Current Knowledge of Herbicides Relevant to Projects in Massachusetts

By Ken Wagner, Ph.D., CLM, Water Resource Services,
with funding from Lake Onota Preservation Association and Friends of Pontoosuc Lake

June 2020

Contents

Forward

The following document is a public service publication generated as a result of a lake management consultation meeting involving the City of Pittsfield, Massachusetts, the Lake Onota Preservation Association (LOPA), the Friends of Pontoosuc (FOP), and Dr. Ken Wagner, PhD, CLM, sponsored jointly by LOPA and FOP on January 13, 2020. During that meeting it became increasingly clear that future permitting of management actions for preservation of our lakes was going to be complex and the "toolbox" for Conservation Commissions as set forth in the Generic Environmental Impact Report for Eutrophication and Aquatic Plant Management in Massachusetts (GEIR) was out of date and lacking a great deal of recent experience. As a result, LOPA and FOP decided to jointly fund Dr. Wagner to write a "white paper" documenting the current "state of the art" concerning the use of herbicides as a management action. It was separately agreed to similarly fund a companion paper relative to application of drawdown. The "white paper" idea evolved into an unofficial update and supplement to the GEIR Section 4.6 on Herbicides (this document) and GEIR Section 4.2 on Drawdown (a companion document). It also required a great deal more time and effort than envisioned and funded by LOPA and FOP which was most graciously provided by Dr. Wagner. This document is detailed and thorough, and consideration of it in its entirety is encouraged, but the key points are embodied in a comprehensive summary near the end of the document. Although begun with parochial interest in the lakes of Pittsfield, we believe it is a document which will be of great benefit to all the Great Ponds of Massachusetts and has applicability to a wide range of waterbodies within the Commonwealth and beyond.

Lee J Hauge

Lee Hauge, President
Friends of Pontoosuc

Michael Riordan, President
Lake Onota Preservation Association

This document is intended to serve as an unofficial supplement to Eutrophication and Aquatic Plant Management in Massachusetts, the Final Generic Environmental Impact Report, or simply the GEIR. It follows the format of the GEIR and adds to Section 4, control of aquatic plants. Familiarity with the original GEIR is advised before reading this supplement. See https://316zc22p4vyyg59gu2uixxxv-wpengine.netdna-ssl.com/wp-content/uploads/2018/02/GEIR-Eutrophication-and-Aquatic-Plant-Management-in-Mass.pdf.

4.6 HERBICIDES AND ALGAECIDES

4.6.1 Overview

The overview from the GEIR remains highly relevant but it is deficient in not being up to date with regard to more recent research and experience and the addition of more active ingredients than were available by the middle of 2002, the cutoff for listing in the GEIR which was published in 2004 in final form after extensive review.

More recent references with some depth include Cooke et al. 2005, a book on lake management, and Gettys et al. 2014, a book on aquatic plants. Cooke et al. 2005 was published not that long after the GEIR and does not include additional herbicides, but it does summarize control experience and possible impacts of treatment as understood prior to publication. Gettys et al. 2014 is the 3rd edition of this best management practices handbook, is now 6 years old, and there is a 4th edition in preparation, but it does provide additional information on newer herbicides and related experience. There is a short chapter on herbicides and chapters covering 16 nuisance species with recommendations on which herbicides work best. There is also a chapter on common concerns expressed about herbicide use with plain language explanation of risks and related considerations. This publication supports an important point of the GEIR that the basis for herbicide regulation is that the herbicide does not present an unreasonable risk of adverse impacts to human health or the environment when used in accordance with its label restrictions. There are a few newer herbicides still not covered, but this is a reference with which all project proponents and conservation commissions should be familiar.

Herbicides and algaecides contain active ingredients that provide the toxicity to target plants. Herbicides also contain inert ingredients or auxiliary compounds that aid application or effectiveness but may not themselves provide any toxicity. Consequently, different formulations may contain different percentages of active ingredient and different auxiliary compounds. The specific herbicide to be used, or range of herbicides to be applied, should be provided in permit applications and the label (a document that can be downloaded from the manufacturer) should probably be included where the regulatory parties may not be familiar or where other involved parties may not be properly aware of exactly what is to be applied.

The GEIR explains that herbicides are typically classified as contact or systemic herbicides based on the action mode of the active ingredient. Contact herbicides are toxic to plants by uptake in the immediate vicinity of external contact, while systemic herbicides are taken up by the plant and are translocated throughout the plant. In general, contact herbicides are more effective against annuals than perennials because they may not kill the roots, allowing perennials to grow back. Seeds are also not likely to be affected, but with proper timing and mulitple treatments, growths can be eliminated much the same way harvesting can eliminate annual plants. Systemic herbicides tend to work more slowly than contact herbicides because they take time to be translocated throughout the plant. Systemic herbicides generally provide more effective control of perennial plants than contact herbicides, as they kill the entire plant under favorable application circumstances. Systemic herbicides will also kill susceptible annual species, but regrowth from seeds will require additional treatments as with contact herbicides, as seeds already formed are not impacted by systemic herbicides.

However, what has been learned since the GEIR has been published is that the division between contact and systemic herbicides is not so sharp and that systemic herbicides can be used at low doses to reduce growths of many species without extreme reduction in populations. Diquat, considered a contact herbicide, has been shown to nearly eliminate milfoil in several Massachusetts lakes, notably Pontoosuc Lake in the Berkshires. If the herbicide was not actually translocated to roots, it must have harmed the plant is ways that prevented regrowth from roots, a common recovery mode in many cases. As milfoil does not form many viable seeds, control has been nearly complete with diquat in at least some instances. Similar results have been found with endothall for some target species. Further, systemic herbicides such as fluridone have been used to slow the growth rate of a broad spectrum of aquatic plants, including many generally desirable native species that can still become nuisances in shallow lakes through overabundance. Few if any species are lost, but the overall density of plants is reduced, a benefit to human uses and many aquatic organisms for which dense plant assemblages do not constitute favorable habitat. Watson Pond in Otis and Long Bow Lake in Becket are examples of such control, which is not permanent but can be beneficial.

There were only six active ingredients approved for use in aquatic herbicides in Massachusetts as of 2002, but six additional ingredients have been added for Massachusetts since then. Herbicides often come in terrestrial and aquatic formulations, creating some confusion among laypersons over which trade name is applicable to which medium. Active ingredients in aquatic herbicides registered for use in Massachusetts were listed in Table 4-4 of the GEIR while plant susceptibility was provided in Table 4-5. These tables have been combined and simplified here (Table 4S-1). Note that product (common) names are examples; there may be more from different manufacturers and even different versions of herbicides with the same name, based on additives or concentration of active ingredient. It is important to understand that just because a commercial herbicide formulation contains an active ingredient that it is not the same as every other herbicide that contains that ingredient.

The highly relevant case of glyphosate illustrates the issue with understanding the entire herbicide formulation, not just the active ingredient, and its intended use. A report promoted by the media suggested greater carcinogenicity than was previously claimed and there have been jury decisions awarding damages to users of products containing glyphosate; such decisions do not make the allegations true. In the case of glyphosate, no new data were supplied and claims of damage are based on selective use of existing data. There is indeed risk, and that risk is heightened for untrained applicators and those involved in or living near large agricultural operations where genetically modified crops are sprayed with herbicides containing glyphosate and supplemental ingredients, many of which have toxic properties. This risk is virtually unrelated to the occasional use of glyphosate-containing herbicides approved for use in aquatic habitats and equating the use

Table 4S-1. Aquatic herbicides and common target species.

Active Ingredient	Common Aquatic Product Names	Primary Mode	Primary Target Aquatic Plants
Copper	Copper sulfate, Cutrine, Komeen, Earthtec, SeClear, Captain	Contact	Algae, floating and attached to plants, plus some plant species
Peroxide	PAK 27, Greenclean	Contact	Algae, floating and attached to plants
Diquat	Reward, Weedtrine, Diquat	Contact	Wide range of aquatic plants, milfoil species, pondweed species, coontail, naiad, waterweed, bladderwort
Endothall	Aquathol, Hydrothol	Contact	Wide range of aquatic plants, milfoil species, pondweed species, coontail, water celery, filamentous green algae
Flumioxazin	Clipper, Propeller	Contact	Filamentous green algae, duckweed, watermeal, hydrilla, fanwort, coontail, naiad, milfoil species, many pondweeds
2,4-D (2,4-dichlorophenoxyacetic acid)	Aquaclean, Navigate	Systemic	Milfoil species, coontail, water lilies, watershield, smartweed, bladderwort, water chestnut
Fluridone	Sonar, Avast, Whitecap	Systemic	Eurasian watermilfoil, hydrilla, fanwort, naiad, waterweed, duckweed, watermeal, reduced growth of many pondweeds
Glyphosate	Rodeo, Aquaneat, Glyphosate	Systemic	Emergent and floating leaved species, Phragmites, cattail, purple loosestrife, water lilies, lotus, smartweed
Imazapyr	Habitat, Imazapyr	Systemic	Water lilies, floating heart, lotus, water chestnut, cattail, Phragmites, smartweed, parrotfeather
Imazamox	Clearcast	Systemic	Phragmites, cattail, water lilies, lotus, floating heart, smartweed, watershield, water chestnut, parrotfeather, variable watermilfoil
Triclopyr	Renovate, Triclopyr 3	Systemic	Milfoil species, waterlilies, lotus, watershield, purple loosestrife, Phragmites, smartweed
Florpyrauxifen-benzyl	Procellacor	Systemic	Milfoil species, floating heart, lotus, watershield, hydrilla, coontail

of herbicides in agriculture or by homeowners with aquatic management by licensed applicators using entirely different formulations is unjustifiable. The dose, duration of exposure, frequency of use, and area of application are much lower for aquatic applications and aquatic glyphosate application should not be compared to terrestrial use.

Detailed information on toxicity and environmental fate of herbicides registered before 2004 for aquatic use in Massachusetts is provided in Appendix III of the GEIR. Additional information on toxicity, especially for newer herbicides, can be obtained online through the MA Department of Agricultural Resources (https://www.mass.gov/herbicides-for-aquatic-vegetation-management), which must approve herbicides before they can be used in Massachusetts and prepares thorough documentation on each herbicide proposed for use in the state.

Those interested in understanding herbicides and their use often use the internet to get information. It is absolutely critical that such information searches focus on unbiased sources, preferably peer reviewed articles or documents produced by competent independent parties like the MA DAR. Herbicide labels (legally binding documents that control use) and material safety data sheets (MSDS for hazard evaluation) can be obtained from vendors and trusted, but any additional claims should be viewed as sales pitches. Likewise, information provided by organizations or individuals with an agenda that includes preventing herbicide application will be slanted and is likely to be unreliable. Always find the motivation behind any source before accepting the information as reliable.

Approval of an herbicide for use in MA follows approval at the federal level and certifies that the product can be used for its intended purpose without unreasonable risk to humans or aquatic ecology. It does not mean that there is no risk or that desired results are guaranteed, only that the expected benefits outweigh the potential negative effects when used properly. Proper planning for application is needed, including consideration of target plants, non-target plants, other potentially impacted biological components of the aquatic system (e.g., fish, invertebrates), and follow up actions to maximize longevity of benefits and minimize adverse impacts. No two lakes are identical and while the considerations are the same, the relevance and importance of influential factors will vary. Project proponents should provide a plan with clear goals and the steps to be followed along with an analysis of alternatives. Conservation commissions considering permits for herbicides under the Wetlands Protection Act should not deny a permit simply because herbicides are “disliked”; the court has upheld the right of applicants to use state-approved methodology as long as it is consistent with current regulations.

4.6.1 Effectiveness

Commonly used herbicides are listed in Table 4S-1 with a list of the most common target plant species for each, but since one does not search by herbicide when a need arises but rather by plant species in need of control, another table is offered here (Table 4S-2) which lists common problem species in Massachusetts and the applicability of available herbicides for their control. Effective control depends on the rate of application, the duration of exposure, and the timing of exposure within the growth cycle of the plant, as well as other species-specific or herbicide-specific factors, so this listing is simplified. It provides a three level rating system: herbicides that routinely control target species at typical application rates, usually low to moderate doses intended to be selective, herbicides that provide at least partial control and may provide greater control with higher doses, prolonged exposure time, or multiple applications, and herbicides not typically used on identified problem species due to limited control potential. A useful additional resource for evaluating herbicide effectiveness on target species is the website of the Institute of Food and Agricultural Science at the University of Florida, which maintains fact sheets of considerations for use of registered herbicides (http://plants.ifas.ufl.edu/manage/developing-management-plans/chemical-control-considerations/).

One concern for effectiveness that has been evaluated since the GEIR was produced is the potential development of resistance in target plant species through repeated use of a single herbicide. Resistance to specific herbicides has developed in 70 plant species in the USA, mostly agricultural species, but also by hydrilla and duckweed to fluridone in Florida where many acres had been treated every year (Koschnick et al. 2009). Using a different herbicide or control approach every few years where there is annual application on a large scale is often advised to minimize the chance of target plants developing resistance. However, where treatment involves mainly spot applications at locations that change each year and represents a small portion of the plant growth area, development of resistance may not be a significant threat. Additionally, resistance has not been observed with contact herbicides (e.g., diquat, endothall) that attack cell membranes and multiple physiological processes as opposed to systemic herbicides that tend to impact one specific process like synthesis of key enzymes or pigments (Koschnick et al. 2009, Gettys et al. 2016). However, the potential for resistance does suggest that permits for aquatic plant control might best include multiple herbicides appropriate to the target species to allow flexibility in control over the long run.

Another concern that has arisen since the GEIR was produced is hybridization among plants. Many pondweeds (genus Potamogeton) create viable hybrids and some have been given separate species names (Les et al. 2009). One (P. ogdenii) has even been accorded protected status under MESA despite being a hybrid of two common, unprotected pondweed species. The advance of genetic assessment of organisms necessitates a rethinking of taxonomy that is ongoing and regulatory adjustment that has yet to occur. Additionally, some invasive species are known to hybridize, including Eurasian watermilfoil with native species, further complicating taxonomy and regulatory implications and potentially conferring additional vigor and herbicide resistance on invasive species, such that these hybrids outcompete both native and invasive parent forms and are harder to control with herbicides (LaRue et al. 2013). This has not yet been addressed to any practical degree in MA.

Table 4S-2. Herbicides commonly applied for control of problem plant species. Part 1 – Algae and invasive species.

Scientific Name	Common Name	Copper	Peroxide	Diquat	Endothall	Flumioxazin	2,4-D (2,4-dichlorophenoxyacetic acid)	Fluridone	Glyphosate	Imazapyr	Imazamox	Triclopyr	Florpyrauxifen-benzyl
Algae													
Chara/Nitella spp	Muskgrass/Stonewort	C	P	P		P					P		
Chlorophyta	Filamentous green algae mats	P	P	P		P							
Chlorophyta, Chrysophyta	Planktonic algae in general	P	P										
Cyanobacteria	Blue-green algae	C	C										
Invasive Species													
Submergent													
Cabomba caroliniana	Fanwort					C		C					
Egeria densa	Brazilian waterweed			C				P			P		
Hydrilla verticillata	Hydrilla	P		C	C	C		C			P		P
Myriophyllum aquaticum	Parrotfeather			C	P	P	C	P		P	P	C	C
Myriophyllum heterophyllum	Variable watermilfoil			C	P	C	C	P				C	C
Myriophyllum spicatum	Eurasian watermilfoil	P		C	C	P	C	C				C	C
Najas minor	Spiny or european naiad	P		C	C	P	P	C			P		
Potamogeton crispus	Curlyleaf pondweed	P		C	C	C		C			C		
Floating leaved													
Nelumbo nucifera	Indian lotus				P	P			C		P	C	C
Nymphoides peltata	Yellow floating heart			C			P			P	P		C
Trapa natans	Water chestnut			P		P	C	P	P	C	C	P	C
Emergent													
Lythrum salicaria	Purple loosestrife								C	C		C	
Phragmites australis	Common reed								C	C	P	C	

C = high level of control with typical application rate. P = partial control or greater with mulitple applications and/or higher dose. Blank entry indicates herbicide not generally effective for corresponding species at typical application rates and exposure times. Please recognize that dose, duration of exposure, formulation and timing of application are all key factors in results.

Note that some herbicides can be mixed or applied sequentially; for example, copper is often used to minimize attached algae on plants and maximize impact of other herbicides.

Note that most herbicides contain additional compounds, some inert and some intended to increase effectiveness; knowledge of additonal ingredients can be helpful in selecting an herbicide but is not always available.

Table 4S-2. Herbicides commonly applied for control of problem plant species. Part 2 – Native species.

Scientific Name	Common Name	Copper	Peroxide	Diquat	Endothall	Flumioxazin	2,4-D (2,4-dichlorophenoxyacetic acid)	Fluridone	Glyphosate	Imazapyr	Imazamox	Triclopyr	Florpyrauxifen-benzyl
Native Nuisance Species													
Submergent													
Ceratophyllum demersum	Coontail			C	P	C	P	C			P		P
Elodea canadensis	Waterweed			C				C					
Elodea nuttallii	Slender waterweed			C				C					
Myriophyllum humile	Low watermilfoil			C		C	C	P				C	C
Najas flexilis	Bushy naiad			C	C	P	P	C			P		
Najas gaudalupensis	Southern naiad	P		C	C	C	P	C			P		
Potamogeton amplifolius	Bigleaf pondweed			P	C	P		P			P		
Potamogeton richardsonii	Richardson's pondweed			P	C	P		P			P		
Potamogeton robbinsii	Robbins' pondweed			P	C	P					P		
Potamogeton spp. (e.g., natans, pulcher, illinoensis)	Broadleaf pondweeds			P	C	P		P			P		
Potamogeton spp. (e.g., pusillus, berchtoldii, spirillus)	Thinleaf pondweeds			C	C	P		P			P		
Potamogeton spp. (e.g., gramineus, epihydrus,)	Other pondweeds			C	C	P		P			P		
Utricularia spp.	Bladderwort			C				C			P		
Vallisneria americana	Water celery	P		P	P			P					
Floating leaved													
Brasenia schreberi	Watershield					P	P	P	C	P	P	C	C
Lemna minor	Duckweed			P		C		C					
Nelumbo lutea	American lotus					P	P		C	P	P	C	C
Nuphar variegata	Yellow water lily					P	P	P	C	C	P	C	
Nymphaea odorata	White water lily					P	P	P	C	C	P	C	
Nymphoides cordata	Little floating heart			C		P	P	P		P	P	P	C
Persicaria amphibia	Water smartweed						P	P	C	P	P	P	
Wolffia columbiana	Watermeal			P		C		C					
Emergent													
Pontederia cordata	Pickerelweed			P					C	C	P	P	
Sagittaria spp.	Arrowhead			P					C	C	C	P	
Typha latifolia	Cattail			P				P	C	C	C	P	

C = high level of control with typical application rate. P = partial control or greater with mulitple applications and/or higher dose. Blank entry indicates herbicide not generally effective for corresponding species at typical application rates and exposure times. Please recognize that dose, duration of exposure, formulation and timing of application are all key factors in results.

Note that some herbicides can be mixed or applied sequentially; for example, copper is often used to minimize attached algae on plants and maximize impact of other herbicides.

Note that most herbicides contain additional compounds, some inert and some intended to increase effectiveness; knowledge of additonal ingredients can be helpful in selecting an herbicide but is not always available.

4.6.2 Impacts to Non-Target Organisms

As explained in the GEIR, concern over impacts to non-target flora centers on protected species and overall impacts to the plant community that may affect habitat for fish and wildlife. Herbicides are intended to kill plants, and while advances in selectivity have been achieved through new or altered formulations, reduced dose, or timing and location of application, more plants than just the target species are normally at risk. In cases of excessive native plant growth, the herbicide may be intended to reduce the overall abundance of plants without targeting one species above all others. Usually, however, the herbicide is matched with the dominant species, and impacts to at least some other species will be less.

Since the GEIR was prepared there have been many treatments with monitoring programs that allow assessment of how well target plants were controlled and how much impact there was on non-target species. Reports have been filed and some papers have been published on degree of control and impacts to non-target species (e.g., Wagner et al. 2007, Jones et al. 2012, Nault et al. 2017). A large database on low dose (<10 ppb) fluridone treatments was developed by K. Wagner and the results exist as several presentations but have not been turned into a peer-reviewed paper yet. Additionally, academic research on results with newer herbicides has also been released (e.g., Glomski et al. 2009, Netherland et al. 2016) and can inform decisions on which herbicide(s) to use to maximize control of target species while minimizing impacts to non-target species. Key advances in our understanding are covered in the following sections on individual active ingredients, but we can say with reasonable certainty what will happen to a wide range of species. There are other factors beyond the herbicide that induce variation (e.g., weather pattern, herbivore presence, additional measures such as drawdown or benthic barrier use), but it is rare to observe widespread loss of species or extremely low vegetation density where not intended. Lake plant communities tend to be resilient.

One area of remaining uncertainty is endangered plant species. These tend to be uncommon where they occur and detection of small shifts in abundance is not reliable with normally accepted plant monitoring methods. Regulatory decisions usually err on the side of protecting those species where the result of the proposed treatment is uncertain, which usually means the project is denied and no useful information on the response of the endangered species is gained. There has been no clear guidance from any source on how to get around this situation.

Impacts to animal life can be direct, as with a toxic effect, or indirect, as with loss of oxygen when many targeted plants decay at once or the habitat is changed by loss of plants. A presentation by Richard Hartley of the MA DFW to the Northeast Aquatic Plant Management Society in 2005 reviewed all available data from investigated fishkills in MA over the preceeding two decades. There were no documented instances of direct toxicity from herbicide treatments, consistent with proper use in accordance with herbicide labels which limit allowable dose in consideration of non-target impacts. A few cases of fishkills relating to lowered oxygen from mass die-off of treated vegetation, all related to contact herbicides (mainly diquat in MA) used on dense plant assemblages, were recorded. However, treatment protocols have been developed to minimize such risk and permits issued under the Wetlands Protection Act (WPA) can specify when and how treatments can be conducted and what must be monitored to inform management decisions, so the associated risk is very low these days.

The real issue is therefore change in habitat. There are aquatic and water-dependent organisms that are favored or disadvantaged by any mix of plant species at any given level, so any change in the assemblage from an herbicide treatment will benefit some species and not others. The 8th interest of the WPA was added several years after the initial act was passed and focuses mainly on fish and wildlife, but has been used by some conservation commissions to deny projects based on change in habitat for any aquatic or water-dependent organism. The difficulty of documenting no loss of habitat for any species creates complications, but it does seem reasonable that overall habitat value for the complete suite of species present or appropriate to the water resource can be improved with well planned herbicide use.

With regard to fish habitat, which is probably of greatest public and regulatory interest except perhaps for endangered species of non-fish organisms, habitat requirements for fish species in lakes are generally understood (Baker et al. 1990, Gettys et al. 2016). We know that pike and pickerel prefer lakes with higher plant density, although complete filling of the water column will impair habitat for even those fish. We know that yellow perch need vegetation for spawning and that bass and sunfish are often associated with vegetation but need open shallow areas of sandy to gravelly substrate to spawn. We know that trout are open water species, even those raised in hatcheries and distributed to lakes in great numbers each year. When the plant community is changed it may shift the balance of habitat suitability among those species and knowing just what mix of vegetative habitat is ideal for a given lake and suite of fish species is challenging. If there is a stated priority for a lake, such as management for a trophy pike or bass fishery or preservation of some native population like brook trout or bridled shiner, the right types and density of vegetation might be discernible. But in the absence of written, approved fish management plans for MA lakes, reliable guidance is limited and tends to come from special interest sources. Assumption of higher priority for gamefish management over other uses is questionable, especially without stated goals or a management plan, but inclusion of fish habitat as a consideration in all vegetation management plans is entirely appropriate and is part of the WPA.

Even where there is consensus regarding fish management goals, data for populations is essential to understanding the benefits and drawbacks of plant management by any means. The MA DFW used to conduct surveys of public lakes roughly every five years, but that valuable effort was accorded much less priority after the 1980s. A few lakes, like Congamond Lake in Southwick that supports extensive bass fishing tournaments that impart considerable economic value, get surveys almost annually but many Great Ponds have not been surveyed more than once in the last 30 years. It is unreasonable to claim impacts without data; comments from fishing organizations or the MA DFW without data need to be considered within that context; claims of impact without data should not be accepted at face value.

Minimizing impacts to non-target plants and animals involves matching the active ingredient to a target species and a formulation approved for use in aquatic environments in MA with consideration of possible impacts on non-target species, the area targeted for control, and the features of the lake that may affect results (e.g., currents, overall flushing rate, interaction with groundwater). Capable licensed applicators and certified lake managers know which herbicides impact which plants under what conditions and should be consulted. There is usually more than one choice of herbicide and multiple herbicides may be needed in lakes with multiple problem plant species. An analysis of the type and magnitude of habitat changes as a result of vegetation control should be conducted but it should be kept in mind that the MA DEP has determined that an invasive species cannot be considered appropriate habitat. Removing invasive species is therefore not detrimental to habitat by definition and the permit application process recognizes this by creating a limited project status for such ecological restoration projects. This allows the project to move forward with fewer performance standards as relates to non-target organism impacts. Valid questions revolve around collateral damage.

The target area will determine the overall extent of possible impact and possible alternative or follow up measures. Where the area containing a target species is relatively small (a swim area, a marina, areas totaling <10% of the plant growth zone), the potential for treatment to have a significant impact on the lake is very limited but alternative control measures (e.g., hand harvesting, benthic barriers) may be applicable. Where the target area is the entire plant growth zone of the lake, the impacts (both positive and negative) may be greater, the specificity of the herbicide for the target species will matter more, and the alternative options for control will be fewer (e.g., deep drawdown). A map of target areas and understanding of the possible extent of impact by the herbicide are therefore important to planning and permitting. Most regulatory guidance recognizes that work occurring over <10% of the plant growth zone is very unlikely to have significant negative impacts unless there is an endangered species present and the target area substantially overlaps with its distribution. Treating as much as 25% of the plant growth zone may have no measurable impact and even whole lake treatments may have minimal impact on the interests of the WPA when they are selective, especially for an invasive species.

Time of year for the application may matter to impacts as well. For example, glyphosate is used on emergent and floating leaved plants and will be more effective later in the growing season when plants are translocating food to the root system. Imazapyr, used on the same species, can be effective over a greater time range within the growing season but has greater non-target species impacts. As another example, fluridone is very effective on invasive Eurasian watermilfoil but requires contact time of several months that may be difficult to achieve near an inlet or in a lake with high flow through and short detention time at the time of intended application, usually spring. Florpyrauxifen-benzyl is an alternative herbicide that requires only a few days of contact time to be effective and also controls milfoil. If timing of treatment matters to non-target organisms, as is the case with many species of pondweed that begin growth later and die back sooner than many target species or fish that spawn in a narrow time window in spring, impact may be altered by treatment timing. Again, consultation with a licensed applicator or certified lake manager can be beneficial in evaluating options.

4.6.3 Impacts to Water Quality

Potential water quality impacts were covered in the GEIR. Herbicides do not tend to directly cause major changes in water quality. Glyphosate contains phosphorus, but Hoyer et al. (2019) demonstrated that this input accounted for <0.4% of the phosphorus load to 21 lakes with a maximum <2.5%. Temperature, oxygen and pH have not been directly altered by herbicide addition. The primary issues are indirect effects, most detrimentally related to oxygen when plants are killed by herbicides and decay in the lake. This is only a real threat when most of the lake is a viable plant growth zone and most of that area is treated with an herbicide that kills most plants. A lake with 25% of its area shallow enough for plant growth (typically <10-20 feet in MA) where less than half of that plant growth area is aggressively treated is unlikely to exhibit any water quality changes; the area and volume involved are simply not large enough. For plant control programs targeting a single or small set of species the change in plant biomass will be lower and impacts will be even less. Label restrictions limit the portion of the lake area that can be treated by broad spectrum herbicides that would be expected to impact a higher portion of the plants present.

One concern, notably raised with regard to plant control proposals at Stockbridge Bowl in the Berkshires in 2019, is the potential for plant control to alter lake water quality and therefore affect biochemical reactions including phosphorus cycling and algae bloom formation. With a large-scale plant control program, the pH might be altered by reduced photosynthesis and shading or allelopathic restriction of algae growth by plants would also be reduced. In shallow lakes almost completely covered by plant growth, complete removal of plants could cause such biochemical shifts, and some shallow lakes have moved from rooted plant dominance to planktonic algae dominance. This has been described as alternative stable states and the influence of climate change has also been implicated (Scheffer and van Nes 2007). Yet such shifts are not likely in a lake where the plant growth zone does not cover most of the lake; it is a shallow lake phenomenon. Further, unless plant control targets the whole plant community, the degree of change in plant cover and biomass will be much less than that required to induce major changes in water quality and biological features. Targeted plant control in stratified lakes is very unlikely to result any measurable water quality change. There is greater risk from a large-scale harvesting program or deep drawdown than from herbicide application, and neither harvesting nor drawdown has been documented to cause such problems in stratified lakes in MA. Climate change, however, has emerged as a major driver in algae bloom formation (Scheffer and van Nes 2007, Gobler 2020).

4.6.4 Applicability to Saltwater Ponds

Little information was offered in the GEIR on the use of herbicides in saltwater ponds and the bulk of experience is with Phragmites control. It is still assumed that considerations are the same as for freshwater ponds.

4.6.5 General Implementation Guidance

The GEIR guidance is generally still valid with regard to implementation. Key data requirements remain as stated and the factors that favor this approach are still applicable. These vary somewhat depending on the lake, target species, and non-target species present. In addition to what is offered in the GEIR, the following insights are offered on performance guidelines from experience gained since the GEIR was produced.

4.6.5.1 Performance Guidelines

Monitoring and Maintenance

Monitoring

Monitoring can play an important role in herbicide applications to control nuisance species. At a minimum, a survey is needed prior to treatment to know where to treat and to document conditions with regard to non-target species. Follow up surveys later in the treatment year and in subsequent years after treatment provide data that can be compared and are useful in assessing treatment effectiveness and compliance with the WPA, MESA or other applicable conditions of the permit. Gathering quantitative data can greatly aid assessment of results and future planning for projects elsewhere as well as on the target lake. A case in point is low dose fluridone treatments, used extensively in the northeast for control of Eurasian watermilfoil and hydrilla, two invasive species. Accumulation of data from over 100 treatments has allowed an assessment of which species are impacted, which are not, and the duration of any impacts under field conditions, as opposed to the useful but not all-encompassing mesocosm tests run before a herbicide is registered for use. Only data from lakes where other major management actions are absent or consistent over time can be used for such analysis, but it is a valuable exercise where data are available.

This type of assessment can help make conservation commissions and regulatory agencies aware of what is already known and avoid excessive permit requirements related to perceived uncertainty of results when much higher certainty actually exists. While assessment of the quantity of any species or vegetation overall is useful, just having presence/absence data from a substantial number of sites laid out on a grid or in transects in the plant growth zone of the lake has proven adequate for assessing impacts except to rare species. Measuring quantity on a simple quartile scale for cover and biovolume (25% increments of cover in two dimensions or portion of the water column filled in three dimensions) is sufficient for determining overall impact, as no control program would likely be considered successful if the target species was reduced by <50% or non-target vegetation was reduced by >50% for an extended time period. Additionally, many licensed applicators have a good feel for which herbicides will impact which non-target species and how long those impacts will last, and those insights are useful.

Applicants for herbicide treatments should provide a reasonable monitoring plan as part of the application. Just who carries out the monitoring program is an additional consideration that depends on the circumstances. Many volunteer groups can do credible plant surveys, especially if the focus is on a dominant target plant intended to be reduced and recovery of an overall native assemblage, the primary goals of most herbicide projects. Most herbicide application firms have staff that can conduct plant surveys if so desired and affordable. Where species protected under MESA are present, a botanist or zoologist approved by NHESP may have to perform a survey. Conservation commissions should consider what is really needed to assess project success and any adverse impacts and impose only necessary conditions; these are management projects, not research endeavors (many of which were previously conducted to get the herbicide approved for use), and conditions should focus on documenting compliance with reasonable permit conditions.

An adequately detailed monitoring program that meets all needs cannot be supplied here; there are simply to many site-specific factors that have to be considered. A few guidelines can be offered, however.

- Natural variation will lead to +10% differences among years, even when survey is done at the same time, so small changes in frequency of occurrence or features such as stem counts and biomass cannot be detected in the vast majority of cases. This also means that surveying the exact same locations is not essential; seed producing annuals will move laterally within most lakes. Treatment where the impact on rare species is important to quantify may require a specialized survey; the NHESP is likely to dictate what will be acceptable.

- Frequency correlates with overall abundance, so just knowing that a plant is present or absent at enough sites is usually enough to evaluate significant changes resulting from treatment. No less than 30 sites should be surveyed, but for larger lakes a recommendation of one site per littoral zone acre is appropriate.
- The use of either strategically placed transects (representing the range of slopes and related conditions in the lake) with points at specified depth intervals (1 to 15 ft in 2 ft intervals is commonly applied) or a grid system (points spaced evenly at nodes in the grid with depth measured at each point) is adequate for assessing plant distribution and changes due to treatment.
- Identification of target species and any rare or endangered species is essential. Identification beyond that depends on project goals. The regulations do not specify beyond native assemblages, but it is helpful to know how many different species are present at a monitoring site. Identification to species is desirable but not always easy, especially with hybridization of pondweeds (genus Potamogeton) and morphotypic variability of some plants. Identification to genus may be sufficient in most cases.
- Monitoring should occur in roughly the same timeframe each year, usually late summer, although some species peak and die back earlier, so each lake may have different timing needs for surveys depending on the plant community present.
- Monitoring should occur prior to treatment and for two years beyond treatment to evaluate results and permit compliance. Additional surveys in the year of treatment may be helpful where follow up treatment is part of the program but is not necessary for compliance assessment.

Maintenance Use of Herbicides

Project proponents and regulatory bodies need to understand the difference between restoration, rehabilitation, and maintenance and how these interact with the general regulatory mandate to protect designated environmental attributes. It is rare that we actually restore a lake or any other habitat. Removal of an invasive species may seem like restoration, but rarely do we completely eradicate invasive species and there may indeed be side effects that change the lake in even subtle ways that defy the term restoration. Instead, what is done most often is an action by which one or more attributes of the lake are changed to support one or more designated uses like water supply, recreation, or habitat. Use of herbicides can minimize invasive species or lower the density of native nuisance species on a whole lake basis, which would be rehabilitation, or over part of the lake, which might be called maintenance. Even under the rehabilitation scenario, lack of follow up control actions may result in a return to former conditions, rendering the lake-wide treatment more of a maintenance activity, depending upon its frequency.

Conservation commissions frequently express an interest in preventive actions or more permanent measures that address the problem one time or very rarely, but this is not a realistic position from the perspective of nuisance plant control. Prevention of the import of invasive species is indeed important but is not supported at state or municipal levels in the manner it should be. Failure of government with the jurisdiction to take preventive action to do so does not convey all responsibility to the project proponent, especially if that proponent is a lake association or individual without complete control of access points and especially if the lake is a statutory Great Pond, owned by the Commonwealth of MA. And once a species has entered a lake, prevention is not going to help with its control.

Given that invasive species can enter a lake by multiple paths with limits on control of access, rapid response is critical to effective eradication of unwanted species. Rapid response plans were developed for MA for multiple invasive species over a decade ago but have not been promoted or followed in most cases and are not supported by the regulatory framework. The current WPA regulations do not treat rapid response any differently than any other control program and by the time one can get a permit to conduct a rapid response action the target species may have spread too far to make the permitted action effective. If a listed species is present in the lake the NHESP must render a decision, typically adding 30 days to the process. Early detection and rapid response are essential if a new invasive species is to be truly eliminated and are not well supported in MA. Once an invasive species becomes established, maintenance is to be expected.

Herbicides, like nearly all other plant control options, are unlikely to provide complete control of the target species from a single application; this is akin to taking medicine for some serious ailment – one dose is unlikely to work. Nuisance species control is more likely a maintenance activity, hopefully with a reduced frequency, but likely to be needed from time to time and often involving more than one technique, like controlling human weight through diet and exercise. Permits typically last for 3-5 years and can usually be renewed at least once with minimal effort, and there should be recognition that nuisance plant control is an ongoing process. The exact combination of herbicides and other techniques to manage a lake will vary with target species, non-target species, target area, lake features, regulatory constraints, and affordability and can be unique for each lake. There is no "one size fits all solution" and applicants and conservation commissions need to recognize this. Just because the lake in the next town did X and seems to have acceptable results does not mean that X is right for the lake in your town, although it certainly bears scrutiny.

4.6.6 Copper

The GEIR adequately covers copper, which is one of the oldest compounds used in lakes, mainy for algae control, but with impact on a variety of rooted plant species. It remains the most commonly used algaecide. Key insights gained since the GEIR was produced include:

- The label for nearly all copper products limits application to half the waterbody. This may necessitate more than one treatment if blooms are severe and encourages earlier response, which is desirable, tends to be more effective, and carries fewer collateral damage issues.
- MA restricts the use of copper for cyanobacteria control if the cell concentration for possible toxin producers is >70,000/mL. This is done out of concern for release of toxins from cells if lysed by copper, as toxins are not usually excreted and are only liberated into the water upon cell death and membrane rupture. However, those toxins will eventually be released naturally if no treatment is conducted, so this is not a simple solution. Additionally, potential toxin producing cyanobacteria do not always produce toxins and there is no requirement to test for toxins, so the protocol is incomplete. What it does do that is useful is encourage tracking of algae and earlier action. Treatment before a bloom actually forms is more effective and avoids many undesirable impacts. Treatment at cell counts between 10,000 and 20,000 cells/mL is advised.

- The dose of copper applied (as copper, no matter what the formulation) rarely needs to exceed 0.1 mg/L in MA lakes. Keeping the copper concentration below 0.1 mg/L minimizes damage to non-target organisms, notably zooplankton and fish.

4.6.7 Diquat

Diquat is adequately covered in the GEIR and its use remains much as it has for the last two decades. However, one potentially important observation is that diquat has been able to control certain perennial plants like Eurasian watermilfoil without direct contact with the root crowns. It was assumed that recovery of milfoil would occur after application of contact herbicides like diquat, but it may be that diquat has some systemic properties or that the root crowns do not survive as well as believed with timely diquat application. Successful control beyond a year or two has been achieved in multiple MA lakes, including Pontoosuc Lake in the Berkshires. Use of diquat as a follow up to a lakewide treatment with another herbicide such as fluridone appears to be a highly applicable strategy.

4.6.8 2,4-D

2,4-D is adequately covered in the GEIR. Continuation of the prohibition of use in water supplies and lakes with substantial groundwater connection is worth noting. 2,4-D cannot be applied to lakes where there is a clear groundwater connection to supply wells, either public or private. For areas with porous sandy soils like Cape Cod a groundwater connection is logically assumed, while for areas with minimally permeable clay soils like the Berkshires it is very unlikely that 2,4-D will move out of the lake into groundwater. However, actually documenting a connection or lack thereof between lakes and water supply wells can be challenging and regulatory bodies may disallow treatment with 2,4-D if any wells are near the lake rather than seek an investigation of connectivity.

4.6.9 Glyphosate

Glyphosate is adequately covered in the GEIR. The only addition of note is that formulations used in aquatic plant control should not be equated to terrestrial formulations; the media and legal furor over alleged carcinogenicity of and risk from glyphosate-based herbicides used in agriculture and property management should not be a factor in permitting for aquatic use. The dose, additives, frequency of application, target area and risk to people are very different from agricultural use and application by licensed professionals cannot be equated to home use. Some towns have banned the use of glyphosate-based herbicides without adequate analysis and it remains to be seen if such actions can withstand state-level policy for approved herbicides. Applicants need to be aware of any local regulations when planning plant control with glyphosate, but it is inappropriate for regulatory bodies to assume that any use of glyphosate represents a significant human health issue.

4.6.10 Fluridone

Fluridone is adequately covered in the GEIR, but there have been changes in its use and experience with fluridone that bear mention. The vast majority of fluridone treatments over the last two decades apply concentrations near the lower end of the allowable scale, often <10 ppb. A newer pelletized formulation with reliable slow release of fluridone has also provided control in more rapidly flushed areas or in smaller targeted areas, especially for Eurasian watermilfoil. An as yet unpublished study by K. Wagner and colleagues evaluated data from over 100 low dose treatments for impacts to non-target plant species. A summary of results is provided in Tables 4S-3 and 4S-4. In general, native assemblages recover in no more than 2 years, matching the allowable time for recovery under the WPA regulations.

The response of aquatic species richness to fluridone at <10 ppb tends to vary with the number of native species present at the time of treatment. Where invasive species have depressed native species richness, increases are observed, while where native species richness is still high there is a slight depression of richness (1 or 2 species) over the five years following treatment. In terms of overall native plant assemblages, low dose fluridone treatments have minimal lasting effect while depressing target species such as Eurasian watermilfoil, hydrilla and curlyleaf pondweed.

4.6.11 Endothall

Endothall is covered in the GEIR and its use has not changed substantially since the GEIR was prepared. Endothall is less used in MA than diquat but is a suitable alternative for many target plants. Endothall can be used for immediate control of hydrilla where pioneer infestations are discovered and can depress native plant assemblages for safety purposes in swim areas. Endothall appears to have some systemic properties despite generally being considered to be a contact herbicide.

4.6.12 Triclopyr

Triclopyr received federal registration for aquatic habitats at the end of 2002 and became accepted for use in MA in 2004. It was addressed in the GEIR in light of impeding registration in MA but there was minimal experience with use at that time. The trade name for the aquatic formulation is Renovate, with 3 pounds of triclopyr per gallon (about 35% triclopyr). Triclopyr is a systemic herbicide that prevents synthesis of plant-specific enzymes, resulting in disruption of growth processes. It was expected to provide selective control of Eurasian watermilfoil and other non-native dicotyledenous species with no anticipated impacts on aquatic animals at concentrations up to 0.5 mg/L. The MA DAR review of triclopyr is informative and was included in the GEIR.

Over the last 15 years triclopyr has proven less effective against Eurasian watermilfoil than fluridone where adequate exposure time can be maintained and the newer florpyrauxifen-benzyl appears to offer better results where exposure time is limited. Yet triclopyr can control Eurasian watermilfoil and has provided greater control of the related variable watermilfoil and parrotfeather than fluridone. It has also provided control of a number of other invasive species including Phragmites, purple loosestrife and water chestnut and certain nuisance native species such as water lilies, watershield, floating heart, lotus and water smartweed.

Table 4S-3. Response of native plant species to low dose fluridone treatment.

Taxon	Response to fluridone	Notes
Bidens beckii	Minimal change	
Brasenia schreberi	Minimal change	
Ceratophyllum demersum	Wide range of response	Possibly different populations respond differently
Chara sp.	Increase then decrease	Later decrease appears related to competition with other plants
Decodon verticillatus	Minimal change	
Eleocharis spp.	Minimal change	
Elodea spp.	Wide range of response	Usually decreases but recolonizes quickly
Iris sp.	Minimal change	
Lemna minor	Minimal change	
Lythrum salicaria	Minimal change	
Myriophyllum sibiricum	Minimal change	
Myriophyllum verticillatum	Minimal change	
Najas spp.	Wide range of response	Usually decreases but recolonizes quickly
Nitella spp.	Minimal change	
Nuphar spp.	Minimal change	
Nymphaea odorata	Wide range of response	Impacted by higher doses, probably a matter of exposure duration
Peltandra virginica	Minimal change	
Polygonum spp.	Minimal change	
Pontederia cordata	Minimal change	
Potamogeton amplifolius	Minimal change	
Potamogeton epihydrus	Minimal change	
Potamogeton gramineus	Minimal change	
Potamogeton illinoensis	Wide range of response	May be a matter of timing or exposure duration; recovers within 2 years
Potamogeton natans	Minimal change	
Potamogeton nodosus	Minimal change	
Potamogeton praelongus	Minimal change	
Potamogeton pusillus	Wide range of response	May be a matter of timing or exposure duration; recovers within 2 years
Potamogeton richardsonii	Wide range of response	May be a matter of timing or exposure duration; recovers within 2 years
Potamogeton robbinsii	Minimal change	
Potamogeton zosteriformis	Minimal change	
Ranunculus spp.	Minimal change	
Sagittaria spp.	Minimal change	
Scirpus/Schoenoplectus sp.	Minimal change	
Sparganium spp.	Minimal change	
Stuckenia pectinata	No change or increased	Tends to colonize quickly where other species are reduced
Typha spp.	Minimal change	
Utricularia sp.	Minimal change	
Vallisneria americana	Wide range of response	May be a matter of timing or exposure duration; recovers within 2 years
Wolffia columbiana	Minimal change	
Zosterella dubia	Wide range of response	May be a matter of timing or exposure duration; recovers within 2 years

Table 4S-4. Change in species richness in lakes subject to low dose fluridone treatments.

Range of Pre-trtmt Native Species	Average number of species in lake						
	Pre-Trtmt	YOT	YAT1	YAT2	YAT3	YAT4	YAT5
<11	7	9	10	9	10	10	12
11 to 17	14	13	14	14	12	14	12
>17	20	18	19	19	19	18	18

4.6.13 Peroxide

Peroxide was not included in the 2004 GEIR. Hydrogen peroxide and several compounds that generate peroxide when added to water (e.g., sodium percarbonate and peracetic acid) act on the cell walls of algae to kill them. As different algal groups have cell walls of different materials and varying susceptibility to peroxide, this active ingredient tends to differentially control cyanobacteria better than green algae or diatoms. The primary commercial products producting peroxides are PAK 27 and Greenclean. Once reacted there are no problem compounds remaining and oxidation of cell contents, including cyanobacteria toxins, may occur. Application should occur before severe blooms or mats form for best control and application is subject to the same cell count limitations for potentially toxic cyanobacteria as for copper products. The cost of peroxides tends to be higher than for copper formulations but the environmental impact profile is generally regarded as preferable for the peroxide.

The MA DAR produced a review of peroxides during the approval process that can be found at https://www.mass.gov/doc/sodium-carbonate-peroxyhydrate-and-hydrogen-peroxide/download.

4.6.14 Flumioxazin

Flumioxazin was not included in the 2004 GEIR. Flumioxazin, the common name for N-(7-fluoro-3,4-dihydro-3-oxo-4-prop-2-ynyl-2H-1,4benzoxazin-6-yl)-cyclohex-1-ene-1,2-dicarboxamide, was approved for use in MA in 2013. It is a contact herbicide, impacting parts of plants exposed to it. Flumioxazin controls plant growth by blocking biosynthesis in several metabolic pathways, resulting in the accumulation of phototoxic porphyrins in plant tissues. Cell membranes are damaged and the physical structure of the plant is disrupted. It acts on a wide range of aquatic plants and can be more effective against filamentous green algae than most other registered compounds.

The MA DAR produced a review of flumioxazin during the approval process that can be found at https://www.mass.gov/doc/flumioxazin/download.

4.6.15 Imazapyr

Imazapyr was not included in the 2004 GEIR. Imazapyr is an imidazolinone herbicide that can control a wide range of emergent and floating leaved aquatic plants but is not effective against submerged aquatic vegetation. It is the primary alternative to glyphosate for control of Phragmites and floating leaved plants like waterlilies. The aquatic formulation is sold under the tradename Habitat and was registered for use in MA in 2012. Uptake of systemic imidazolinone herbicides is primarily through the foliage and roots. The herbicide is then translocated to buds or areas of growth where it inhibits acetohydroxyacid or acetolactate synthase (ALS), an enzyme involved in the synthesis of essential amino acids required for protein synthesis and cell growth. Imazapyr disrupts protein synthesis and interferes with cell growth and DNA synthesis, causing the plant to slowly die. ALS is not present in mammals, birds, fish, or insects, making imazapyr specifically toxic to plants.

The MA DAR produced a review of imazapyr during the approval process that can be found at https://www.mass.gov/doc/imazapyr/download.

4.6.16 Imazamox

Imazamox was not included in the 2004 GEIR. Imazamox is the common name for (±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1Himidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid and is a systemic herbicide. Imazamox is a member of the imidazolinone class of herbicides that also includes imazapic, imazapyr, imazethapyr, imazamethabenz, and imazaquin. It can be used for control of emergent, floating leaved and submergent aquatic plants. The mode of action is much like that of the closely related imazapyr, but imazamox is formulated for activity below the water surface. It is marketed under the tradename Clearcast. Clearcast has proven less effective overall on many submergent species than other systemic herbicides but is a broad spectrum herbicide, impacting a wider range of species than most other systemic herbicides. It has received only modest use in MA to date.

The MA DAR produced a review of imazapyr during the approval process that can be found at https://www.mass.gov/doc/imazamox/download.

4.6.17 Florpyrauxifen-benzyl

Florpyrauxifen-benzyl was not included in the 2004 GEIR. Florpyrauxifen-benzyl, more technically 2-pyridinecarboxylic acid, 4-amino-3chloro-6-(4-chloro-2-fluoro-3-methoxy-phenyl)-5-fluoro-, phenyl methyl ester, is an arylpicolinate systemic herbicide intended for use for foliar application to emergent aquatic vegetation or direct application to water to control submergent vegetation. As a synthetic auxin it produces effects on the plant including alterations in cell wall elasticity and gene expression, and non-productive tissue growth that results in leaf curl and disruption of the plant phloem, interfering with transport of nutrients and causing death in days to weeks. Target species include invasive hydrilla, Eurasian watermilfoil and floating heart. It is marketed under the tradename ProcellaCOR. It was registered for use in MA in 2019, so there is a very limited track record for this herbicide, but it requires only a few days of contact time, making it valuable for more complete control of aquatic plants in areas with shorter detention time.

The MA DAR produced a review of florpyrauxifen-benzyl during the approval process that can be found at https://www.mass.gov/doc/florpyrauxifen-benzyl/download.

4.6.18 Regulations

4.6.18.1 Applicable Statutes

The GEIR covers the key regulatory aspects of herbicide use, which include the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) Public Law 92-516, the Massachusetts Pesticide Control Act (Chapter 132B), state law Chapter 111 section 5E under which the MA DEP issues Licenses to Apply Chemicals, and the Wetlands Protection Act (WPA), administered by municipal conservation commissions with oversight by MA DEP. If the proposed project occurs within an Estimated or Priority Habitat of Rare Wildlife in the most recent version of the Natural Heritage mapping, a copy of the Notice of Intent under the WPA must be submitted to the Natural Heritage and Endangered Species Program (NHESP) within the MDFG for review before it enters the normal submission process through the MA DEP and local conservation commissions.

The court decision regarding applicability of NPDES provisions to herbicide applications mentioned in the GEIR has been upheld and the License to Apply Chemicals issued by MA DEP has been constructed to meet this need in most cases.

4.6.18.2 Impacts Specific to Wetlands Protection Act

The regulations relating to the WPA were modified in 2014 and there were changes that have bearing on lake management by herbicides. The 8 identified interests of the WPA and the interaction with herbicides remain the same and can be summarized as follows:

1. Protection of public and private water supply – Detriment (prohibition of many herbicides from drinking water supplies) or neutral (as a function of use restrictions or lack of impact). Herbicide use in lakes used for public water supply is generally discouraged but is possible with limits.
2. Protection of groundwater supply – Detriment (prohibition of some herbicides, notably 2,4-D, within the recharge zone of wells) or neutral (as a function of use restrictions or lack of impact). Herbicides applied to lakes have almost never been found in drinking water wells in MA and are generally removed by uptake, conversion to other compounds, and passage of water through soil, but monitoring has been required in some cases and the restriction on 2,4-D remains in effect. Risk is higher in sandy soils and lower in silty soils.
3. Flood control - Neutral (no significant interaction).
4. Storm damage prevention – Neutral (no significant interaction).
5. Prevention of pollution – Generally neutral (no significant interaction) but oxygen can be lowered by rapid plant die off, which is limited by label restrictions. An unpublished evaluation by MA DFW in 2005 found water quality impacts from herbicide application to be rare in MA.
6. Protection of land containing shellfish – Generally neutral (no significant interaction) for rooted plant control where label requirements are followed (no toxicity or indirect effects).
7. Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover); information on fisheries and role of target and impacted non-target plants in fish habitat is needed for evaluation. An unpublished evaluation by MA DFW in 2005 found no fishkills from direct toxicity but rare impacts from lowered oxygen.
8. Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover). This interest of the WPA was added years after the

original 7 interests and is less well defined. It is generally intended to cover possible impacts on birds, mammals and other wildlife that may use the lake. A habitat evaluation is used to assess possible impacts if the target species is not an invasive plant and focuses on the role of aquatic plants as habitat for non-fish wildlife known to utilize the lake.

Several observations relating to permitting developments under the WPA since the GEIR was produced are worthy of mention. The GEIR was developed to make the job of conservation commissions easier, providing guidance on choice, implementation and regulation of specific lake management techniques. Every town was provided with a copy and it has been available online for many years. An abridged version focused on practical guidance, entitled The Practical Guide to Lake Management in Massachusetts (Wagner 2004) was also provided in hard copy and placed online. Yet it is rare today to encounter a conservation commission that has read the applicable sections when the required hearing is held. The MA DEP prepared a 34-page document intended to aid proponents and commissions, but it does not cover the material on each technique at a level necessary for proper understanding. In the case of herbicides, where the number of active ingredients has doubled between 2004 and 2020, this supplement is provided, but the original GEIR and related practical guide provide a valid framework for considering projects.

As herbicide applications in MA must be performed by licensed applicators, concerns over impacts only possible with product misuse should not be a factor in permitting. The relation of herbicide application to the WPA therefore revolves around whether or not the lake is a public water supply, if there is any potential for wells to be impacted where sandy soils dominate, if there is any potential for rapid plant die off and depression of oxygen in the lake, and how the change in the plant community will affect habitat for fish and wildlife. In the vast majority of permitting processes, review of impacts will boil down to impacts on any listed species that may be present under MESA by NHESP and any impacts on fish and wildlife habitat from expected changes in the plant community under WPA by the conservation commission. Applicants and consultants have input to each of these processes and other organizations may offer insights, most notably the MA DFW for fish and wildlife habitat considerations.

It is important to consider all lake functions and uses and how any lake management practice, including herbicide application, affects those functions and uses during the permitting process. There will be conflicts, as not all uses are compatible, and priorities are needed but not specified under law in MA. This leaves conservation commissions as arbiters of lake management disputes, a role that they are not properly equipped to fulfil in many cases as volunteers with no required training. It is therefore incumbent upon all involved parties to provide appropriate input without misleading or misrepresenting; data and relevant peer-reviewed studies should prevail over opinion and unsubstantiated claims garnered from unstated or unreliable sources.

The NHESP has primacy for decisions on any lake management action involving a listed species under MESA, meaning that protection of a listed species is considered first in the permit process and the project may go no further than this step if deemed unacceptable by NHESP review. If acceptable, the project is then considered by the local conservation commission and evaluated by the corresponding regional office of the MA DEP. Whether the target plant is an invasive or native species does matter under the WPA. By MA DEP policy, invasive species are not considered to have habitat value. Therefore, by definition, removal of an invasive species cannot have a negative impact on fish and wildlife habitat. Such projects are considered "ecological restoration" projects under the WPA regulations and may be subject to lesser performance standards under what is termed "limited project" status. In other words, a certain amount of impact to non-target species can be accepted to achieve control over the targeted invasive species. Collateral damage to native species remains a consideration and unreasonable impact to the rest of the lake ecosystem is not allowable. What constitutes reasonable or unreasonable is not always clear, leading to some conflicts and the need to consider short- and long-term effects, both positive and negative.

Where the target plant is a native species that can cause nuisance conditions (e.g., water lilies, certain pondweeds), there is no option for limited project status under the current WPA regulations, last adjusted in 2014. Control of native vegetation that has become too dense to allow recreation and may cause ecological problems such as stunted fish populations, wide swings in pH or oxygen, or reduced plant diversity is subject to performance standards that must be met for the herbicide treatment to be approvable. In many cases those standards can be met, especially since the regulations allow for two growing seasons of recovery from any adverse impacts, but there can be challenges. Improvement to one or more interests of the WPA might be demonstrable but with the addition of aquatic habitat as an interest of the WPA, a number of potential conflicts are set up.

Some fish (e.g., pike and pickerel) prefer denser vegetation while others (e.g., trout, smallmouth bass) prefer open water and many (e.g., largemouth bass, sunfish, perch) utilize both open water and aquatic vegetation extensively. A habitat benefit to one species may represent a habitat loss to another. Wading birds benefit from some vegetative cover in shallow areas, as that cover draws small fish upon which the birds feed, but that feeding is compromised when the vegetative density is too high. Many ducks feed on submergent vegetation but cannot move quickly through dense patches of topped out plants, making them more susceptible to predators. The situation is the same for benthic macroinvertebrates, with changes in the plant community affecting some positively and others negatively, which can in turn affect food value of plant growths for fish and wildlife. The issue is much more complex than the existing regulations appear to recognize, leaving conservation commissions as arbiters with limited information and guidance. Any project should seek balance between habitat types offered by the lake and consider all uses, human and non-human.

Additionally, there is a fundamental problem with our current laws and corresponding regulations as pertains to nuisance species. We have a law that prohibits the import of any potential nuisance species (which includes all invasive species, which are by definition non-native and capable of causing ecological and/or economic damages termed nuisances by law) but we have no law that requires action when a nuisance species is present and becomes a nuisance. We have laws that forbid impact to listed species and limit impact to wetlands (which includes lakes), and where control of a nuisance species conflicts with the need to protect wetland interests, conservation commissions are left to determine how much impact to non-target species is acceptable. The MA DEP can aid in this determination but may not have the information needed to make an appropriate determination. The NHESP will determine if the risk to a listed species is acceptable but may also not have the necessary information to make a properly informed decision. It is therefore incumbent on project proponents to make the issue clear in permit applications and provide as much data as possible, or at least point out the lack of data that would prevent drawing properly supported, negative conclusions about the proposed project.

4.6 Herbicides

The result of any uncertainty as described above is usually a decision to protect listed species or wetland functions on the uncertain chance that control of a nuisance species may cause undesirable impacts. The decision to not allow action is not necessarily a protective decision, and decisions with severe negative ecological consequences have resulted in Massachusetts under existing laws and regulations. Most agencies and commissions do not participate in crafting management solutions, acting only as umpires for proposed actions, and the lack of any obligation to solve environmental problems is a major shortcoming of the permit process. Knowledge of what has happened in other treatment cases is helpful, as is monitoring of incremental implementation with adaptive management as more is learned. Applicants should be mindful of this when crafting permit applications and conservation commissions should be open to information available from reliable sources.

4.6.18.3 A Call for Reason in Herbicide Use and Permitting

One of the difficult permitting situations is when a shallow, manmade lake is overrun with vegetation indigenous to the region. As a manmade lake, it has no true "native" plants; everything invaded if it was not intentionally planted. As a shallow system, most if not all the lake is a plant growth zone, potentially limiting the extent of open water and the diversity of habitat types. These systems are subject to natural processes and to the laws of MA intended to protect natural aquatic environments but are not truly "natural". They are like buildings that serve a public need, but which require maintenance like roof replacement, exterior and interior painting, window washing, and other property maintenance over time to support their intended uses. The density of plants may impair recreation, aesthetics and property value, which translates into lost tax base for the municipality. Dense vegetation may even translate into a health threat; swimmers have died by entanglement in plants and various parasites and pathogens are promoted by such vegetation (e.g., schistosomes that cause swimmer's itch, leeches, attached toxic cyanobacteria). Yet if the dense vegetation does not translate into lost habitat value or direct impacts on fish, wildlife or some other interest of the WPA, there is no clear impetus under the WPA to grant a permit to control that vegetation.

The above case is not rare and applies to many MA lakes at least in part. Based on an unpublished evaluation by ENSR staff in the 1990s, over half the lake area and two thirds of lake volume in MA were created by human action, mainly damming of streams, and that does not include the two largest waterbodies, Quabbin and Wachusett, both manmade for water supply. Most of our lakes include shallow areas created by human actions and therefore susceptible to plant overgrowth and in need of management if we want to maintain the uses for which those habitats were created. Some dams have been removed in what could be considered restoration efforts, but most lakes with dams have become important features of communities and landscapes and will not be subject to dam removal. The value of these lakes is recognized but the existing environmental laws control their management such that value is lost if there is not cooperation among stakeholders and regulators. What is needed is reason and logic on the part of both applicants and conservation commissions.

The WPA allows for recreational access, for boating lanes, and for overall balance between habitat types. It does not allow for wholesale conversion of an aquatic habitat into a swimming pool or environment free of any obstruction any person finds objectionable to their view or active use. Plant control plans should reflect cognizance of the range of wetland functions provided by the lake and a sensitivity to all users, human or otherwise. Zones set aside for habitat, swimming, boating, fishing and other uses are encouraged, with management as warranted to support those uses. Herbicides approved for use in MA, applied by licensed applicators who understand the goals of the program, have a useful role in such programs. By virtue of being approved for use in MA, the government is saying that the benefits of proper use of an herbicide outweigh the risks that may exist. Determining proper use can be debated but the debate needs to be grounded in science, not biased opinion or unsubstantiated claims. The frequency of herbicide use is a point of discussion but is not clear grounds for rejection if the commission simply dislikes herbicides or wants a one-time solution that rarely exists.

It is important to consider the area and volume of a lake to be treated in any proposed project. Projects involving a small (on the order of 10%, but this is not a distinct threshold) portion of the plant growth zone (the littoral zone where plants can grow, out to a depth between 10 and 20 feet in MA lakes, depending on water clarity and substrate types) have minimal probability of impacting the lake overall unless the target zone substantially overlaps with critical habitat for some rare species. As the plant growth zone covers the shallowest part of any lake, the portion of lake volume involved in a treatment will be even less than the percent area. And where the plant control program targets a single species or small set of species within a larger plant community, overall impact to habitat will be less than the total affected area might suggest. There is no regulatory guidance for an acceptable portion of a lake treated beyond the 50% limit imposed for some herbicides by their legal labels, but it is suggested here that treating up to 10% of the plant growth zone represents no threat to the interests of the WPA in the vast majority of cases and that treating as much as 25% may have no measurable impact. Even whole lake treatments may have minimal impact on the interests of the WPA when they are selective, especially for an invasive species.

It is reasonable to expect applicants to provide a complete program to extend for at least the life of the permit, possibly including non-chemical follow up actions to prolong the benefits of herbicide use where appropriate (e.g., benthic barriers in swim areas or for property access, hand pulling of scattered growths of any invasive species that might have survived, drawdown to enhance nearshore sediment features and limit colonization). It is not reasonable for commissions to tack on conditions unrelated to plant control, such as overall watershed management planning that has no bearing on an in-lake plant problem. While a conservation commission is under no obligation under the law to become a partner in the management of a lake, as part of the community in which the lake exists, it should be incumbent on commissions and applicants to cooperate to determine the best approach to reaching reasonable management goals, and a clear statement of those goals should guide the planning and permitting processes.

Consideration of the goals of all stakeholders and organizations with an interest in some aspect of the lake, including the MA DFW, the NHESP, lake associations, sportsmen’s groups, marina owners, boaters not living on the lake, swim clubs, and municipalities, is encouraged. Ultimately some priorities may need to be established and decisions based on data from the lake or experience with other comparable systems will have to be made. Establishing priorities and making management decisions may extend beyond the charge of conservation commissions but they have an important role to play and should approach project proposals with careful consideration of lake uses and values.

When considering management options, most regulatory programs call for evaluation of the no action alternative, or functionally doing nothing. While taking no action is seemingly the least expensive in terms of direct capital outlay, this is often a very expensive option in terms of lost tax base and a variety of other water resource benefits, as economic assessments have demonstrated (e.g., Boyle and Bouchard 2003, Hanley and Roberts 2019). Our knowledge of economic impacts has increased markedly since the original GEIR was produced (compare Lovell et al. 2005 with Rosean et al. 2016); while the cost of control is substantial, the monetary benefits of control are routinely higher. However, economics are not a major factor in most regulatory programs and the focus is usually on protecting the resource. Yet the no action alternative does not equate with protection in the vast majority of cases; doing nothing will often result in dominance by invasive species, lost wetland functions, compromised habitat, and impairments that are recognized under federal and state laws (e.g., the impaired waters list produced biennially by states under federal mandate). Doing nothing because herbicide use has potential drawbacks is not a defensible position without an assessment of the drawbacks of inaction.

The same considerations apply to limiting herbicide application by area or timing. There may be good reasons to leave a portion of a lake untreated or to avoid treating during certain times of year when non-target impacts may be unreasonably high, or when application will be less effective. Label restrictions for area and timing may also apply. Yet deciding to do less than a recommended area for economic reasons or because the permitting authority is uncomfortable will usually yield suboptimal results. Providing a refuge for an invasive species may prolong the time and number of treatments needed to gain control. Treating after seeds or other reproductive structures are formed and released will likely necessitate more treatment later. Where and when to apply an herbicide may be just as important as if to apply it and projects might best be approached from a multi-year perspective with clear goals. There may be no clear endpoint but there should be quantifiable targets against which progress can be measured.

4.6.19 Future Research Needs

Some of the assessment tasks suggested in the GEIR have been completed and have been discussed in this document. Others remain to be accomplished and more will arise with new herbicides and new invasive species. While not research per se, there is a real need for monitoring support for lakes from the Commonwealth, especially for Great Ponds that are the property of the Commonwealth. Much less monitoring occurs now than used to be the case, and responsibility has been pushed onto project proponents. At the very least, basic water quality data, vegetation, and fish surveys should be conducted by agencies of the Commonwealth, providing a reliable database on which to draw when considering impacts of proposed herbicide application. Agency priorities and related staffing and funding are not directed in this manner, however, and direction from the top down is needed to meet this need.

4.6.20 Summary

While the original GEIR provides considerable background and guidance, developments in the field of herbicides have been extensive since 2004 and the permitting landscape in MA has also changed. Additional considerations warranted exploration and this supplement was prepared to inform project proponents and conservation commissions to facilitate better plant management programs and permitting decisions. Key points not contained in the original GEIR include:

1. There were only six active ingredients approved for use in aquatic herbicides in Massachusetts when the GEIR was produced, but six additional ingredients have been added for Massachusetts since then. A table of approved herbicides with common target plants is provided. It is important to understand that just because a commercial herbicide formulation contains an active ingredient that it is not the same as every other herbicide that contains that ingredient.
2. The internet provides an unfiltered source for information on herbicides. Consider the source before accepting the information as valid. A good case in point is the media and legal frenzy over glyphosate, based on selective science and massive agricultural or unregulated property owner use and virtually unrelated to proper aquatic use.
3. Effectiveness of different available herbicides for various likely target plants is revisited and a new table that matches herbicides with target species is provided.
4. Where treatment involves mainly spot applications at locations that change each year, especially with contact herbicides, there is little concern over development of resistance by plants. However, the potential for resistance does suggest that permits for aquatic plant control might best include multiple herbicides appropriate to the target species to allow flexibility in control over the long run.
5. Impact on non-target species is a function of susceptibility, dose and exposure duration. Studies over the past 20+ years have found very little direct impact on non-target animals and variable but rarely lasting impact on non-target plants. A substantial analysis for low dose fluridone treatments revealed no significant loss of species and almost universal recovery of the native assemblage from any impacts within two years, the time period allowed under the WPA. Evaluations of other herbicides suggest some impact to non-target plants but rarely extensive or lasting effects when not intended.
6. Species protected under MESA are usually rare and detecting impacts can be challenging without monitoring protocols generally unnecessary for more common species. Lack of data for actual impact tends to result in denial of permits where the herbicide could impact a protected species or in permit conditions that limit effectiveness of the action on the intended target species or increase cost. The statutory need to protect listed species may support such restrictions, butthe inability to achieve balance in decisions relating to protected and nuisance species remains an impediment to aquatic plant management in MA and can only be overcome by research not currently supported by the government.
7. The primary impact issue where there are no MESA listed species is change in habitat. Any change in the assemblage from an herbicide treatment will benefit some species and not others. The difficulty of documenting no loss of habitat for any species creates complications, but overall habitat value for the complete suite of species in a lake can be improved with well planned herbicide use.

8. The MA DEP has determined that an invasive species cannot be considered to have habitat value. Removing invasive species is therefore not detrimental to habitat by definition and the permit application process recognizes this by creating a limited project status for such ecological restoration projects.
9. Projects involving <10% of the plant growth zone have minimal probability of impacting structural habitat or water quality. As the plant growth zone covers the shallowest part of any lake, the portion of lake volume involved in a treatment will be even less than the percent area. Treating as much as 25% of the plant growth zone may have no measurable impact on the interests of the WPA and even whole lake treatments may have minimal impact when they are selective, especially for an invasive species.
10. Conservation commissions must weigh the evidence provided by any group involved in the permit process and should not simply accept unsubstantiated claims. Lack of data for the targeted resource or insufficient support for statements (not based on data or documented experience elsewhere) are grounds for disregarding claims. This extends to project proponents, project opposition groups, and state agencies or other quasi-governmental organizations with a stake in the outcome. Let the data do the talking.
11. Project proponents and regulatory bodies need to understand the difference between prevention, restoration, rehabilitation, and maintenance and how these interact with the general regulatory mandate to protect designated environmental attributes. Prevention is highly desirable but not well supported by the current management and regulatory systems, particularly as relates to rapid response to new infestations. It is rare that we actually restore a lake or any other habitat. Lakes are usually rehabilitated for some desired use and maintained to continue to support that use. The desire to have a plant control action taken once and expect that no follow up will be necessary is unreasonable.
12. The exact combination of herbicides and other techniques to manage aquatic plants will vary with target species, non-target species, target area, lake features, regulatory constraints, and affordability and can be unique for each lake. There is no "one size fits all solution" and applicants and conservation commissions need to consider the details of each case.
13. Conservation commissions should consider how herbicide application affects all lake functions and uses during the permitting process. There will be conflicts, as not all uses are compatible, and priorities are needed but not specified under law in MA. This leaves conservation commissions as arbiters of lake management disputes and it is therefore incumbent upon all involved parties to provide appropriate input without misleading or misrepresenting; data and relevant peer-reviewed studies should prevail over opinion and unsubstantiated claims.
14. Where native species cause nuisance conditions there is no option for limited project status under the current WPA regulations. Excessive vegetation may indeed cause ecological problems and applicable performance standards can be met in most cases, especially since the regulations allow for two growing seasons of recovery. The issue is more complex than the existing regulations recognize, however, leaving conservation commissions with limited information and guidance. Projects should seek balance between habitat types offered by the lake and consider all uses, human and non-human.
15. The fundamental problem with our current laws and corresponding regulations as pertains to invasive and nuisance species is that they are set up to protect desirable features but not to solve environmental problems. As such, there is guidance on avoiding problems but not enough for how to fix problems when they occur. Laws forbid import of species and damage to existing resources but do not mandate rehabilitation when damage occurs. Conservation commissions

should recognize that project proponents are fulfilling what should more properly be a government role in managing public lakes.

16. Over half the lake area and two thirds of lake volume in MA were created by human action. The plant growth zone in many lakes is subject to natural processes and to the laws of MA intended to protect natural aquatic environments but is not truly “natural”. It is like a building that serves a public need, but which requires maintenance over time to remain useful. The value of these lakes is recognized but the existing environmental laws control their management such that value is lost if there is not cooperation among stakeholders and regulators. Doing nothing is not a protective action. What is needed is reason and logic on the part of both applicants and conservation commissions.
17. The WPA allows for recreational access, boating lanes, and overall balance between habitat types in lakes. Plant control plans should reflect cognizance of the range of wetland functions provided by the lake and a sensitivity to all users, human or otherwise. Herbicides approved for use in MA, applied by licensed applicators who understand the goals of the program, have a useful role in such programs. By virtue of being approved for use in MA, the government is saying that the benefits of proper use of an herbicide outweigh the risks that may exist. Any debate over proper use needs to be grounded in science, not biased opinion or unsubstantiated claims. The frequency of use is a point of discussion but is not clear grounds for rejection if the commission simply dislikes herbicides or wants a one-time solution that rarely exists.
18. It is reasonable to expect applicants to provide a complete program to extend for at least the life of the permit, possibly including non-chemical follow up actions to prolong the benefits of herbicide use where appropriate. It is not reasonable for commissions to tack on conditions unrelated to plant control, such as overall watershed management planning that has no bearing on an in-lake plant problem. While a conservation commission is under no obligation under the law to become a partner in the management of a lake, as part of the community in which the lake exists, it should be incumbent on commissions and applicants to cooperate to determine the best approach to reaching reasonable management goals, and a clear statement of those goals should guide the planning and permitting processes.

4.6.21 New References

Bonvechio KI, Bonvechio TF. 2006. Relationship between Habitat and Sport Fish Populations over a 20-Year Period at West Lake Tohopekaliga, Florida. North American Journal of Fisheries Management 26:124-133.

Baker, J.P., H. Olem, C.S. Creager, M.D. Marcus, and B.R. Parkhurst. 1993. Fish and Fisheries Management in Lakes and Reservoirs. EPA 841-R-93-002. Terrene Inst./USEPA, Washington, DC.

Boyle K, Bouchard R, 2003. Water Quality Effects on Property Prices in Northern New England. LakeLine Vol 23 (3):24-27.

Cooke GD, Welch EB, Peteron SA, Nichols SA. 2005. Restoration and Management of Lakes and Reservoirs, 3rd Edition. Taylor and Francis, Boca Raton, FL.

Gettys LA, Haller WT, Petty DG. 2014. Biology and Control of Aquatic Plants. Aquatic Ecosystem Restoration Foundation, Marietta, GA.

Glomski LM, Netherland MD, Nelson LS. 2009. Potential impact of submersed 2,4-D and triclopyr applications on native emergent plants. APCRP Technical Notes Collection. ERDC/TN APCRP-CC-10. Vicksburg, MS: U.S. Army Engineer Research and Development.

Gobler, C.J. (Editor). 2020. Climate change and harmful algal blooms: Themed issue of Harmful Algae. Vol 91.

Hanley N, Roberts M. 2019. The economic benefits of invasive species management. People and Nature 1:124-137.

Hoyer MV, Schwartz MK, Horsburgh CA. 2019. Empirical analysis of water quality, long-term fish, and aquatic plant population data in relation to aquatic plant management actions. Aquatics 41 (3):16-27.

Jones AR, Johnson JA, Newman RA. 2012. Effects of repeated, early season, herbicide treatments of curlyleaf pondweed on native macrophyte assemblages in Minnesota lakes. Lake Reserv Manage. 28:364-374.

Koschnick TJ, Haller WT, Netherland MD. 2006. Aquatic plant resistance to herbicides. Aquatics 28:4-6.

LaRue EA, Zuellig MP, Netherland MD, Heilman MA, Thum RA. 2013. Hybrid watermilfoil lineages are more invasive and less sensitive to a commonly used herbicide than their exotic parent (Eurasian watermilfoil). Evol Appl. 6:462–471.

Les DH, Murray NM, Tippery NP. 2009. Systematics of Two Imperiled Pondweeds (Potamogeton vaseyi, P. gemmiparus) and Taxonomic Ramifications for Subsection Pusilli (Potamogetonaceae). Systematic Botany 34:643–651

Lovell SJ, Stone SF, Fernandez L. 2006. The economic impacts of aquatic invasive species: A review of the literature. Agricultural and Resource Economics Review 35:195-208.

Maceina MJ, Marshall MD, Sammons SM. 2008. Impacts of Endothall Applications on Largemouth Bass Spawning Behavior and Reproductive Success. North American Journal of Fisheries Management 28:1812-1817.

Nault ME, Barton M, Hauxwell J, Heath E, Hoyman T, Mikulyuk A, Netherland MD, Provost S, Skogerboe J, Van Egeren S. 2017. Evaluation of large-scale low-concentration 2,4-D treatments for Eurasian and hybrid watermilfoil control across multiple Wisconsin lakes. Lake Reserv Manage. 34:115-129.

Netherland M, Heilman M, Willis B, Beets J. 2016. Efficacy and Selectivity Studies for a New Aquatic Herbicide - PROCELLACOR™

https://bugwoodcloud.org/mura/mipn/assets/File/UMISC-2016/Wednesday/1/Netherland_etal_Efficacy%26SelectivityStudiesforProcellacorHerbicide.pdf

Pothoven SA, Vondracek B, Pereira D. 1999. Effects of Vegetation Removal on Bluegill and Largemouth Bass in Two Minnesota Lakes. North American Journal of Fisheries Management 19:748-757.

Rosaen AL, Grover EA, Spencer CW. 2016. The costs of aquatic invasive species to Great Lakes states. Anderson Economic Group, East Lansing, MI

Scheffer M, van Nes E. 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. Hydrobiologia 584:455–466.

Wagner KI, Hauxwell J, Rasmussen PW, Koshere F, Toshner P, Aron K, Helsel DR, Toshner S, Provost S, Gansberg M, Masterson J, Warwick S. 2007. Whole-lake Herbicide Treatments for Eurasian Watermilfoil in Four Wisconsin Lakes: Effects on Vegetation and Water Clarity. Lake Reserv Manage. 23:83-94.

Wagner KJ. 2004. The Practical Guide to Lake Management in Massachusetts. Executive Office of Environmental Affairs, Boston, MA.