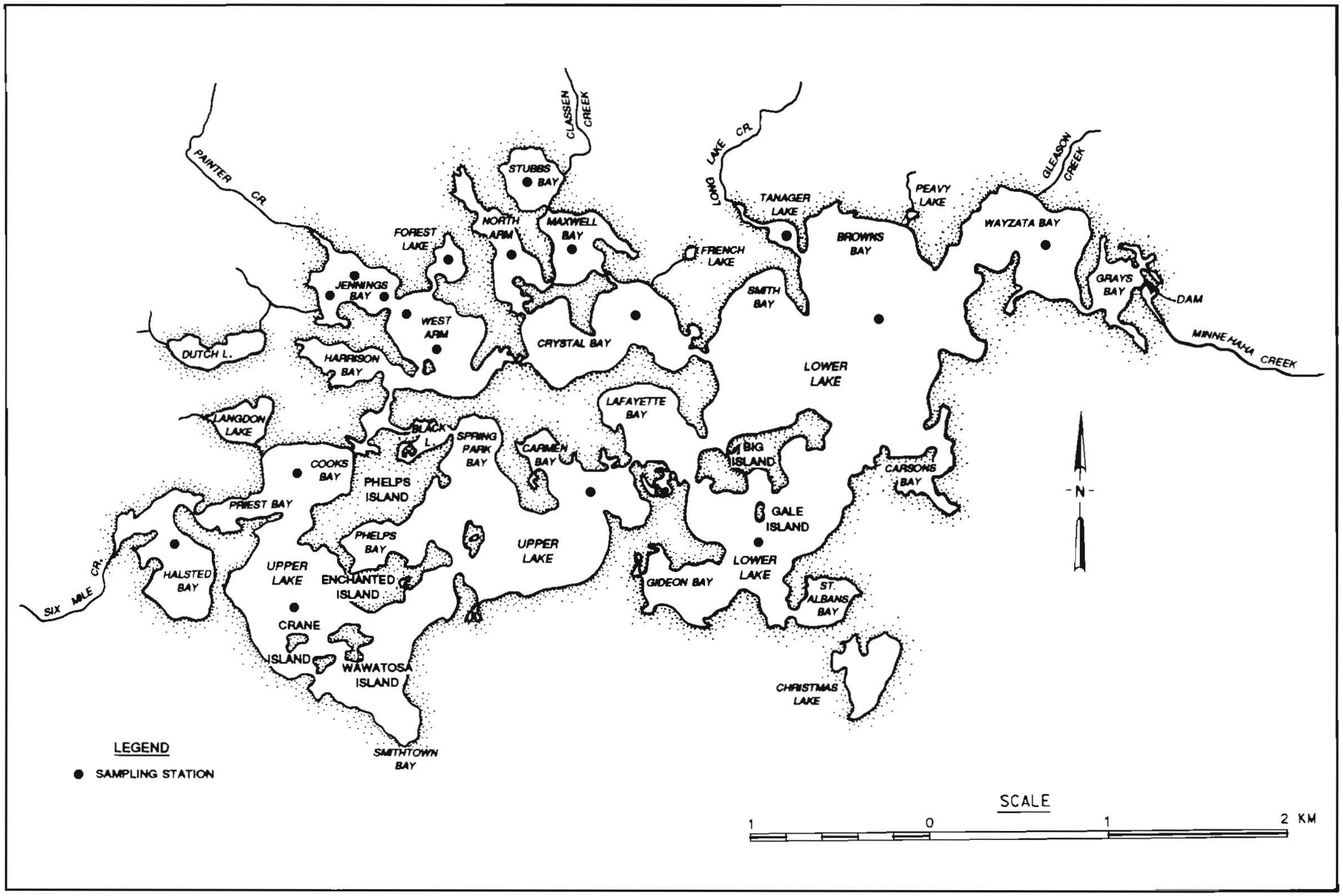

Figure 5. Water quality sampling locations, 1982 MPCA survey

An empirical model developed by Duarte and Kalff (1987) can be used to roughly estimate the maximum depth of colonization (MDC) by submersed plants based on SD transparency data. The model is a logarithmic regression equation, expressed as $MDC^{0.5} = 1.51 + 0.53 \ln SD$, where the MDC and SD values are determined in meters. A plot of the MDC-Secchi model, adjusted for the latitude of Lake Minnetonka, is presented as Figure 6. The use of this plot, together with detailed morphometric maps of the lake, should facilitate calculations of potential areal coverage by Eurasian watermilfoil and other submersed vegetation in individual sub-lakes and bays (cf., Canfield et al. 1985).

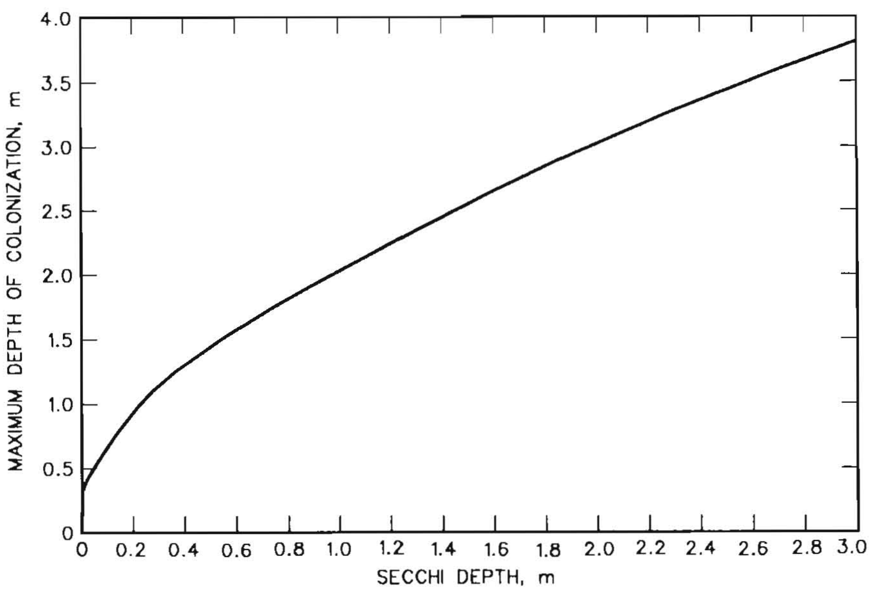

Figure 6. Relationship between maximum depth of colonization of submersed macrophytes and Secchi disk transparency for the latitude of Lake Minnetonka

Temperature

Annual temperature regimes in Lake Minnetonka are typical of many north temperate dimictic lakes (Moyle 1950; Megard 1970a,b; Hickok and Associates, Inc. 1987). Turnover normally begins in fall (during late September or early October) and continues until the onset of ice formation in late November. Ice cover on the lake lasts about 5 months, with the ice-free period beginning in mid-April. Following turnover in spring, thermal stratification occurs in the three deepest basins (i.e., Lower Lake, Upper Lake, and Crystal Bay) when water temperatures exceed 6° to 8° C. Stratification of most shallower areas does not occur, however, until water temperatures exceed 17° to 18° C (Megard 1970b).

Vertical water temperature profiles taken during summer show pronounced thermal stratification (Megard 1970b, Affeldt 1985). The epilimnion is usually 8 to 10 m deep in the Upper and Lower Lakes, but tends to be much shallower (3 to 6 m) in Crystal Bay and other basins. Maximum surface water temperatures of 24° to 26° C occur in late July and August; minimum summer temperatures between 6° and 8° C are maintained at depths generally below 20 m in Browns Bay (Lower Lake), Crane Island (Upper Lake), and Crystal Bay (Affeldt 1985, see Table 6).

Collected over as much of the ice-free period as possible, vertical water temperature profiles of the littoral zone of major basins would help to define the growing season for Eurasian watermilfoil in the lake. These determinations would also be useful in characterizing maximum depths to which watermilfoil may occur due to inhibitory effects of low water temperatures on photosynthesis and total biomass production (Stanley and Naylor 1972; Barko and Smart 1981a).

Oxygen

Anoxic waters and steep oxygen gradients develop in Lake Minnetonka during the stratified period in summer (Table 6). Affeldt (1985) reported dissolved oxygen concentrations in June and July 1982 of <0.1 mg/L in the hypolimnion at all stations. In the shallower basins, e.g., Halsteds Bay, Maxwell Bay, Stubbs Bay, North Arm, West Arm, Jennings Bay, and Tanager Lake, anoxia (i.e., dissolved oxygen <0.1 mg/L) usually occurs at depths below 6 m. However, in the majority of deep-water areas, i.e., in the Lower and Upper Lakes, anoxia prevails below 12 m (Megard 1970b, Affeldt 1985). Throughout the lake, epilimnetic waters are usually well oxygenated, sustaining dissolved oxygen concentrations above saturation for nearly the entire summer. The highest oxygen concentrations (around 15 mg/L) often occur in the most fertile basins, resulting mainly from the photosynthesis of expanding algal populations (Megard 1970b).

Nutrients

Epilimnetic nitrogen (TKN) and phosphorus (TP) concentrations determined in the 1982 MPCA survey are presented in Table 7. Averages for the entire sampling period show the lowest TKN and TP concentrations in the Lower Lake and in Carmen Bay of the Upper Lake. The TKN and TP concentrations were considerably higher in the more productive Halsteds Bay, Tanager Lake, West Arm, and Jennings Bay. Relatively low ratios of TN:TP in these locations (Table 8) are suggestive of highly favorable environments for nitrogen-fixing blue-green algae (cf., Smith 1983).

With the removal of major point sources of nutrient input (i.e., sewage facility discharge), internal loading appears to be an important mechanism promoting continued high productivity in the lake. Data collected by the MCWD during summer stratification in 1985 indicated hypolimnetic (near-bottom) TP concentrations three to six times greater than those in the epilimnion (Hickok and Associates, Inc. 1987). Nutrients from the hypolimnion are released into surface waters during periods of thermal destratification in spring and fall (Megard 1970b). Periodic mixing followed by lake warming during summer is likely to stimulate high rates of phytoplankton production, as evidenced in Lake Minnetonka by high chlorophyll *a* concentrations (Table 5).

Reduced nutrient concentrations in the water column, if they occur as an eventual result of sewage diversion, may affect submersed plant growth in Lake Minnetonka indirectly through influences on algal biomass production (cf., Wetzel 1983; Barko, Adams, and Clesceri 1986). Algal production can then be expected to diminish, with a concomittant increase in submersed plants due to greater water clarity. Because rooted submersed plants rely heavily on sediment as a major nutrient source, their growth in eutrophic systems such as Lake Minnetonka is probably most closely related to light availability in the overlying water. Thus, factors (including nutrient loading) that may affect irradiance conditions in the lake can be expected to influence the depth distribution of submersed plants including Eurasian watermilfoil.

Routine determinations of total alkalinity (as milligrams $CaCO_3$/L) in combination with pH and independent determinations of dissolved inorganic carbon would be useful in assessing the total pool of carbon (C) available for aquatic plant photosynthesis in the lake. These evaluations could have important bearings on the biomass production and distribution of aquatic plants, including Eurasian watermilfoil, in various embayments (Smart and Barko 1986, 1990; Smart 1990).

Sediment Characteristics

Sediment types from the waterline to the 2.1-m contour of Lake Minnetonka were investigated in a survey by the Minnesota Department of Conservation (Moyle 1950). A synopsis of the areas occupied by these sediment types (i.e., sand, sand/clay, sand/gravel, gravel/rubble, mucky/organic, and rock) is presented in Table 9. Of the 805.7 ha surveyed, nearly 60 percent was sand/clay and mucky sediments, categories most likely to support some degree of submersed plant growth. Sand/clay and mucky sediments were found predominantly in the northern and western bays (particularly in Harrisons Bay, Halsteds Bay, and West Arm), whereas combinations of sand, gravel, rubble, and rock were more common in the shallows of the Upper and Lower Lakes and bays.

Sediments at water depths greater than 2.1 m were not included in the Department of Conservation survey. However, based on limited descriptions of sediments in the Lower Lake area (Wood 1938), more than 75 percent of the bottom of Lake Minnetonka appears to be covered with sediments of organic origin (Moyle 1950).

Determinations of particle size and chemical composition of sediments in Lake Minnetonka would allow more accurate comparisons of site suitability for the growth of Eurasian watermilfoil than at present. We recommend that future sampling extend from the shoreline to at least the 6.1-m contour to include depths within the littoral zone and some area just beyond. Laboratory procedures for evaluating sediment texture and determining nutrient concentrations in both dissolved and extractable nutrient pools can be found in Barko and Smart (1986) and Barko et al. (1988).

Aquatic Plants in Lake Minnetonka

General distribution

Much of Lake Minnetonka is suitable habitat for rooted aquatic plants, and the lake has supported considerable plant growth for at least as long as records have been kept. Moyle (1950) described the vegetation of the lake prior to 1950. At that time, the lake supported an abundant crop of pondweeds and other aquatic plants to depths of 2 to 3 m. Rooted vegetation covered an estimated 800 ha or more, or about one sixth of the lake. Vegetation was especially abundant in the shallow, fertile northern and western bays, including Maxwell Bay, Stubbs Bay, North Arm, Halsteds Bay, West Arm, and Harrisons Bay, and in all of the bays of the Lower Lake except Wayzata Bay. Scattered plant growth occurred in the shallows of the main Upper and Lower Lake sections.

The dominant submersed species were curlyleaf pondweed (*Potamogeton crispus*), coontail (*Ceratophyllum demersum*) and northern watermilfoil (*Myriophyllum sibiricum = M. exalbescens*). Canada waterweed (*Elodea canadensis*), floatingleaf pondweed (*Potamogeton natans*), variable pondweed (*Potamogeton gramineus*), flatstem pondweed (*Potamogeton zosteriformis*), sago pondweed (*Potamogeton pectinatus*), and water buttercup (*Ranunculus longirostris*) were also common.

A quantitative study of the vegetation of the lake was conducted in 1970 (Peterson 1983). At that time, naiads, coontail, northern watermilfoil, and several pondweed species were the most abundant submersed plants (Table 10). At present, except for isolated rocky areas and sandbars, most of the shallows appear to support abundant plant growth.

Eurasian watermilfoil is not the first exotic aquatic plant to dominate the vegetation of Lake Minnetonka. Curlyleaf pondweed (*Potamogeton crispus*), the most abundant submersed plant reported in 1950, is an exotic species from Europe that appeared in the lake sometime after 1900 (Moyle 1950). There appears to have been little public concern about curlyleaf pondweed in the lake, probably because relative to the present milfoil invasion: (a) recreational use of the lake was less intense and less motorized; (b) curlyleaf pondweed is an early-season species, i.e., it grows rapidly in the spring and early summer and dies back by the time the swimming and boating season begins; and (c) there was apparently little public awareness that the most abundant plant in the lake was an exotic species.

Eurasian watermilfoil was first discovered in Lake Minnetonka in 1986 (USAED, St. Paul 1989). Invasion probably occurred earlier but was not detected immediately, since Eurasian watermilfoil closely resembles Northern watermilfoil, a native watermilfoil species that is abundant in the lake. At present, Eurasian watermilfoil is widely distributed in the lake (Figure 7). Quantitative measurements of the fraction of the littoral zone currently colonized by Eurasian watermilfoil and the relative biomass of milfoil compared with that of other species are lacking, and will be required to assess the success of management efforts. Studies of the distribution and abundance of Eurasian watermilfoil must differentiate this species from Northern watermilfoil, which is abundant in Lake Minnetonka.

Without management, Eurasian watermilfoil may displace other plant species, at least temporarily. However, as discussed in previous sections, the extent to which native species are replaced varies considerably among locations. Replacement of existing species was very extensive in the Madison, WI, area lakes (Lind and Cottam 1969, Nichols and Mori 1971), a group of productive water bodies with a history of abundant submersed plant growth and prolonged disturbance. In less productive, less disturbed lakes, such as Devils Lake, Wisconsin (Lillie 1986), and Lake Opinicon, Ontario (Keast 1984), Eurasian watermilfoil invaded unvegetated habitat or otherwise produced minimal displacement of native aquatic plants.

Like the Madison lakes, Lake Minnetonka is a relatively fertile lake that supports abundant submersed vegetation and has a long history of human-induced disturbance. Thus, similar Eurasian watermilfoil dynamics may be expected in the two areas. If so, widespread replacement of other species and strong domination of the vegetation of Lake Minnetonka by Eurasian watermilfoil are likely.

History of plant and algae control

Control of aquatic plants and algae has been practiced in Lake Minnetonka since at least 1956. Figure 8 shows the amount of lake surface area treated to control rooted aquatic plants from 1956 through 1989, as determined from MDNR permit records (MDNR, unpublished). In addition to the herbicides used to control rooted plants, large areas of the lake have been treated with copper compounds to control planktonic and filamentous algae (Figure 9). Throughout this period, herbicide use has been the predominant means of aquatic plant control. Arsenic compounds were used in large quantities from 1956 until they were discontinued in 1970. Organic herbicide use increased dramatically in the late 1960s, as organics replaced arsenic, and again in the early 1980s, in association with a substantial increase in the total area of aquatic vegetation controlled.

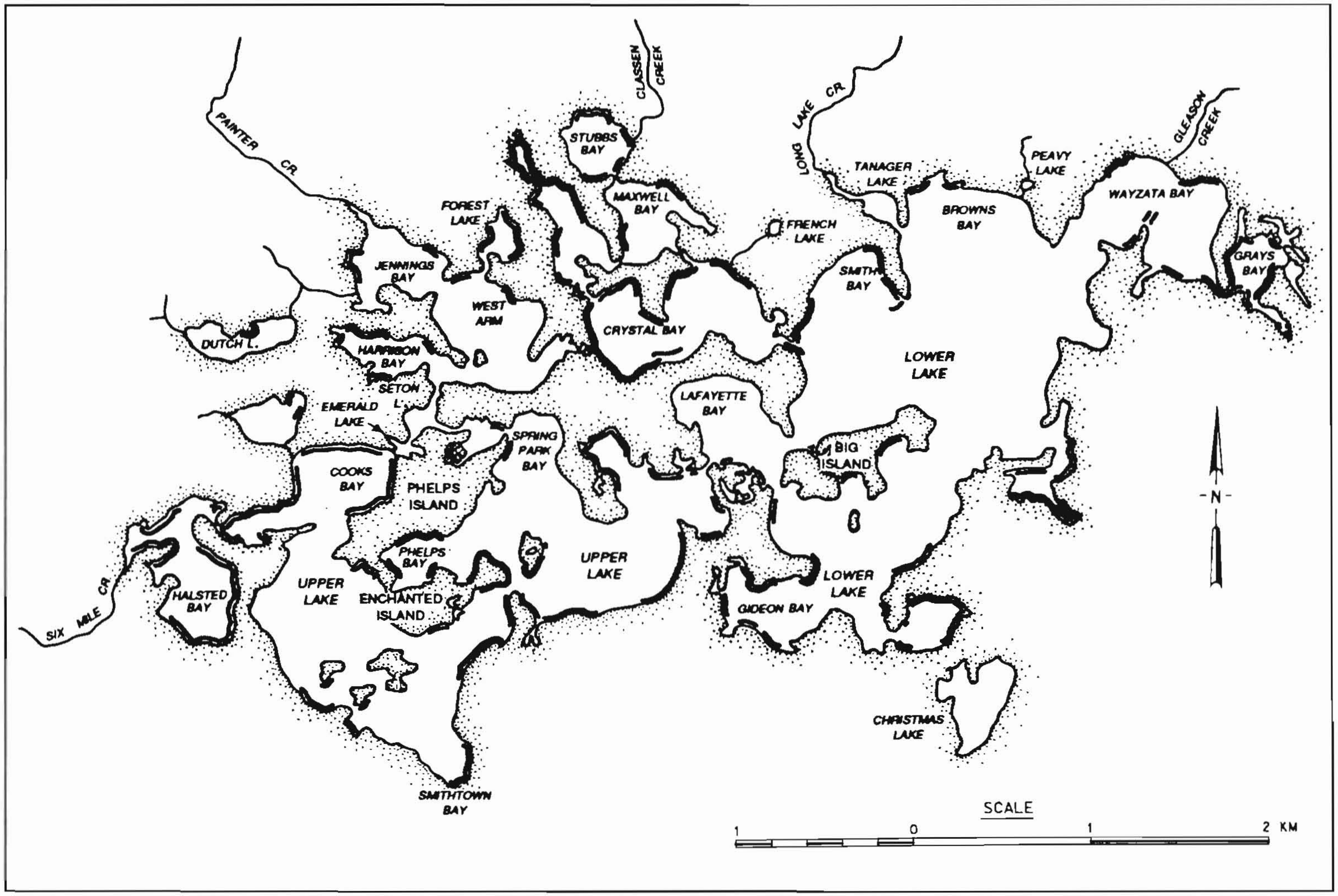

Figure 7. Distribution of Eurasian watermilfoil in Lake Minnetonka, 1989. (Shaded areas show shoreline where Eurasian watermilfoil is present, not actual amount of area covered)

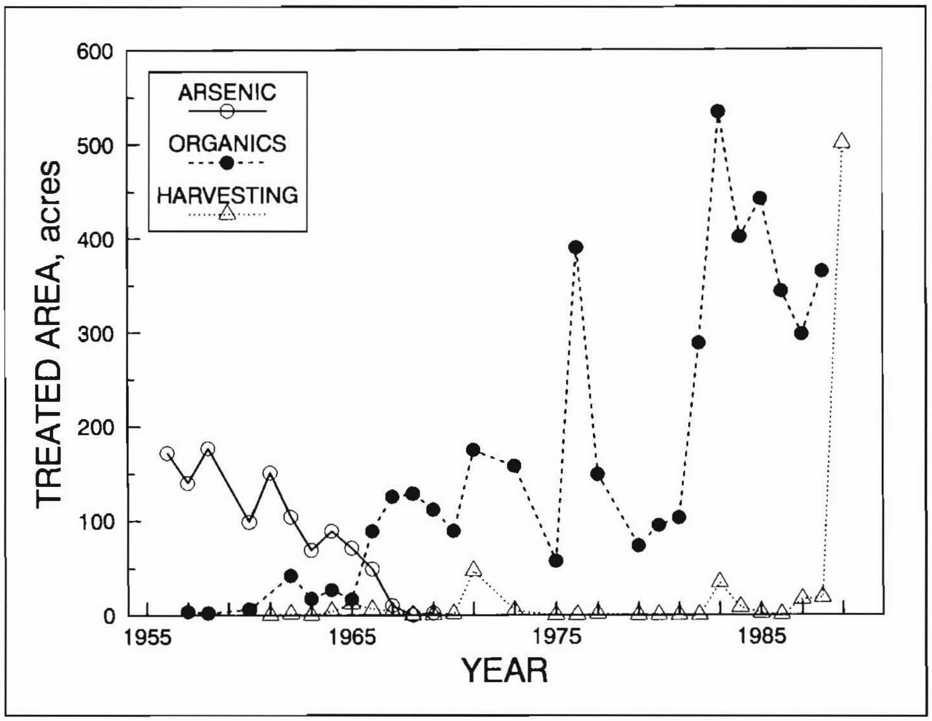

Figure 8. Amount of Lake Minnetonka surface area treated with arsenic, organic herbicides, or mechanical harvesting to control rooted vegetation (to convert acres to square meters, multiply by 4,046.9)

Herbicide use peaked in 1983 and has generally declined since then. In recent years, the major organic herbicides used in the lake have been endothall, diquat, and 2,4-D (Table 11). Historically, mechanical harvesting of aquatic plants has been a very minor component of the plant control effort in the lake, although it has increased dramatically in the last few years (Figure 8).

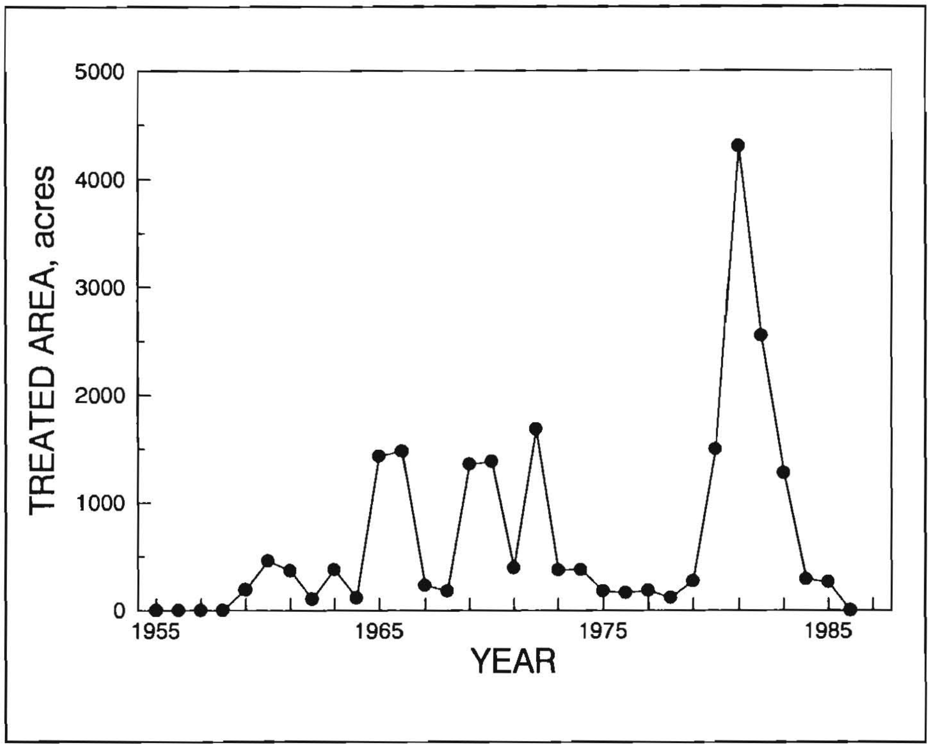

Figure 9. Amount of Lake Minnetonka surface area treated with copper compounds to control planktonic and filamentous algae (to convert acres to square meters, multiply by 4,046.9)

3 Options for the Management of Eurasian Watermilfoil

Factors Influencing the Need for Management

Factors that influence the vigor of Eurasian watermilfoil growth will determine the extent of the nuisance. Lakes such as Lake Minnetonka, which have moderately turbid water and widespread shallow areas with nutrient-rich sediments, experience the most severe problems because these conditions support luxuriant milfoil growth and encourage canopy formation. In these lakes, multiple biomass peaks will often necessitate repeated control. In contrast, management of Eurasian watermilfoil in oligotrophic lakes may be required only in those areas having sediments sufficiently rich to support dense plant growth. Populations growing in deep clear water, either in Lake Minnetonka or elsewhere, typically will not form a dense canopy at the surface and thus should not require management.

The growth of Eurasian watermilfoil varies considerably from year to year in most lakes. Declines in Eurasian watermilfoil, when they occur, should reduce the demand for control. However, postdecline populations of Eurasian watermilfoil in the Madison, WI, lakes were still considered undesirable (Andrews 1986). Thus, the decline in nuisance populations of this species may not eliminate the perceived need for management. The selected management approach should be flexible in design in order to deal with declines, and conversely increases, in the population density of this species. Such flexibility will guarantee cost savings by increasing the overall treatment efficiency.

Control Techniques

Many techniques have been used to control Eurasian watermilfoil. These techniques differ in terms of (a) conditions required for successful control, (b) impact on nontarget organisms, (c) environmental impact, (d) flexibility, and (e) cost (Table 12). No currently available technique is as selective for Eurasian watermilfoil as would be desirable. All techniques are expensive (cf., Andrews 1986), and financial support for management is likely to decline as the public discovers that prolonged control efforts will be required.

Physical techniques

Physical control techniques include drawdown and bottom barriers. Drawing down the water level to expose submersed plants can be an effective technique for reducing plant abundance in shallow areas. Drawdown is extremely inexpensive in lakes that have control structures capable of lowering the water level, but is prohibitively expensive elsewhere. Maximum plant control results from lowering the water level during cold months so that exposed plants freeze. The control structure for Lake Minnetonka allows a maximum drawdown of approximately 1.2 m. Wintertime drawdown could reduce plant growth above the low water level, but may be opposed because of potential adverse affects on downstream water quality.

Bottom barriers control aquatic plant growth for many years, if properly maintained, but are very expensive. Because of their expense, they are normally used only in localized high-use areas, particularly where harvesting is impossible and/or chemical control is unacceptable. Bottom barriers will probably not be used in Lake Minnetonka since the Minnesota Department of Natural Resources currently opposes their use (USAED, St. Paul 1989).

Chemical techniques

Chemical herbicides offer a rapid, easily applied method for controlling aquatic vegetation. Under conditions favorable to their use, herbicides can be extremely effective. Concerns about herbicide use relate primarily to (a) their potential effects on nontarget organisms and (b) their long-term cumulative effects. Impacts on nontarget aquatic life vary considerably among herbicides (Andrews 1986). Long-term effects of herbicide use are poorly understood because very few long-term studies of herbicide impacts have been conducted.

Herbicides are used annually to control aquatic vegetation in about 350 acres of Lake Minnetonka (see Figure 8). Areas of relatively pure Eurasian watermilfoil are usually treated with 2,4-D because it is relatively selective for milfoils, which are dicots, and has a minimal effect on many native species, particularly those that are monocots. Areas with a mixture of species are treated with endothall or diquat, because these herbicides control a broad range of aquatic plants. During 1989, fluridone was applied on a trial basis to three areas of Eurasian watermilfoil totaling 25 acres, located in Grays and Smith Bays and south of Eagle Island.

Expanded use of chemical herbicides to control Eurasian watermilfoil in Lake Minnetonka is unlikely. The MDNR policy limits herbicide treatments to a maximum 15 percent of the littoral area, and current herbicide applications approach this value. Even if MDNR policy were to change, there would likely be public opposition to expanding the extent of herbicide treatments. Given these limitations, herbicide use should probably be restricted to areas of Lake Minnetonka where harvesting is not possible, such as around docks and other obstacles. Herbicides would also be the most effective technique to eliminate small, newly established Eurasian watermilfoil populations in other lakes in the region.

Mechanical techniques

Harvesting, dredging, rototilling, and fragment barriers are forms of mechanical plant control. If cut plant material is picked up, harvesting removes at least some of the nutrients with the harvested plants. In most cases, nutrient removal will not be sufficient to mitigate eutrophication (Barko, Adams, and Clesceri 1986), i.e., harvesting is unlikely to reduce subsequent plant growth or to produce a measurable improvement in water quality. Because plants grow back rapidly after harvesting, two to three harvests per year are usually required to provide adequate control. Harvesting, dredging, and rototilling procedures all produce fragmented plants, and are therefore ill suited for use in situations where Eurasian watermilfoil has not fully dispersed or for eradication of pioneer populations.

Only recently has mechanical harvesting become a major tool in the management of aquatic plants in Lake Minnetonka. In 1989, permits granted by the MDNR allowed the harvest of approximately 202.4 ha as compared with 7.3 ha the year before. With current MDNR restrictions on herbicide use in the lake, mechanical harvesting is expected to become the most widely used practice in Lake Minnetonka for aquatic plant control. Rototilling and dredging are not currently used to control vegetation in this lake.

Harvesting practices in the lake have provided a variety of advantages over other conventional control technologies. These include immediate removal of problem aquatic plants without the addition of deleterious substances, minimal disruption of water use during harvesting operations, and relatively low cost. However, prolonged, widespread harvesting could conceivably have pronounced repercussions, since Eurasian watermilfoil is known in some cases to respond positively to mechanical disturbances (Carpenter 1980a). Harvesting mixed stands of submersed plants is likely to promote replacement of more desirable aquatic plants by this opportunistic species. Furthermore, vegetative fragments lost during harvesting operations may be dispersed to areas currently uninfested by watermilfoil.

Unlike the other mechanical controls, fragment barriers are used to restrict the spread of nuisance plants rather than to control existing populations. Because no existing barrier design is 100 percent effective, barriers do not prevent the spread of nuisance species; spread is merely slowed. Thus, benefits derived from barrier deployment must be evaluated in terms of enhanced recreational value and reduced costs for the number of years over which milfoil encroachment into uncolonized areas is delayed. Fragment barriers are not currently deployed in Lake Minnetonka or at the outlet of the lake into Minnehaha Creek. A barrier at the outlet of the lake might slow the spread of Eurasian watermilfoil into Minnehaha Creek and the lakes with which it connects, if it is not already present in them. However, Eurasian watermilfoil is already present "downstream" in the Mississippi River from above St. Paul to the Wisconsin border.

Biological techniques

Biological control offers the promise of highly specific control of nuisance plant species with minimal potential for adverse environmental impacts. Herbivorous fish, herbivorous insects, and plant pathogens are all under investigation for use in the biological control of aquatic plants. However, the only operational biological control technique for Eurasian watermilfoil is the white amur (grass carp). The white amur can control milfoil, but prefers to eat other, more desirable species. Thus, the amur is a poor choice for use in lakes having sizable populations of native aquatic plants.

The US Army Corps of Engineers and the US Department of Agriculture are engaged in an ongoing effort to discover and evaluate potential biological control agents for milfoil, but few promising candidates have been identified. A fungal pathogen, *Mycoleptodiscus terrestris*, is currently being evaluated in experimental pond trials. This organism significantly reduces the biomass of milfoil plants in laboratory and field assays (Gunner et al. 1988) and appears to be quite host specific (Gunner 1987). Even under the most favorable of circumstances, it will be 2 to 5 years before the fungus becomes available for widespread use. It will be at least 5 to 10 years before any additional agents are ready for routine operational use.

Management Strategies

Eradication

Eradication is a theoretically appealing approach to management of exotic plants, but rarely if ever succeeds. We are not aware of any documented cases of successful Eurasian watermilfoil eradication, although numerous failed attempts have been described (cf., Newroth 1988a). Hydrilla has apparently been eradicated from a few locations in California, but only by drastic measures such as draining the lake and treating the exposed sediments, any remaining water, and all tributaries with herbicides.[1] There is widespread agreement that successful eradication using less extreme techniques depends on early discovery of exotic plant populations and prompt application of effective control techniques. If populations are discovered in time, several control techniques can successfully eradicate them. Of these, herbicides are generally superior to mechanical controls because they do not promote fragmentation.

Most eradication attempts fail because pioneer plant populations are not detected sufficiently early. Detection and eradication of pioneer exotic populations is difficult even when the target species is highly visible, as shown by the explosive expansion of purple loosestrife despite energetic programs for its detection and elimination. Populations of totally submersed plants are particularly difficult to detect. Eurasian watermilfoil characteristically tolerates highly turbid water, in which fragments and newly established plants are not visible. Identification of Eurasian watermilfoil populations in Minnesota will be further complicated by the presence of several widely distributed native milfoil species that closely resemble Eurasian watermilfoil.

Barring the application of extreme control measures, eradication of Eurasian watermilfoil from Lake Minnetonka is impossible. Attempts to eradicate Eurasian watermilfoil should concentrate on newly established populations in other area lakes.

Long-term success of eradication also depends on successfully preventing reinvasion. Transport on boats and trailers is undoubtedly the most important means of fragment dispersal between lakes. Attempts to eradicate Eurasian watermilfoil from Minnesota Lakes should be combined with an education and boat trailer inspection program to minimize human-mediated transport of plants. Control of Eurasian watermilfoil around boat ramps should be given a high priority to minimize the number of fragments picked up by boat trailers.

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1 Personal Communication, 1990, Nate Dechoretz, California Department of Food and Agriculture, Sacramento, CA.

High-intensity management

High-intensity management strategies for Eurasian watermilfoil expend large amounts of money and effort to reduce the abundance of the plant and to slow its spread. Proponents of such an approach argue that intense efforts can contain populations of nuisance plants (Newroth 1980), thereby minimizing interference with recreation and reducing long-term maintenance costs. High-intensity management has been used most often in British Columbia, where it has involved a combination of underwater rototilling, dredging, and herbicide treatments to contain existing plant populations, in combination with education and boat trailer inspection programs to limit spread from colonized to uncolonized bodies of water.

Realizing that aquatic plant management is a long-term venture in which plant-control resources are always limited, high-intensity management should be restricted to poorly established Eurasian watermilfoil populations of limited size in critical high-use areas. As with eradication, Lake Minnetonka is a poor candidate for high-intensity watermilfoil management. If this strategy is adopted in Minnesota, it would be most appropriate in lakes with small, newly established milfoil populations.

Historically, efforts to limit the spread of Eurasian watermilfoil have met with only marginal success, slowing expansion but rarely preventing its dispersion. For example, despite 2 years of intensive control operations (diver dredging, bottom barrier placement and derooting) in Shuswap Lake, British Columbia, Eurasian watermilfoil increased in density and extent, and spread to other lakes in the drainage system (Einarson 1987). After several years of a major public education and quarantine program in British Columbia, boaters continued to transport Eurasian watermilfoil fragments, and the spread of the plant into previously uncolonized lakes continued unabated (Newroth 1985).

Maintenance management

Most Eurasian watermilfoil control efforts have been directed toward maintenance. Maintenance strategies concentrate control efforts in areas where nuisance species are in greatest conflict with recreational or other lake uses; however, these strategies do not seek to achieve long-term reductions in plant growth. Once nuisance plant populations become well established and extensive, as in Lake Minnetonka, maintenance is the only realistic management option. In such cases, plant growth typically greatly exceeds the capacity for plant control, and plant management resources need to be applied only where they will produce the greatest benefit.

Under these conditions, formulation of a detailed vegetation management plant is a prerequisite to efficient management. Nichols, Engel, and McNabb (1988) provide suggestions concerning the formulation of a vegetation management plan. The plan should (a) articulate aquatic plant management goals, (b) determine the extent and location of areas to be managed to meet goals, (c) prioritize management needs, and (d) distribute available plant control resources to maximize the extent to which goals are met. Goals of the plan might include, for example, keeping beaches and boat landings free of plant growth, opening boat lanes from the shore to open water, maintaining optimal plant cover for fish production, or restoring the diversity of submersed plant communities for aesthetic purposes.

The nature of the goals selected will determine how much control is desirable and which techniques are appropriate. In Lake Minnetonka, for example, herbicide use should first be allocated to high-priority treatment areas that are ill suited to other techniques, since the total area that can be treated with herbicides is limited.

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Table 1
Factors Influencing Growth and Morphology of Eurasian Watermilfoil

Factor	Influence of Factor on Watermilfoil Growth
Water clarity	Low water clarity limits watermilfoil to shallow rooting depths and leads to canopy formation. High water clarity allows milfoil growth at greater depths.
Temperature	Plants photosynthesize and grow over a broad temperature range (ca. 15° to 35° C). Maximum growth rates occur at relatively high water temperatures (ca. 30° to 35° C). Growth is initiated in the spring once the water temperature reaches approximately 15° C.
Inorganic carbon	Plants grow best in relatively alkaline lakes. Plants can grow in lakes of low alkalinity, but not as vigorously as elsewhere.
Mineral nutrients	Nuisance growths of the plant are primarily restricted to moderately fertile lakes, or fertile locations in less fertile lakes. Uptake of nutrients from sediments by roots is a very important source of mineral nutrients, particularly P and N. Major cations and bicarbonate are taken predominantly from the water.
Sediment texture	Plants grow best on fine-textured inorganic sediments of intermediate density, because nutrient availability appears to be greatest there.
Water movements	Vegetative spread of plant fragments is aided by water currents. The plant usually does not occur in high-energy environments.
Ice scour	Ice scour may exclude the plant from shallow areas of lakes in cold climates.
Desiccation and freezing	Desiccation during drawdown is a viable control measure, particularly when accompanied by freezing during the wintertime.

Table 2
Apparent Relationship Between Management and Eurasian Watermilfoil Persistence

Lake	Technique	Approximate Percentage of Milfoil Affected[1]	Decline[1]
Chesapeake Bay	None	~0	Yes[a]
Lake Wingra, WI	Harvesting	<5[b]	Yes[c]
Devils Lake, WI	None	0[d]	Yes[d]
Guntersville Reservoir, AL	Herbicides Drawdown	7[e] 100[2]	Noe
Okanagan Valley lakes, BC	Harvesting, rototilling, cultivation, bottom barriers	18[f]	Locally[f]
Cultus Lake, BC	Rototilling	33[f]	No[f]
Shuswap Lake, BC	Rototilling, cultivation, dredging, bottom barriers	44[f]	No[f]

[1] Reference sources are identified as follows:
[a] Bayley et al. 1968.
[b] C. S. Smith, US Army Engineer Waterways Experiment Station, Vicksburg, MS, personal observation.
[c] Carpenter 1980a.
[d] R. A. Lillie, Wisconsin Department of Natural Resources, Fitchburg, WI, personal communication.
[e] D. Webb, TVA, Muscle Shoals, AL, personal communication.
[f] Newroth 1988b.
[2] Based on the assumption that fluctuating water levels disturb the entire shallow-water plant community.

Table 3
Morphometric Characteristics of Lake Minnetonka, Minnesota

Basin	Area ha	Maximum Depth, m	Mean Depth m	Volume 10^6 m^3
Grays Bay	76.1	6.1	2.8	2.10
Lower Lake	2,481.0	30.8	8.5	212.16
Carsons Bay	47.0	6.1	3.0	1.36
St. Albans Bay	68.0	13.1	4.3	2.86
Upper Lake	1,732.8	25.6	6.7	114.93
Black Lake	30.0	7.6	2.8	0.85
Seton Lake	16.2	7.0	2.1	0.33
Emerald Lake	8.1	4.9	2.0	0.02
Halsted Bay	220.2	10.1	4.0	8.64
Crystal Bay	336.0	26.8	8.5	28.57
Maxwell Bay	120.2	9.5	4.3	5.20
Stubbs Bay	80.2	11.6	4.0	3.30
North Arm	132.0	14.0	4.3	5.81
West Arm	334.0	9.8	3.4	11.42
Jennings Bay	120.2	6.7	2.5	3.05
Total	5,802.0			400.60

Note: Derived from data presented in the Minnehaha Creek Watershed District Management Plan (Hickok and Associates, Inc. 1987).

Table 4
Area of Land (hectares) in Major Land Use Categories for the Watershed of Lake Minnetonka, 1980

Municipality	Residential	Commercial	Industrial	Public and Recreational	Vacant and/or Agricultural
Hennepin County					
Deephaven	300.0	5.3	1.2	29.2	8.9
Excelsior[1]	75.3	7.3	9.3	18.6	16.6
Greenwood[1]	59.1	1.2	0.4	0.8	19.4
Independence	36.4	0.4	2.0	67.6	977.7
Long Lake[1]	79.8	9.3	8.9	11.7	42.9
Maple Plain	13.0	2.0	3.2	2.8	25.9
Medina	68.4	5.7	18.6	305.6	1,903.6
Minnetonka Beach[1]	57.1	0.0	2.4	33.2	4.5
Minnetrista	221.9	0.8	0.8	73.7	4,541.7
Mound[1]	378.5	16.2	14.2	81.8	204.1
Orono[1]	1,013.4	23.9	102.4	581.0	2,806.5
Plymouth	337.7	17.0	77.7	39.7	1,024.7
St. Bonifacius[1]	50.2	6.9	6.1	4.9	140.1
Shorewood	246.2	10.5	3.2	102.8	826.3
Spring Park[1]	42.5	9.7	7.7	4.9	12.2
Tonka Bay[1]	94.3	7.3	0.0	21.1	110.1
Wayzata[1]	442.5	30.8	23.9	52.6	168.0
Woodland[1]	94.7	0.0	0.0	0.8	53.4
Carver County					
Chanhassen	97.2	5.7	7.7	128.7	990.3
Laketown Township	99.2	1.6	30.8	764.0	3,325.9
Victoria[1]	172.5	5.3	18.2	553.0	663.2
Waconia Township	2.0	0.4	0.8	1.6	68.8
Watertown Township	6.9	0.0	0.4	2.4	240.9
Total	3,988.8	167.3	339.9	2,882.5	18,175.7

Sources: Metropolitan Council (1982), Hickok and Associates, Inc. (1987).
[1] Located entirely within the watershed.

Table 5
Water Clarity in Lake Minnetonka

Sampling Site	Secchi Depth, m				Chlorophyll *a*, µg/L			
	Mean	Min.	Max.	Rank[1]	Mean	Min.	Max.	Rank[1]
Lower Lake								
Browns Bay	2.43	1.8	3.2	1	12.4	3.71	23.1	2
Wayzata Bay	2.42	1.9	3.0	2	12.2	3.64	25.0	1
Gale Island	2.23	1.7	2.6	3	14.8	5.54	30.2	3
Upper Lake								
Carmen Bay	2.13	1.7	2.6	4	17.5	7.33	34.9	4
Crane Island	1.55	1.2	1.8	5	20.0	9.81	33.1	5
Cooks Bay	1.30	1.2	1.4	8	26.9	9.41	40.1	8
Other Bays								
Crystal Bay	1.31	0.85	2.1	7	24.9	11.80	44.3	7
North Arm	1.35	0.91	1.8	6	24.5	11.60	42.9	6
Maxwell Bay	1.11	0.53	1.8	9	28.0	11.00	46.5	9
Stubbs Bay	0.83	0.53	1.1	11	38.1	21.60	58.7	10
West Arm	0.63	0.53	0.9	13	72.8	26.10	109.0	12
Forest Lake	0.99	0.88	1.1	10	38.8	8.72	50.4	11
Jennings Bay	0.58	0.38	1.0	14	84.3	26.10	113.0	13
Halsteds Bay	0.66	0.45	1.1	12	115.0	60.90	153.0	14
Tanager Lake	0.55	0.45	0.6	15	107.0	64.50	150.0	15

Note: Results are derived from Secchi disk transparency and chlorophyll-*a* data obtained by the MPCA during 2-week-interval samplings from late June to September 1982 (Affeldt 1985).
[1] Increase in rank indicates decrease in water quality.

Table 6
Temperature and Dissolved Oxygen Concentrations in Lake Minnetonka

Sampling Site	Date	Column Depth, m	Temperature, °C Minimum	Temperature, °C Maximum	Dissolved Oxygen, mg/L Minimum	Dissolved Oxygen, mg/L Maximum
Lower Lake						
Browns Bay	6-30	28	7.9	22.3	<0.1	8.8
	7-13	32	7.0	24.0	<0.1	8.3
	7-29	20	8.5	25.0	<0.1	8.1
	8-18	24	8.5	24.8	<0.1	8.8
	9-01	28	8.7	21.4	<0.1	8.2
	9-21	24	8.9	16.8	<0.1	9.6
Wayzata Bay	6-30	14	9.4	22.4	<0.1	9.2
	7-13	14	10.0	24.0	<0.1	8.4
	7-29	16	10.0	25.5	<0.1	8.5
	8-18	14	10.5	25.0	<0.1	9.2
	9-01	14	11.0	21.6	<0.1	8.0
	9-21	14	11.2	17.0	<0.1	9.3
Gale Island	6-30	20	8.8	22.3	<0.1	9.0
	7-13	20	9.5	24.0	<0.1	8.8
	7-29	18	9.0	25.0	<0.1	8.3
	8-18	20	9.1	25.1	<0.1	9.8
	9-01	20	9.7	21.4	<0.1	7.8
	9-21	20	9.9	16.8	<0.1	9.9
Upper Lake						
Carmen Island	6-30	12	16.2	22.6	<0.1	9.1
	7-13	14	14.8	24.5	<0.1	8.5
	7-29	14	15.5	25.5	<0.1	8.0
	8-17	14	15.2	25.1	<0.1	9.1
	9-01	16	14.3	21.3	<0.1	7.5
	9-21	14	16.4	17.2	7.3	10.0
Crane Island	6-30	24	6.9	22.2	<0.1	9.5
	7-13	24	6.9	25.0	<0.1	8.9
	7-29	20	7.0	25.5	<0.1	8.0
	8-17	24	6.9	25.0	<0.1	9.8
	9-01	24	6.9	21.3	<0.1	7.4
	9-21	24	7.0	17.2	<0.1	9.5
Cooks Bay	—	—	—	—	—	—
Other Bays						
Crystal Bay	6-30	24	6.1	23.7	<0.1	10.3
	7-13	24	6.3	25.7	<0.1	9.1
	7-29	20	6.0	25.5	<0.1	9.5
	8-18	24	6.2	25.0	<0.1	10.7
	9-01	24	6.5	21.7	<0.1	8.0
	9-21	28	6.6	16.7	<0.1	8.9
North Arm	6-30	10	8.9	24.1	<0.1	9.5
	7-13	12	8.8	26.2	<0.1	9.2
	7-29	10	9.0	26.0	<0.1	9.7
	8-17	10	9.4	24.0	<0.2	9.1
	8-31	12	10.0	20.8	<0.1	7.3
	9-20	12	9.0	16.4	<0.1	7.1

(Continued)

Note: Results are derived from Secchi disk transparency and chlorophyll-*a* data obtained by the MPCA during 2-week-interval samplings from late June to September 1982 (Affeldt 1985).

Table 6 (Concluded)

Sampling Site	Date	Column Depth, m	Temperature, °C Minimum	Temperature, °C Maximum	Dissolved Oxygen, mg/L Minimum	Dissolved Oxygen, mg/L Maximum
Other Bays (Concluded)						
Maxwell Bay	7-13	10	12.0	25.5	<0.1	8.6
	7-29	8	12.5	25.5	<0.1	9.2
	8-18	10	11.0	25.0	<0.1	11.3
	8-31	8	14.3	20.7	<0.1	7.1
	9-20	10	12.0	16.4	<0.2	6.9
Stubbs Bay	7-13	8	9.6	27.4	<0.1	10.9
	7-29	8	9.0	25.5	<0.1	9.8
	8-18	8	10.5	25.4	<0.1	11.3
	8-31	8	11.3	20.4	<0.1	7.5
	9-20	8	12.0	16.0	<0.1	5.2
West Arm	6-30	10	18.5	23.0	<0.1	11.6
	7-14	10	18.2	25.8	<0.1	12.6
	7-29	8	19.5	25.5	<0.1	9.3
	8-17	8	20.7	23.9	<0.1	6.6
	8-31	10	19.9	20.7	<0.1	4.6
	9-20	8	16.3	16.3	8.5	8.6
Forest Lake	6-30	8	7.0	23.7	<0.1	6.1
	7-14	8	7.4	26.0	<0.1	10.6
	7-29	10	7.0	26.5	<0.1	7.9
	8-18	12	7.1	24.2	<0.1	9.8
	8-31	12	8.5	20.6	<0.1	8.1
	9-20	8	9.7	16.0	<0.1	6.4
Jennings Bay	6-30	6	18.9	23.2	<0.1	11.4
	7-14	7	19.0	26.0	<0.1	15.6
	7-29	6	20.0	25.5	<0.1	8.8
	8-17	7	21.3	24.4	<0.1	8.2
	8-31	7	20.6	20.7	6.2	6.8
	9-20	6	16.4	16.5	8.0	8.9
Halsteds Bay	6-30	9	18.7	23.0	<0.1	15.3
	7-14	8	19.0	25.5	<0.1	9.7
	7-29	8	19.0	26.0	<0.1	12.6
	8-18	8	18.9	25.1	<0.1	15.1
	8-31	8	20.8	21.3	5.5	8.3
	9-20	10	15.7	16.6	8.9	9.5
Tanager Lake	6-30	5	12.3	24.0	<0.1	13.0
	7-13	6	12.0	24.5	<0.1	10.2
	7-29	5	14.5	26.0	<0.1	10.0
	8-18	6	14.1	25.5	<0.1	14.5
	9-01	6	15.6	21.5	<0.1	8.8
	9-21	6	14.8	15.9	10.2	12.8

Table 7
Epilimnetic (0 to 2 m) Nutrient Concentrations in Lake Minnetonka

Sampling Site	Total Phosphorus, mg/L				Total Kjeldahl Nitrogen, mg/L			
	Mean	Min.	Max.	Rank[1]	Mean	Min.	Max.	Rank[1]
Lower Lake								
Browns Bay	0.023	0.005	0.051	1	0.965	0.88	1.17	1
Wayzata Bay	0.033	0.012	0.061	2	1.003	0.93	1.24	3
Gale Island	0.035	0.010	0.082	4	0.992	0.88	1.13	2
Upper Lake								
Carmen Bay	0.030	0.012	0.058	3	1.040	0.92	1.28	4
Crane Island	0.044	0.018	0.084	9-10	1.202	1.04	1.44	6
Cooks Bay	0.041	0.013	0.061	8	1.193	0.78	1.37	5
Other Bays								
Crystal Bay	0.037	0.022	0.058	6	1.265	0.99	1.51	7
North Arm	0.040	0.028	0.054	7	1.318	1.14	1.48	8
Maxwell Bay	0.038	0.016	0.058	5	1.423	1.08	1.78	9
Stubbs Bay	0.044	0.018	0.082	9-10	1.673	1.18	2.18	10
West Arm	0.102	0.069	0.126	12	1.975	1.51	2.45	11
Forest Lake	0.071	0.038	0.117	11	—	—	—	—
Jennings Bay	0.134	0.100	0.164	14	2.173	1.48	2.91	12
Halsteds Bay	0.155	0.118	0.189	15	2.568	1.82	3.34	13
Tanager Lake	0.123	0.096	0.158	13	—	—	—	—

Note: Data are derived from total phosphorus and total Kjeldahl nitrogen determinations by the MPCA during 2-week-interval samplings from late June to September 1982 (Affeldt 1985; MPCA unpublished, 1990).

[1] Increase in rank indicates decrease in water quality.

Table 8
TN:TP Ratios for Lake Minnetonka

Sampling Site	TN:TP Ratio[1]
Lower Lake	
Browns Bay	41.9
Wayzata Bay	33.3
Gale Island	28.3
Upper Lake	
Carmen Bay	34.1
Crane Island	27.3
Cooks Bay	29.1
Other Bays	
Crystal Bay	34.2
North Arm	33.0
Maxwell Bay	37.5
Stubbs Bay	38.0
West Arm	19.4
Forest Lake	—
Jennings Bay	16.2
Halsteds Bay	16.5
Tanager Lake	—

Note: Results derived from mean TKN and TP values presented in Table 7.
[1] Ratios below 29.1 favor dominance by blue-green algae (Smith 1983).

Table 9
Sediment Types Within the 2.1-m Contour at Different Locations in Lake Minnetonka

Location	Area, ha					
	Sand	Sand and Clay	Sand and Gravel	Gravel and Rubble	Muck	Rock
Lower Lake	73.7	34.8	31.2	13.8	11.3	0.4
Wayzata Bay	14.6	8.1	1.6	0.4	1.2	—
Gideons Bay	15.8	8.5	1.2	1.6	15.8	—
Lafayette Bay	6.5	9.7	0.8	—	8.5	—
Grays Bay	2.8	—	—	40.1	—	—
Carsons Bay	1.2	1.6	—	1.6	16.6	—
St. Albans Bay	—	—	—	1.6	24.7	—
Total	114.6	62.7	34.8	59.1	78.1	—
Upper Lake	60.3	42.9	3.6	0.8	4.1	0.4
Phelps Lake	15.4	30.8	—	—	—	—
Cooks Bay	7.3	2.2	—	0.4	—	—
Total	83.0	75.9	3.6	1.2	4.1	—
Northern and Western Bays						
Halsteds Bay	24.7	—	—	—	23.5	—
Harrisons Bay	1.6	3.6	4.1	—	49.4	—
Jennings Bay	6.5	—	—	—	5.3	—
West Arm	8.5	21.9	2.0	—	27.9	—
Crystal Bay	14.2	19.4	—	—	2.4	—
North Arm	1.2	16.6	1.2	—	4.9	—
Stubbs Bay	—	15.8	0.8	—	1.4	—
Maxwell Bay	5.7	10.9	—	—	2.4	—
Total	62.4	88.2	8.1	—	117.2	—

Source: Moyle 1950.

Table 10
Abundance of Submersed Plant Species in Lake Minnetonka, 1970

Species	Comparative Abundance
Northern naiad (*Najas flexilis*)	1.47
Coontail (*Ceratophyllum demersum*)	1.33
Southern naiad (*Najas guadalupensis*)	1.19
Northern watermilfoil (*Myriophyllum exalbescens*)	1.04
Flatstem pondweed (*Potamogeton zosteriformis*)	0.87
Sago pondweed (*Potamogeton pectinatus*)	0.75
Berchtold's pondweed (*Potamogeton berchtoldii*)	0.61
Nitella (*Nitella* sp.)	0.33
Water stargrass (*Heteranthera dubia*)	0.30
Water celery (*Vallisneria americana*)	0.25
Illinois pondweed (*Potamogeton angustifolius*)	0.14
Clasping leaf pondweed (*Potamogeton richardsonii*)	0.11
Slender pondweed (*Potamogeton pusillus*)	0.09
Pondweed (*Potamogeton strictifolius*)	0.02
Horned pondweed (*Zannichellia palustris*)	0.02
Waterweed (*Elodea occidentalis*)	0.02
Curlyleaf pondweed (*Potamogeton crispus*)	0.01

Source: Peterson 1983.

Table 11
Amounts of Organic Herbicides Used in Lake Minnetonka, 1985-1988

Active Ingredient	Commercial Formulations Applied	Average Amount Applied Annually lb active ingredient	Average Area Treated Annually acres
Endothall	Aquathol K liquid	698	123
	Aquathol granules	23	2
	Hydrothol 191 liquid	29	22
	Hydrothol 191 granules	63	14
Diquat		506	164
2,4-D	Various granular formulations	177	22
Copper	Copper sulphate	1,709	1,046
	Copper chelates	52	50

Table 12
Comparison of Control Techniques

Evaluation Parameter	Control Technique: Drawdown	Bottom Screens	Fragment Barriers	Harvesting	Herbicides	Biological (Fungus)
Capital intensive	No	No	No	Yes, unless leased	No	No
Flexible to changing management plan	Yes	Possibly	Possibly	No, unless leased	Yes	Yes
Permit needed	MDNR MPCA	Not allowed	MDNR	MDNR	MDNR	
Cost per acre	Nominal	$10,000 to $15,000	N/A	$200 to $600	$75 to $600	Unknown
Large-scale applications	Yes	No	Yes	Yes	Yes	Not at present
Small-scale applications	No	Yes	No	No	Yes	Yes
Dock/harbor areas	?	Yes	No	No	Yes	Yes
MDNR acceptibility	Variable	Prohibited	High	High	Up to 15% of littoral area	Unknown
Species selectivity	Low	Low	Low	Low	Depends on herbicide	High