The Practical Guide to Lake Management in Massachusetts

A Companion to the Final Generic Environmental Impact Report on Eutrophication and Aquatic Plant Management in Massachusetts

Commonwealth of Massachusetts
Executive Office of Environmental Affairs

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Prepared for the

Department of Environmental Protection
and
Department of Conservation and Recreation

Executive Office of Environmental Affairs,
Commonwealth of Massachusetts

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INTRODUCTION: ABOUT THIS MANUAL

This manual has been prepared as a companion guide to the Final Generic Environmental Impact Report (GEIR) on Eutrophication and Aquatic Plant Management in Massachusetts (Mattson et al. 2004). The GEIR is a larger document with more information, intended to satisfy the requirements for such a document under the Massachusetts Environmental Policy Act. This companion guide was developed to provide key information in a more concise and user-friendly format for Conservation Commissions, lake groups, and interested citizens. As this guide was developed from the GEIR, the efforts of all those involved in the preparation of the GEIR are acknowledged, especially Drs. Mark Mattson and Paul Godfrey, the primary authors of the original version of the GEIR, from which much of the information in this manual is taken.

The focus of this guide is on key aspects of each potential lake and watershed management technique that might be considered for the control of eutrophication and aquatic plants. It is intended to provide the reader with a general overview and enough information to evaluate whether or not a given technique is appropriate to the situation. It also indicates issues for each technique that must be considered in a more thorough feasibility assessment. For those involved with managing a lake, this manual provides information essential to understanding options and narrowing the choices, but is not always a substitute for competent advice from lake management experts. For Conservation Commissions, this guide highlights the salient issues that must be addressed if a management technique is to be applied properly under the Wetlands Protection Act and associated statutes. However, it cannot anticipate and address all possible situations that may arise or every factor that may go into a decision.

Lake and watershed management is a complex process that is interdisciplinary by nature and involves so many facets that it is difficult to know where to start in many cases. Compromises are almost always made between study and action, protection and conservation, restoration and maintenance, and expense and expedience. With limited time, funding and information, such compromises may indeed be necessary, although the regulatory framework within which management actions are permitted has minimum standards that set limits on management without appropriate justification. Iterative steps in the management of watersheds and lakes is often encouraged; small steps that move in the perceived correct direction cost less and have less potential to damage non-target organisms or features. However, some techniques are not effective unless applied at a larger scale, and ultimately the cost of management may be quite high. This guide cannot provide the solution to all potential problems or the answer to all possible questions, but it does provide a substantial amount of information intended to start interested groups in the right direction.

The organization of this manual is simple. Following this introduction is a section on lake and watershed features and processes, which is considered essential information for understanding management techniques and associated issues. Then there is a brief section on developing a lake and watershed management plan, distilled from the more lengthy discussion in the GEIR. The remainder of the manual is a compendium of management techniques aimed at controlling the input of nutrients or the accumulation of vascular plant and algal biomass. For each technique there are concise sections on how it works, what benefits it can provide, significant shortcomings or potentially undesirable impacts, factors that favor its use, information necessary to proper application, implementation guidance, permits that may be needed, and approximate costs. The information in this manual is abridged from the GEIR, and readers are encouraged to review relevant sections of the GEIR to gain additional insight on techniques of interest. Readers may also want to consult the references provided in this guide and in the more extensive ones in the GEIR, and should consider consulting relevant websites for updates and additional information. Two especially relevant websites are those of DEP's Watershed Management Program (www.state.ma.us/dep/brp/wm/wmpubs.htm) and DAR's Pesticides Program (www.state.ma.us/dfa/pesticides/water/aquatic/herbicides.htm).

ESSENTIAL BACKGROUND INFORMATION

The Origin and Nature of Lakes

The lakes in Massachusetts were created in two principal ways: by glacial activity approximately 12,000 years ago or by damming streams or small lake outlets, most of latter occurring during the early industrial age of the country for water power. In many respects, lakes are like people. They are born, grow older and die, with many possible conditions along the way. Through natural processes, lakes will become shallower and more eutrophic (nutrient-rich) and eventually fill in with sediment until they become wet meadows. The aging process is not identical for all lakes, however. Some lakes age quickly, others very slowly, and not all start out in the same condition. Many lakes that were formed by the glaciers no longer exist while others have changed little in 12,000 years. The rate of aging is determined by many factors including the depth of the lake, the nutrient richness of the surrounding watershed, the size of the watershed relative to the size of the lake, erosion rates, and human induced inputs of nutrients and other contaminants. Lakes are therefore highly variable in specific features, and goals for the management of each may vary as well.

Existing lakes can be subdivided into categories depending on their position along a continuum of fertility. Nutrient-poor lakes are termed oligotrophic, nutrient-rich lakes are eutrophic, and those in between are mesotrophic. Variations on this system are possible, and any system to boil the complexity of a lake into a single word will not be completely adequate to describe lakes. Lakes in one part of the Commonwealth may share many characteristics (depth, hydrology, fertility of surrounding soils) that cause them to be generally similar. Massachusetts can be divided into regions based on typical phosphorus levels in lakes (Figure 1).

Lakes that are created by damming streams may at first be eutrophic as nutrients in the previous stream's floodplain are released into the water column. Over a period of decades, the initial productivity tends to change until the impoundment takes on conditions governed more by the entire watershed, with depth and detention time as critical determinants of response to watershed inputs. Impoundments may never completely escape the legacy of their creation. They are commonly shallow and the pre-existing nutrient-rich bottom sediments may provide nutrients for abundant aquatic plant growth early in the life of the lake.

Human activity can unduly accelerate the process of lake aging or, in the case of introduced species or pollutants, force an unnatural response. Unnatural responses include the elimination of aquatic species as a result of acid deposition, algal blooms resulting from excessive nutrient enrichment, and the development of a dense monoculture of a non-native aquatic plant. However, it would be unrealistic to assume that managing cultural impacts on lakes can convert them all into infertile basins of clear water. Understanding the causes of individual lake characteristics (i.e., understanding the lake ecosystem) is a fundamental part of determining appropriate management strategies.

An ecosystem is a system of interrelated organisms and their physical-chemical environment. We need an operational unit that can be reasonably studied and will help explain all or most of the characteristics of the lake. The most useful definition of the lake ecosystem is the lake and its watershed because the watershed defines the terrestrial sources of the lake's water (Figure 2). Most impacts on lakes can be related to characteristics of the watershed, although acid rain, mercury deposition and drought have demonstrated that not everything important to lakes occurs within the watershed. A lake is a web of interactions between hundreds of biological species, chemical compounds, hydrological processes and human actions, all in constant change. A tug on any part of the web ripples throughout the rest of the ecosystem. Ecology is the scientific study of these relationships and limnology is the study of freshwater ecology. Lake management involves the application of ecological principles and data to establish and maintain desirable conditions.

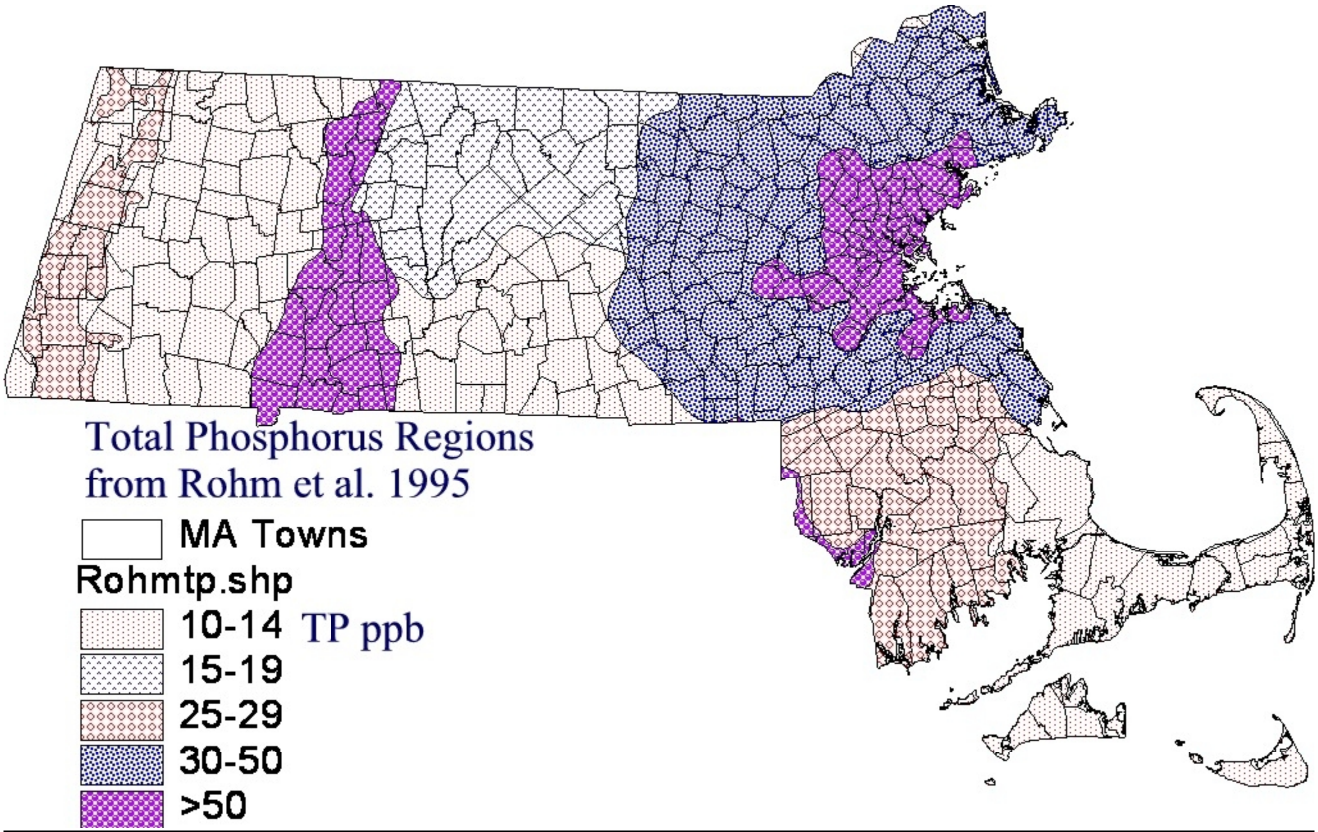


Figure 1. Regions of Massachusetts Based on Phosphorus Levels in Lakes (after Rohm et al. 1995)

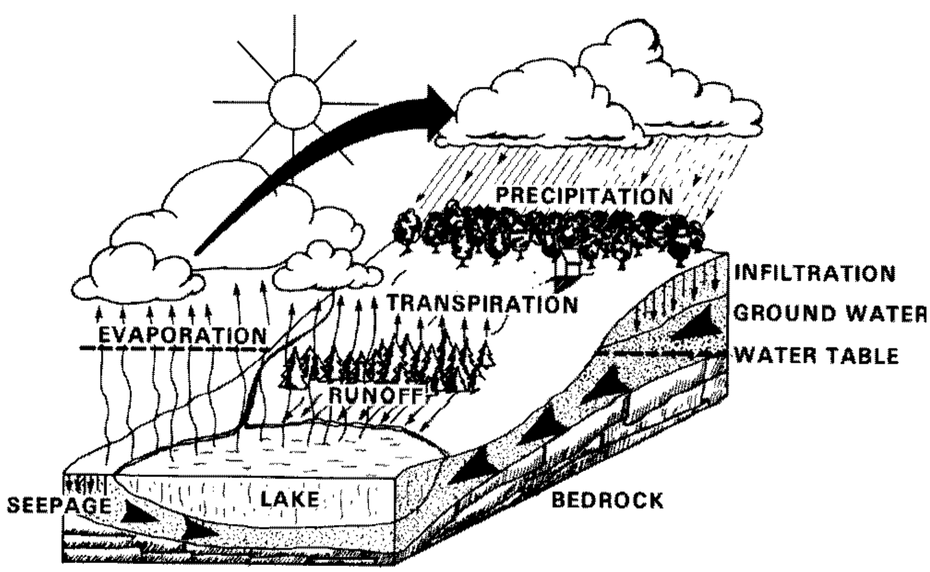


Figure 2. The Hydrologic Cycle (Olem and Flock, 1990)

Key Features of Lakes

Water

Water is very abundant both on earth and in all living organisms. Water has properties that make life in lakes possible, particularly lakes in the northern parts of the world. Unlike most other compounds, water does not become increasingly denser as it becomes colder. Instead, water increases in density as it is cooled until it reaches 4^oC (39^oF). Upon further cooling to 0^oC (32^oF), it becomes lighter and floats on the surface until it has cooled sufficiently to freeze. If this were not true, lakes would freeze solid in our winters. Water also has a high specific heat and high latent heat of fusion; thus they are slow to thaw in spring and slow to cool in winter, thereby providing an extremely stable thermal environment for aquatic life. Water also vaporizes at temperatures common to our climate, producing water vapor and continuing the hydrological cycle of precipitation, runoff and infiltration, evaporation and transpiration. Water is one of the best solvents available and many compounds dissolve in it. These properties help to explain much of what we observe in lakes.

Hydraulic Residence

The average time required to completely renew a lake's water volume (lake volume divided by outflow rate) is called the hydraulic residence time or flushing rate. Hydraulic residence time is a function of the volume of water entering or leaving the lake relative to the volume of the lake (i.e., the water budget). The larger the lake volume and the smaller the inputs or outputs, the longer will be the residence time. Lake residence time may vary from a few hours or days to many years. Lake Superior, for example, has a residence time of 184 years. However, Massachusetts lakes typically have residence times of days to months. Our largest lake, Quabbin Reservoir, has a residence time of approximately three years. Mill Pond in West Newbury, MA with an area of 16 acres and mean depth of 4.1 feet has a residence time of 14 days, while Lake Massasoit (aka Watershops Pond, an impoundment of the Mill River) in Springfield has an average residence time of about a week. The flushing rate of a lake will determine how it responds to many inputs.

Mixing

The thermal structure of lakes also helps determine productivity and nutrient cycling. Lake thermal structure is determined by several factors. Lakes receive the vast majority of their heat at the surface from solar heating. Since warmer water floats, the water column must have an energy input to mix that heat deeper and in most lakes wind provides that energy. A lake that is completely protected from the wind will have a very warm but shallow layer at the surface with cold water below. A lake exposed to strong winds will have a cooler but thicker upper layer overlying the colder water. For many shallow Massachusetts lakes, the mixed layer may extend to the lake bottom. Deeper lakes may form a three-layered structure that throughout the summer consists of an upper warm layer (the epilimnion), a middle transition layer (the metalimnion, within which the point of greatest vertical change is called the thermocline), and a colder bottom layer (the hypolimnion).

A lake's thermal structure is not constant throughout the year. Beginning at ice out in early spring, all the lake's water, top to bottom, is close to the same temperature; the density difference is slight and water is easily mixed by spring winds. With warmer days, the difference between the surface and bottom waters increases until stratification occurs if lake depth is sufficient (Figure 3). Eventually, solar heating declines and the upper layer begins to cool and sink. Eventually in the fall, the lake has a similar temperature top to bottom. In winter, ice forms at the surface and a new, inverse stratification (cold over cool water) is created and persists until spring. The degree of stratification is important to the cycling of nutrients, variability in oxygen in deeper waters, movement of incoming water through the lake, and types of aquatic organisms that live in the lake (Figure 3).

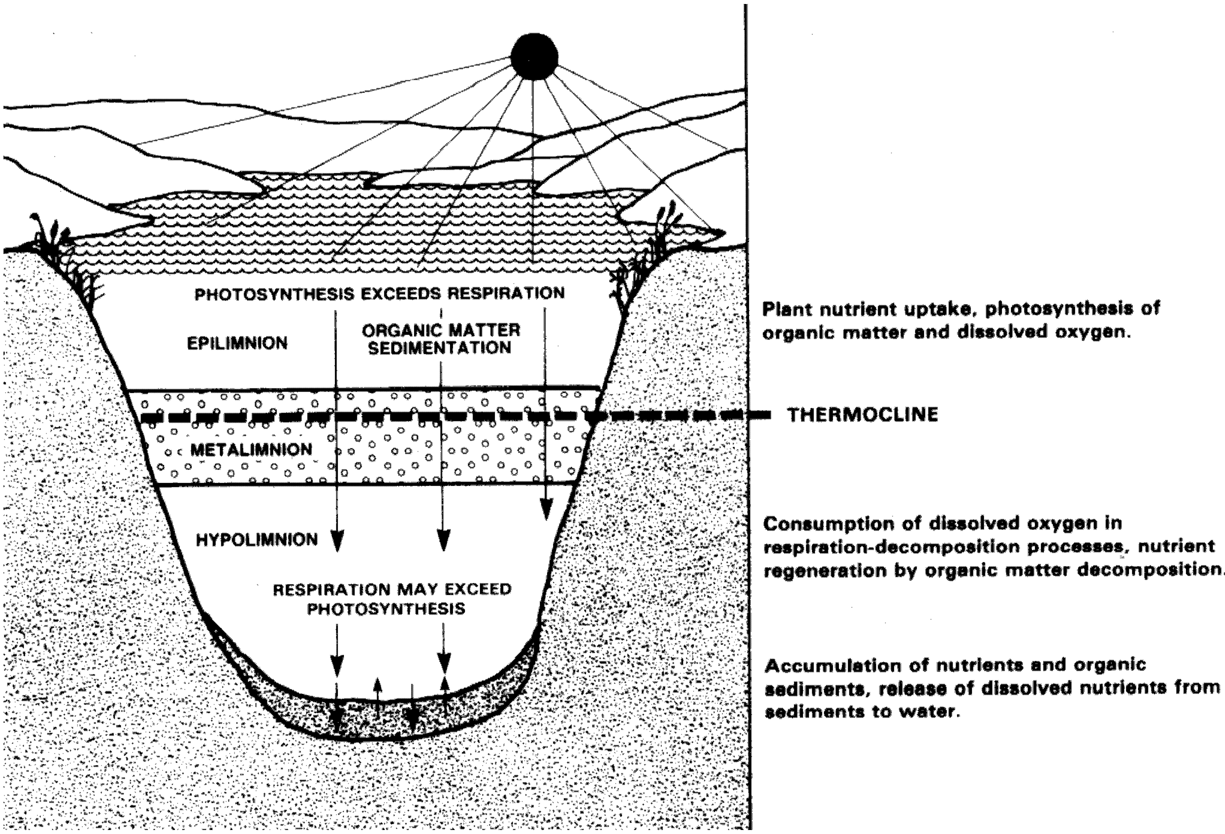


Figure 3. Influences of Photosynthesis and Respiration/Decomposition Processes on Oxygen and Nutrients in a Stratified Lake (after Olem and Flock, 1990)

Nutrients

Lakes may suffer from many impacts of human cultural development. Of primary concern for this review are nutrients. All plants need an appropriate balance of the essential major nutrients, particularly phosphorus, nitrogen, and carbon. They also need light. Assuming that light is readily available, plants take up nutrients in the proportion that their cells require. The nutrient that is in shortest supply relative to the plant's needs will limit the growth of the plants. This is called the limiting nutrient concept. The ratios of plant needs to the concentration of nutrients in water suggest that phosphorus is the scarcest nutrient relative to plant demand for most freshwater systems. Some freshwater and most estuarine systems have nitrogen as the limiting nutrient, and trace elements can sometimes be limiting, but phosphorus is the logical target of management to control algae in lakes. Phosphorus is easier to control than many other nutrients, particularly carbon and nitrogen. The latter two have gaseous phases, so the atmosphere becomes a major source where both are quite abundant.

Lake managers typically compartmentalize all forms of phosphorus into three categories: dissolved, particulate and their sum, total phosphorus. Dissolved phosphorus is readily available for uptake by plants and, consequently, is usually found only in low concentrations during the growing season. At that time, most of the phosphorus will either be adsorbed to particles such as fine soil or clay or in living or dead plant or animal cells. However, the death and decay of an organism will begin the process of releasing the phosphorus in dissolved form where it can almost instantly be taken up by other organisms.

A map of typical total phosphorus levels for Massachusetts lakes provides a general expectation of phosphorus concentration for any lake under study (Figure 1). While this does not provide a quantitative breakdown of nutrient sources that can help pinpoint likely areas for nutrient control, it can provide a sense of the typical conditions for the region and suggest reasonable goals for nutrient management. A lake with much higher phosphorus levels than typical for that region may be a strong candidate for successful improvement by reducing cultural sources of phosphorus. Keeping phosphorus concentrations below the expected level for the corresponding area may require frequent management action.

Development of a nutrient budget (loading analysis) provides insight into the causes of lake eutrophication. Nutrient budgets depend on the determination of the amounts of a nutrient that are provided by sources such as natural surface runoff, non-point source pollution, leaking septic systems, atmospheric deposition, groundwater and wildlife. Nutrient budgets also determine the quantity of nutrients lost to the lake system by outflow and by deposition to the sediments. Quantifying nutrient loading requires assessment of the water budget and determination of the concentration of the nutrient in each source of water. Thus the quantity of nutrient provided by a tributary is the concentration times the volume of water per unit time (the flow). This is called the "load" for the nutrient and source being quantified. Just like a bank account, the input loads (deposits) minus the output mass (withdrawals) should equal the total change in the mass of nutrient in the lake. Knowing the relative inputs and costs of reducing them aids the development of a workable lake management strategy for controlling water quality and therefore preventing algal blooms. Nutrient budgets are less useful in the control of rooted aquatic plants.

Internal loading refers to nutrients recycled from the sediments. Internal loading may be a large source of phosphorus to the lake in certain circumstances. When lake sediments become anoxic (lacking available oxygen) as they would in a stratified eutrophic lake, phosphorus that is normally adsorbed to iron oxides under oxygenated conditions is released in dissolved form. This hypolimnetic phosphorus may be returned to upper water layers during turnover or even during stratification under unusual circumstances. Also, resuspended sediment (caused by wind or motorized watercraft) may release phosphorus back into the water column. Additional phosphorus may be "pumped" from shallow water sediments by aquatic macrophytes with roots in the sediment, particularly when the plants die at the end of the growing season. As might be expected, such internal phosphorus loading is often hard to estimate. The timing of this internal loading may make it more important than its magnitude suggests; internal cycling of nutrients may not be important in a yearly budget, but may be very important during the summer stratification period, which is also the growing season.

Nutrient budgets are commonly determined in two primary ways: by direct measurement or by estimation from various empirical relationships determined in past studies. Accurate determination of a nutrient budget by direct measurement is monitoring-intensive, requiring nearly constant measurement of water flow and frequent measurement of nutrient concentration in all or most incoming and outgoing components. One rainstorm may provide a large percentage of the nutrient input; if unmeasured or not measured with sufficient frequency at sufficient sites, the budget will be grossly in error. Groundwater samples may be difficult and/or expensive to collect. Flow rates are hard to determine precisely without expensive automated equipment, especially during storm events.

It is rarely possible to achieve or afford this level of monitoring. Consequently, nutrient budgets are often determined by loading estimates based on land uses and by models established from large databases. Detailed research on many watersheds has provided important loading factors or export coefficients to be expected from various types of land use, numbers of residents, sediment storage and other more easily measured factors. The quality of the nutrient budget will depend on the similarity between the study watershed and the calibrated watersheds in the literature. No method is likely to produce a very accurate estimate of the nutrient budget if monitoring frequency is low or if the watersheds are only moderately comparable. However, the credibility of the estimate can be substantially increased if multiple methods are used and produce roughly comparable results. Agreement among multiple models, especially when calibrated for the study watershed with some real data specific to that system, can increase confidence in budget estimates. Key parts of a nutrient budget are shown in Figure 4. Generation of nutrient budgets is essential to many algal control efforts, but is less applicable to rooted plant control.

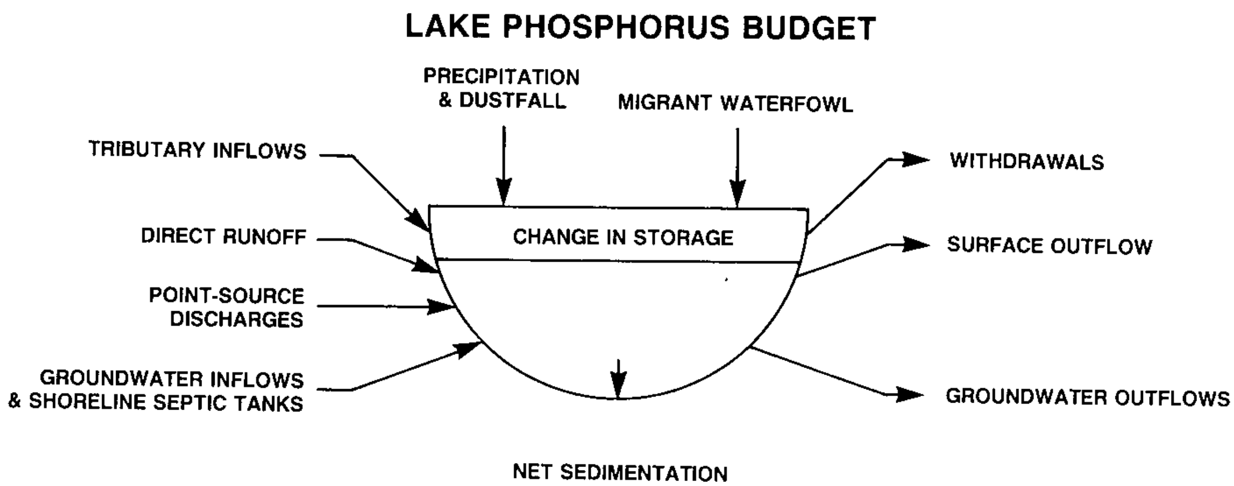


Figure 4. Elements of a Phosphorus Budget (after Olem and Flock, 1990)

Particulates

Particulates may be either inorganic or organic, but lake managers typically define them as any object larger than 0.45 thousandths of a millimeter (0.45 micrometers). Larger particles will not stay suspended in water for long, but smaller particles may settle very slowly or not at all. Colloids are fine particles with almost the same density as water that remain suspended. Larger or heavier particles such as algae, bacteria, aquatic animals and silt will eventually settle to the bottom, although some of these may actively swim or possess flotation devices to counter the effects of gravity. These living particulates are addressed separately below.

Inorganic particles are relevant to aquatic plants and algae because they can contribute nutrients that have been adsorbed on the particles. In addition, they can accelerate the process of filling the lake to the point where a shallow, soft and nutrient-rich bottom is widely available for rooted aquatic plant growth. Most inorganic particulates will have originated from terrestrial sources, although wave action and human activity can stir up lake bottom sediments and redeposit them. Organic particles, sometimes referred to as detritus, are living or dead biota - plants, animals and bacteria. These eventually settle to the bottom where they decompose and release their nutrients.

Bacteria

Although never seen by most people, bacteria play a pivotal role in the life of lakes. They are the most abundant group of organisms in a lake and most of them are critical in converting any organic material to inorganic form. They may be free-floating in the water column, attached to a substrate or in the sediments. Many are aerobic, requiring oxygen for the conversion of organic material to inorganic forms and energy. Many others are anaerobic, using other chemical pathways to derive energy. One such group, the sulfate reducing bacteria, is instrumental in converting inorganic mercury to the highly toxic organic form, methyl mercury, as a byproduct of their growth. Some bacteria are photosynthetic (e.g., cyanobacteria, also called blue-green algae). Some bacteria create human health problems or have proven to be useful indicators of the likely presence of threats to human health. *Escherichia coli* is usually an innocuous bacterium found in our intestines, but its abundance in a lake indicates sewage, septic inputs or other fecal contaminants and the potential for the transfer of human bacterial and viral diseases.

Algae

Algae are mostly microscopic plants that may be free-floating (phytoplankton) or attached to a substrate (periphyton). They may be single-celled or have many cells. In a moderately rich lake, there could be nearly one hundred species of algae in a tablespoonful of lake water. In a eutrophic lake, there may be millions of cells in a gallon of water. Algae are divided into several major groups, principally based on the relative combination of photosynthetic pigments and characteristics of the cell wall, food storage form, and flagella, but each group has particular characteristics that often contribute to lake problems.

The blue-greens are evolutionary intermediates between heterotrophic bacteria and algae. They are considered to be bacteria (Cyanobacteria) with the photosynthetic pigment, chlorophyll. Blue-greens often form nuisance blooms, appearing like thick green paint on the lake's surface and causing taste and odor problems in drinking water. Many blue-greens, particularly certain troublesome species, have the ability to "fix" nitrogen. While other algae must obtain their nutrients from dissolved inorganic (nitrate, nitrite, and ammonia) or organic nitrogen in the water, these blue-greens can use atmospheric nitrogen that is dissolved in the water. A shortage of inorganic and organic nitrogen can give nitrogen-fixing blue-greens a competitive edge, and they use other characteristics (flotation) to maintain it. Many of them have a gelatinous sheath that makes them undesirable to microscopic grazers. Three genera of blue-greens are so commonly associated with problems in lakes that lake managers have given them nicknames: Annie for *Anabaena*, Fannie for *Aphanizomenon* and Mike for *Microcystis*.

Conversely, diatoms are rarely problems in recreational lakes and usually form an important part of the food chain. They construct silica shells of many shapes with intricate markings. A hundred years ago, it was quite the fad to view slides of different diatom shells in elaborate displays. Electron microscopy has made the view even more spectacular. Despite their glass shells, these algae are easily eaten by small aquatic animals called zooplankton. Common planktonic diatoms include *Asterionella*, *Fragilaria*, *Tabellaria, Aulacoseira* and *Cyclotella*. Other chrysophytes ("golden" algae) live in shells that look like wine glasses or spiny coats with whipping flagella to move them about. Some of these non-diatom chrysophytes can cause taste and odor problems in drinking water reservoirs, but are rarely a problem in recreational lakes.

Green algae (Chlorophyta) are an incredibly diverse group ranging from single-celled to complex multicellular organisms that may be on the main evolutionary line to vascular plants. They are important constituents in the food chain, but some species can cause blooms in eutrophic lakes. They generally prefer a higher ratio of nitrogen to phosphorus than blue-green algae.

The dinoflagellates (Pyrrophyta) tend to be less abundant than the above groups but are interesting because some of the dinoflagellates cause harmful algal blooms in marine environments. Freshwater forms are not known to be toxic, but are often associated with high organic content waters. Cryptomonads, a related group of flagellates, are capable of photosynthesis but may prey upon bacteria. Because all are motile, they can often dramatically change their position in the water column to take advantage of local conditions. Often, they are found at the top of the thermocline where sinking organic material is slowed by the denser water but light is still sufficient. Euglenoids are another mostly flagellated group that share pigment composition with the green algae, but make use of organic particles and dissolved compounds more like the dinoflagellates and cryptomonads. They can form surface scums that vary in color from green to red, and at high abundance are normally indicators of very poor water quality.

Most other algal groups are relatively rare in freshwater lakes and occur mainly in marine environments (i.e., red and brown algae). Each of the above groups has species with characteristics that may allow them to become very abundant and troublesome. Sometimes, knowing which species is in “bloom” can help understand the cause of the bloom. For example, certain blue-green algae often bloom when phosphorus is abundant and nitrate is low because they can fix nitrogen from dissolved air. They often prefer a period of calm water because they float and consequently shade out competing species. The concurrence of these conditions will usually result in blue-greens, but the absence of one element may shift the balance to another species or another algal group. The diatoms tend to prefer times of high mixing, cooler temperatures and higher silica availability - conditions found at spring and fall turnover. Many dinoflagellates seem to prefer conditions with above average organic material.

The dynamics of the thermal, light and nutrient regimes in lakes cause a fairly predictable pattern in the seasonal succession of algal species (Figure 5), but there may be surprises at any time. Typically, though, spring and fall turnover favor the diatoms which may become very abundant but usually do not cause severe impacts on human use, although some species cause taste and odor problems in drinking water reservoirs and can clog filters. After thermal stratification, green algae often become dominant for most of the summer when nitrogen is available, but they may be replaced by blue-green algae at higher temperatures, lower nitrogen concentrations, and high pH.

Because there are so many species of algae and identification requires considerable expertise, limnologists have developed surrogate measures of algal biomass. One of these is to measure the chlorophyll that all algae share, chlorophyll *a*. Chlorophyll *a* can be measured very accurately and quite easily. Unfortunately, the correspondence between the amount of chlorophyll and the actual biomass of algae is somewhat variable. Not all algal species have equal amounts of chlorophyll per unit volume and the amount of chlorophyll in each species varies with the nutritional health of the cells. Nevertheless, chlorophyll has become a reliable and useful measure for lake management. A second, less closely related measure of algal biomass is Secchi disk transparency. It involves lowering a black and white disk into the water and recording how far down it remains visible (Figure 6). Visibility has been reasonably well related to chlorophyll and forms a part of lake assessment that almost anyone can accomplish.

Aquatic Macrophytes

As opposed to algae that are usually microscopic plants, these are large aquatic plants, easily visible to the naked eye. In shallow lakes with soft bottoms, the vast majority of lakes in Massachusetts, these are often the most abundant plants. Algae and macrophytes often compete for light, so it is unusual to find both as problems in any particular lake, although it does happen. Macrophytes may be rooted or free-floating, although most are rooted (Figure 7). They may also be submergent, emergent, or floating-leaved. There are many taxonomic groups but the above categories are often the most useful for understanding the causes of a macrophyte problem and determining an appropriate management strategy. In fact, within each category, many species may look very similar as their growth habit responds to common lake conditions. However, even though many macrophyte species appear similar, their propensity to cause problems in lakes varies (Table 1). Effective management of macrophytes usually requires species identification. For example, a drawdown may reduce densities of fanwort (*Cabomba caroliniana*) but may increase densities of naiad (*Najas flexilis*) based on their overwintering strategies (vegetative vs seeds).

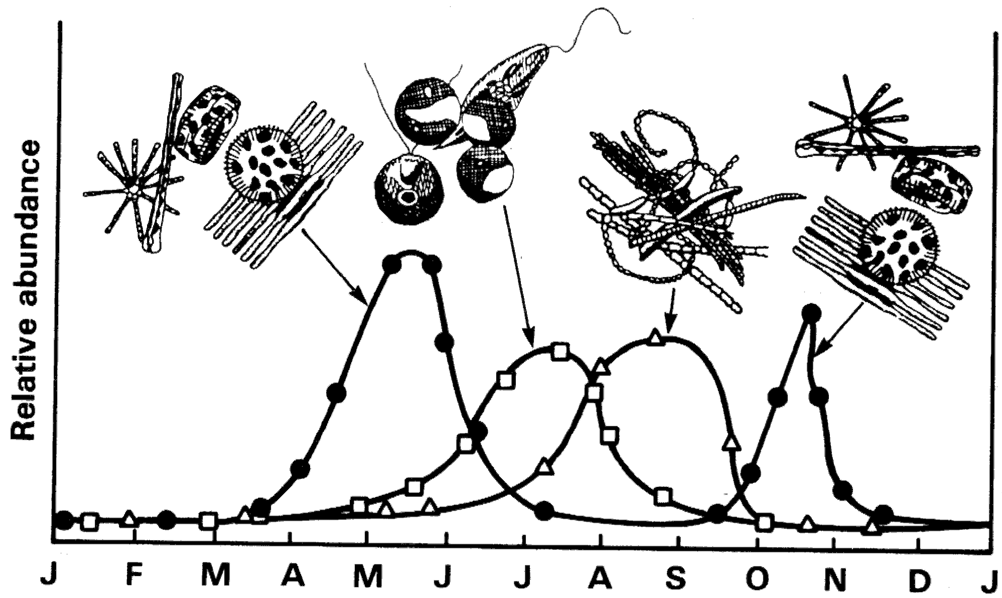


Figure 5. Seasonal Succession of Phytoplankton (Olem and Flock, 1990)
Diatoms tend to dominate in spring and fall, with greens and blue-greens dominant during summer, but many variations are possible.

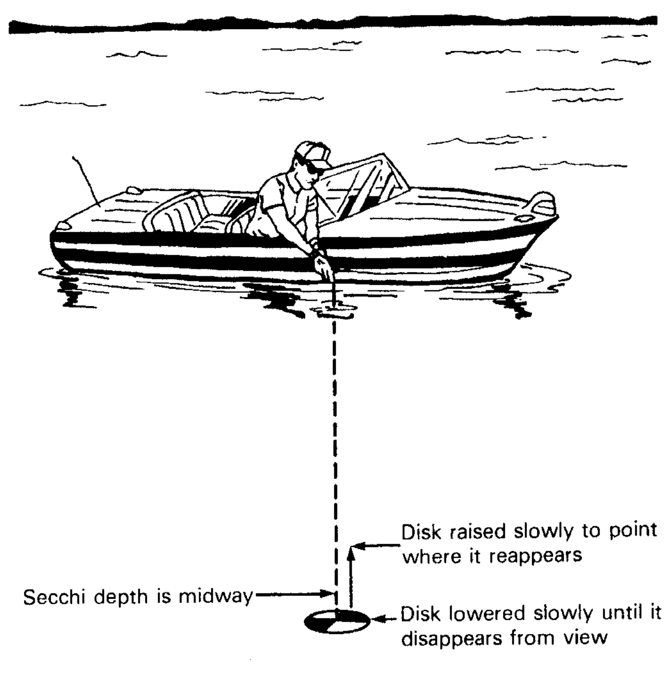


Figure 6. Measurement of Secchi disk Transparency (Olem and Flock, 1990)

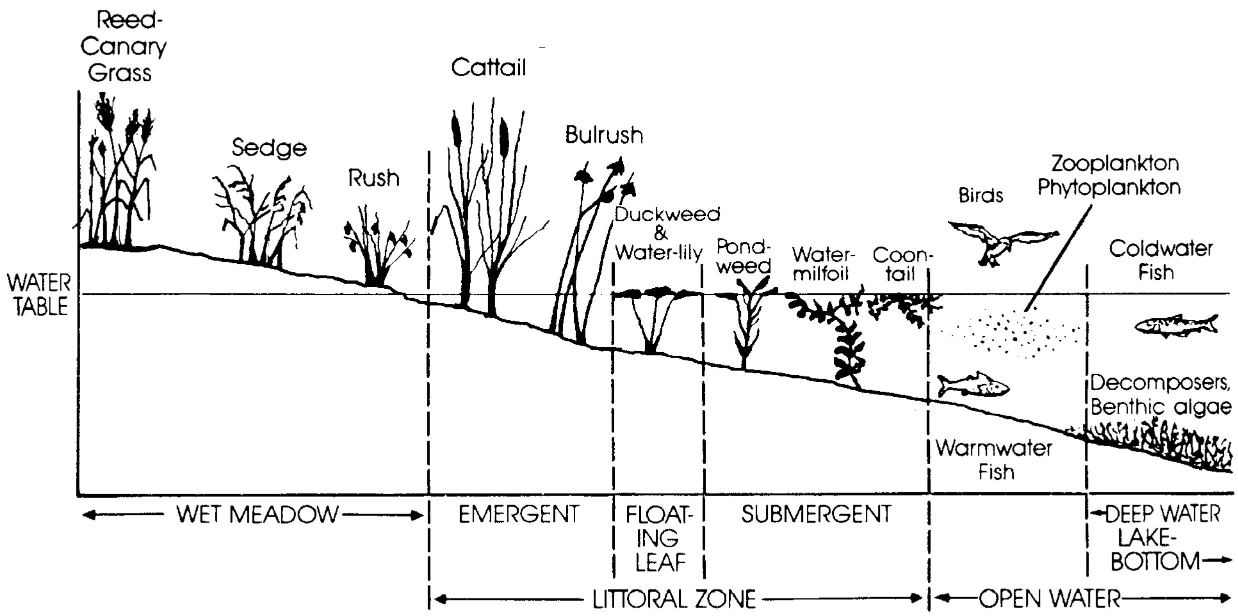


Figure 7. Typical Aquatic Plant Zones in Lakes and Ponds (From Kishbaugh et al., 1990)

Table 1. Introduced Species Known to Create Nuisance Conditions in Massachusetts

Scientific Name	Common Name
Cabomba caroliniana	Fanwort
Egeria densa	Brazilian elodea
Hydrilla verticillata	Hydrilla
Lythrum salicaria	Purple loosestrife
Marsilea quadrifolia	Pepperwort
Myriophyllum aquaticum	Parrotfeather
Myriophyllum heterophyllum	Variable watermilfoil
Myriophyllum spicatum	Eurasian watermilfoil
Najas minor	Spiny naiad
Nelumbo sp.	Lotus
Nymphoides peltatum	Little floating heart
Phragmites sp.	Reed grass
Trapa natans	Water chestnut

Rooted aquatic plants typically grow from a root system embedded in the bottom sediment. Unlike algae, they derive most of their nutrients from the sediments just like terrestrial plants, but they may be able to absorb nutrients from the water column as well. Because they need light to grow, they cannot exist where the lake bottom is not exposed to sufficient light. The part of a lake where light reaches the bottom is called the photic zone. For many plants, nutrients in the sediments may be in excess and growth is limited by light, particularly during early growth when the plant is small and close to the bottom. Emergent plants solve the light problem by growing out of the water, but that limits them to fairly shallow depths. Free-floating plants also are not limited by light, except in cases of self-shading when growths are dense, but cannot use the sediments as a source of nutrients. Finally, floating-leaf plants have attempted to achieve the best of all worlds by having their roots in the sediment and leaves at the surface, but they still have depth limits.

Introduced Plant Species

A subset of aquatic macrophytes, these plants tend to have high nuisance potential. As a gateway for settlement of the country and as part of the modern trans-world travel network, Massachusetts is highly susceptible to introductions of non-native species. Recently introduced species, unlike the natural biota and even the non-native biota introduced more than a hundred years ago, have few or no enemies, and are often invasive pests that can totally dominate and eliminate native populations. They are easily introduced in a variety of unwitting ways, most notably through the aquarium and horticulture trades, with dispersal among lakes by boats. Waterfowl are also important vectors. In many situations where a non-native species has been introduced, a near monoculture of that species develops, reducing recreational utility and habitat value.

Introduced non-native species can displace a healthy and desirable aquatic community and produce economically and recreationally severe impacts even though no other change has occurred in the watershed. The introduction of a non-native and undesirable species can result from the actions of a single person who does not realize the eventual impact and may not be aware that he/she has introduced the non-native species.

Consider some examples. Introductions of Eurasian watermilfoil (*Myriophyllum spicatum*) in Lake Champlain (Vermont/New York), Lake George (New York), Okanagan Lake (British Columbia) and many lakes in Massachusetts and other states threaten otherwise healthy lakes. Within just a few years, a small patch of the introduced species can grow to fill the lake, top to bottom, within the photic zone. Another nuisance species, fanwort (*Cabomba caroliniana),* is a popular aquarium plant and may have been introduced from freshwater aquariums. Purple loosestrife, a beautiful non-native wetland plant, completely crowds out native species and creates stands so dense that wildlife habitat is degraded. It was introduced by horticulturists and gardeners. There are many non-native species of concern, not all as invasive as these examples. In most cases, they demand special attention. While an overabundance of native species and diminution of desired uses can be managed over time, introduced species generally require quick action if eradication is to be achieved. The environmental cost of delay is usually higher than the risk of immediate use of most control options. The quicker the response, the smaller the degree of intervention needed to protect the environment. It may be difficult to impossible to actually eradicate an invasive species, but the probability of achieving and maintaining control is maximized through early detection and rapid response.

The Massachusetts Department of Environmental Protection developed a database of non-native (i.e., introduced) aquatic plants based on surveys in 1993-94. The database does not represent a comprehensive listing of all lakes with non-native species, but is considered representative of conditions at the time. Of the 320 lakes surveyed, 64% had non-native species. The most commonly observed non-native species in these surveys were *Myriophyllum* (milfoil), *Cabomba* (fanwort) and *Lythrum* (loosestrife).

No non-native species were found in 115 of the surveyed lakes, although there is some debate as to how long a species must be present to be considered "native". Variable milfoil (*Myriophyllum heterophyllum)* is not native to Massachusetts or New England, but remains a potential nuisance species. Likewise, some species of *Phragmites* are considered native but may still be invasive. Some species not found in the 320 surveyed lakes are known from other Massachusetts lakes now, most notably *Hydrilla* in one Cape Cod lake and *Myriophyllum aquaticum* in another Cape Cod lake. All of the species listed in Table 1 have been found in Massachusetts as of 2002, and the frequency of most has increased since the 1994 listing. DCR staff updated the earlier DEP survey for most of these lakes through 2003 (see Appendix VI of the GEIR).

Native Plant Species

In general, a healthy native plant community is considered desirable for a lake. Where the sediment is suitable and light penetrates, rooted plants will grow. The question is not whether or not rooted plants will be present in most lakes, but rather what types and at what density. A diverse assemblage of species indigenous to the area will in most cases not constitute a nuisance to people, and will provide valuable habitat. Invasive species, often defined as non-native or introduced forms, have a tendency to dominate the plant community as a consequence of competitive superiority and/or low loss rates to herbivores (plant eaters). In theory, a native assemblage will be more balanced. However, some native species can become "invasive", expanding into areas either not previously colonized or at one time occupied by other native species. Such imbalances can lead to nuisance conditions, as with dense coverage by water lilies (*Nymphaea* or *Nuphar*) or watershield (*Brasenia*). Submergent growths of naiad (*Najas*) or coontail (*Ceratophyllum*) can become too dense, break free of the sediment, and become nuisances to boaters or swimmers. Native plant communities may therefore require management to remain in balance.

While the management of introduced species often focuses on eradication (which is itself a very difficult task), management of indigenous species with nuisance potential tends to favor control only to the extent necessary to restore balance. This may require ongoing maintenance, and it is generally true that rooted plant management is likely to require repetitive actions over a prolonged time period.

Aquatic Animals

Plants provide the habitat and food for many forms of animal life ranging from microscopic rotifers that filter tiny algae, to zooplankton that hunt larger algae, to insects, to fish and aquatic mammals that eat even larger plants or animals. A change in any part of this trophic web ripples throughout the system in subtle or even dramatic ways. As a very simplified example, consider the classic four level trophic system. Certain algal species may be preyed upon by zooplankton. Zooplankton are preyed upon by planktivorous fish species such as golden shiners (*Notemigonus crysoleucas*) that are then preyed upon by larger piscivorous species such as largemouth bass (*Micropterus salmoides*). Reducing the algal population by some other form of control may also reduce the zooplankton, the planktivorous fish and the piscivorous fish. Conversely, adding more piscivorous fish or increasing their ability to find their prey may reduce the planktivorous fish and reduce predation on zooplankton. The zooplankton can then increase in abundance and reduce algal biomass. Usually, the interrelationships are much more complicated, and it is generally difficult to predict the outcome. For example, increasing piscivorous fish may increase zooplankton predation on edible algae but give relatively inedible algae (e.g., blue-greens) an advantage. Loss of algae may promote macrophyte growth and provide shelter for planktivores, reducing piscivore impacts. Variability in biological response to management tends to be high.

Alterations, even temporary ones, may have serious effects on the biota. For example, one of the most critical periods in the life history of fish is during spawning. Some lake management practices may be relatively benign except when they coincide with the spawning period for fish that occur in the lake. Depending on the species, fish spawning generally occurs in spring or fall (Table 2). Care must be taken to evaluate possible impacts of the timing and magnitude of lake management actions.

Table 2. Spawning Conditions for Common Massachusetts Fish Species (after Everhart et al., 1975)

Species	Spawning Time	Site	Method
Yellow Perch *Perca flavescens*	Early spring	Brush, aquatic plants	Deposited "rope" of eggs, usually on vegetation
White Perch *Morone americana*	Late spring	Sand or gravel bottom	Egg scatterer
Bluegill *Lepomis macrochirus*	Early summer	Littoral zone	Parental care; nest is a circular depression
Pumpkinseed *Lepomis gibbosus*	Summer	Littoral zone	Parental care; nest is a circular depression
Largemouth Bass *Micropterus salmoides*	Late spring	Littoral zone	Parental care; nest is a circular depression
Smallmouth Bass *Micropterus dolomieui*	Spring, early summer	Gravel bottom	Nest builder
Brown Bullhead *Ameiurus nebulosa*	Late spring	Littoral zone	Crevices or nests
Chain Pickerel *Esox niger*	After ice out	Littoral zone	Eggs scattered among vegetation in shallow areas
Lake Trout *Salvelinus namaycush*	Oct-Dec.	Sand or gravel bottom	Eggs scattered over gravel
Brook Trout *Salvelinus fontinalis*	Sept.-Dec.	Gravel bottom of tributaries	Deposited in "redd" or nest
Brown Trout *Salmo trutta*	Fall	Gravel bottom of tributaries	Deposited in "redd" or nest
River Herring *Alosa aestivalis* (Blueback) *Alosa psuedoharengus* (Alewife)	Spring	Sand or gravel bottom	Egg scatterer

Note that some animals are also introduced, ranging from many fish species stocked for angling purposes to invertebrates that may represent a disruption of energy flow in the aquatic food web. Angling is a major lake use, and a major role of the Department of Fish and Game is managing lake fisheries for the enjoyment of the angling public, but many of the fish in our lakes today are not native to the area. Both largemouth and smallmouth bass and both brown and rainbow trout are introduced species. Many baitfish species have been introduced as well, either intentionally to form a forage base for growing gamefish or accidentally as escapees from bait buckets. It was a common management practice in the late 1800s and first half of the 1900s to move fish from lake to lake, introducing a range of species to each lake and allowing "nature" to decide what would become abundant. It was also common to "reclaim" a lake (poison the existing fish and restock) when fishing was considered very poor over an extended period of years, usually as a consequence of overabundant panfish. Stocking is much more focused and tightly controlled these days, and is part of the overall management plan for many lakes and regions of the Commonwealth. Reclamation by poisoning is no longer practiced in Massachusetts.

Other possible introductions of greater concern include zebra mussels (*Dreissenia polymorpha*) and various non-native relatives. These bivalve molluscs (small freshwater clams) can out-compete all other molluscs, cover rocks, docks and other hard substrates, and filter the water to the extent that the open water food web may collapse. Zebra mussels have not been found in Massachusetts as of this writing, but are known from the region and pose a great threat to water supplies and recreational lakes, as well as to the overall ecology of lakes. Non-native zooplankton, crayfish, and other invertebrates threaten native biodiversity, but as of yet have not proven to disrupt overall lake ecology in Massachusetts. This is probably more a matter of lack of study than lack of impact.

LAKE MANAGEMENT PLANNING

The Lake Management Plan

Developing a lake management plan is a useful and necessary process to select and guide the implementation of complex management techniques. It may not be absolutely necessary in all cases, but is always appropriate for setting overall management goals and laying out the techniques that will be used to achieve those goals. Small projects, such as the installation of benthic barriers around a boat launch or swimming area, do not require a detailed lake management plan, but at a lakewide scale, such application would benefit from such a plan. In some cases it may not make sense for a town or state agency to develop a detailed plan for a system which they do not control unless cooperation of other towns, agencies or landowners is obtained. However, having the framework of a plan in place may facilitate that cooperation, and development of management plans by multiple towns in a watershed is encouraged.

Like any sound construction, the foundation of a lake management plan must be secure before the next level can be supported. That is, an error at the beginning will magnify throughout the entire process. When developing a lake and watershed management plan, it is very important to keep in mind that:

- **Not all plans need to have each of the components fully developed, and depending on the management issues, plans may not need to address some of the components at all**. Carefully consider resources and uses when prioritizing plan elements.
- **The size and detail of the plan should reflect the complexity of the lake and its management issues**. In general, a plan may range from a couple of pages for a small privately owned pond to several hundred pages for a large public lake with many uses and management issues.
- **The outline presented here provides a menu of options, but should not necessarily be adopted verbatim**. Elements and options are best evaluated in consultation with an experienced lake management professional.

As a general rule, having thorough data for these components will enable the production of a more valuable lake and watershed management plan and will increase the likelihood of successful protection and/or restoration of the water body. The other general rule is that the greater the potential impact or expense of a proposed management technique, the greater is the need for complete information.

The common elements of lake management plans can be summarized as follows:

- **Problem Statement**: List issues/problems that should be addressed. Why is management action under consideration, and what previous reports, data, historic management actions and past recommendations support this need?
- **Management Goals:** Get public input by all stakeholders to provide a concise statement of goals, desired future uses and characteristics. Goals should be specific, measurable, and realistic/feasible.
- **Watershed and Lake Characteristics**: Include maps of watershed boundary, watercourses, drainage systems, geology, topography, soils, land use, any zoning, and pollutant sources. Provide maps of lake bathymetry and sediment types/depth. Collect data for hydrology and water quality and construct nutrient budgets. Model the system to the extent practical and necessary to predict results of management actions. Collect data for bacteria, algae, vascular plants, zooplankton, invertebrates, fish, reptiles, amphibians, birds and mammals, and check available maps and records for protected species.
- **Past In-Lake Management Techniques**: Review all physical, chemical and biological controls, and any other in-lake management techniques that have been implemented.

- **Existing Watershed Management Techniques:** Review all regulatory (e.g., zoning, resource protection bylaws, health statutes) and non-regulatory (i.e., educational, procedural and structural) management techniques that are in place and being used within the watershed.
- **In-Lake and Watershed Management Alternatives:** Evaluate options for feasibility, impacts, costs, and effectiveness to attain the goals.
- **Management Recommendations:** Include both short- and long-term management options for in-lake and watershed management, with time frames. Preventive and mitigative measures should be included. A description of the monitoring and evaluation process to be used for all proposed actions should be included, with pre- and post-management elements.
- **Plan Approval:** Present the plan at one or more well-publicized public meetings, and offer an opportunity for comment.
- **Implementation:** The five phases to implementation (funding, design, regulatory review, construction or application and follow up monitoring and evaluation) will be lake- and community-specific, but may involve considerable interaction with outside agencies and consultants.

The lake management plan represents the assimilation of all the previous steps into one understandable written document describing long-term goals for the lake and ways to achieve those goals, along with their ecological and financial consequences. If properly developed, it should be useful for a long time, modified as more is learned about the lake and progress is made.

Most plans focus on mitigating perceived problems, but protection will almost always be essential to maintain desirable qualities. Some lake users may perceive that a lake meets most of its intended uses and is unlikely to change, but lakes are dynamic systems prone to change even without human interference. A “hands off” approach can not be expected to preserve key qualities of the lake system, although knowing when not to take action can be as important as knowing what techniques to apply and when. It will be no less important for all of the lake management plan development steps to be followed for lakes to be protected than it is for lakes with serious problems.

All the steps of management planning can be difficult, but do not underestimate the importance of the early steps. The problem statement serves to clarify user perception of the problem and to distinguish between perception and reality. As stated earlier, individual lakes fall along a continuum of lake evolution from pristine, nearly sterile bowls of water to shallow, productive wetlands; all are natural states. Public perception also varies along a continuum with every individual preferring a slightly different view of a lake. Public perception may be in sharp conflict with the natural state of a lake and with a realistic expectation of what can be accomplished. The development of a problem statement is eventually a reconciliation of perception with reality. Reality in this case is determined by water quality monitoring and watershed evaluation, the latter being the tool to differentiate between human impacts and the natural state to the extent possible. At this early stage, it is imperative to involve as much of the community as possible in management planning. All subsequent steps will be easier if the chosen plan has broad community support created by participation in the plan’s development coupled with a realistic expectation of what can be accomplished.

With the previous steps in place, evaluation of possible management strategies becomes a focal point for the plan. A number of the diagnostic tools permit limited cost/benefit analysis. This review is principally focused on defining procedures acceptable in Massachusetts for the implementation of lake management controls. It recognizes that there are appropriate short-term strategies that are steps along the path of a long-term strategy. There may be short-term strategies that merely attempt to maximize human resource usage without significantly changing the natural state of a lake. Long-term strategies may have limited impact in the short-term but may eventually produce the closest approximation to a sustainable and healthy lake condition, maximize human resource use and may be more cost-effective. The appropriate choice will depend on community priorities, regulatory restrictions, specific characteristics of the lake, community resources and the effectiveness, adverse impacts and costs of the available lake management techniques. This is admittedly a lot to consider all at once, but effective lake management is rarely a simple process.

As described, implementation appears to be the last step. It is actually part of a cycle of assessment and action, but does normally require the prior steps to be successful. However, for many previous implementation projects, it was almost the only step. The importance of completing the previous steps in arriving at an acceptable and successful implementation phase cannot be overemphasized. These steps can promote community support, develop funding and minimize the effort required to continue implementation in successive years.

This review, within the limits of available science and experience, attempts to describe management techniques that have been applied in Massachusetts and have a high probability of success under appropriate conditions. Lake management controls applied in accordance with this review have a reasonable chance of success, based on our present knowledge. Controls that are not covered by this review either have a seriously limited chance of success (often with major negative impacts) or represent a change in scientific knowledge and experience since this report was written. In the latter case, the burden of proof must fall on those proposing the strategy. However, regulatory agencies need to keep up with the science and recognize the value of experimentation in lake management. Few impacts to lakes are irreversible, and few targeted benefits can be achieved without at least temporary impact to some untargeted resources. Successful lake management requires balancing varied and sometimes competing interests.

Predicting the Outcome of Management

Knowing exactly how an aquatic system and all its inhabitants will respond is not usually possible; uncertainty is a fact of life, especially in lake management. The direction of anticipated change and the general magnitude of change can be predicted, however, at least for water quality and algae-related features of lakes. For management aimed at controlling nutrients to minimize algal blooms, many studies of watersheds have produced scientific literature statistically comparing nutrient inputs with average lake nutrient concentration, average chlorophyll concentration and Secchi disk transparency. Knowledge of any one of these parameters provides a rough estimate of all the others for relatively large, stratified north temperate lakes without dominant rooted plant growth. For other lakes, particularly lakes with abundant plant growth, these “empirical” models will not work as well and may not work at all, but we rely on them to make general predictions of lake response to nutrient controls.

Quite a few of these models have been developed; all are remarkably consistent and suggest that the general models are robust even though the confidence one can place in a specific prediction for a particular lake is limited. The details of the many available models and how to use them is beyond what this guide is intended to cover, but the ultimate goal is to understand how nutrient loading relates to lake attributes that affect lake uses.

Water clarity is often a key determinant of satisfaction with the appearance of a lake, and exhibits a strong curvilinear relationship with phosphorus (Figure 8). A change at low total phosphorus levels results in a much larger change in transparency than the same absolute change at a higher total phosphorus level. There is, however, considerable variation possible at any phosphorus level. The sources of variability can be very important to management decisions, and include the nature of the zooplankton community, the availability of phosphorus, and other sources of turbidity (such as suspended inorganic sediment). It is very difficult to predict exactly how a change in phosphorus loading will affect the clarity of an individual lake without considerable information on these other sources of variation in the relationship.

A variation on this approach is to use the empirical models to develop an index that can be related to perception of trophic state. One of the most widely used of these indices is Carlson’s Trophic State

Index (TSI). Knowing the total phosphorus, chlorophyll *a*, or transparency, one can calculate the TSI. The TSI scale ranges from 0 to 100 with each 10 units of increase representing a doubling in algal biomass. Unlike the measurements of nutrients or chlorophyll, the TSI has been related to problem perception (Figure 9). The primary value of the TSI will be in presenting comparative information to decision-makers in an easy to visualize, non-technical form.

Increasing levels of modeling sophistication are warranted when the choices to be made based on modeling results carry major costs. It is quite appropriate, however, to use simpler models to generate results for potential management scenarios for comparative purposes and to elucidate the level of management needed. It is extremely frustrating to conduct a program to reduce nutrient loading by 50%, only to find that no visible change in water clarity is gained because the system was out in the right hand portion of the graph in Figure 8 (high P, low clarity). It is very helpful to know the general order of magnitude of the loading reduction needed to meet program objectives before embarking on a load reduction campaign. Exact numerical predictions from models should not be believed in most cases, but the models do reliably indicate the direction and approximate degree of change to be expected.

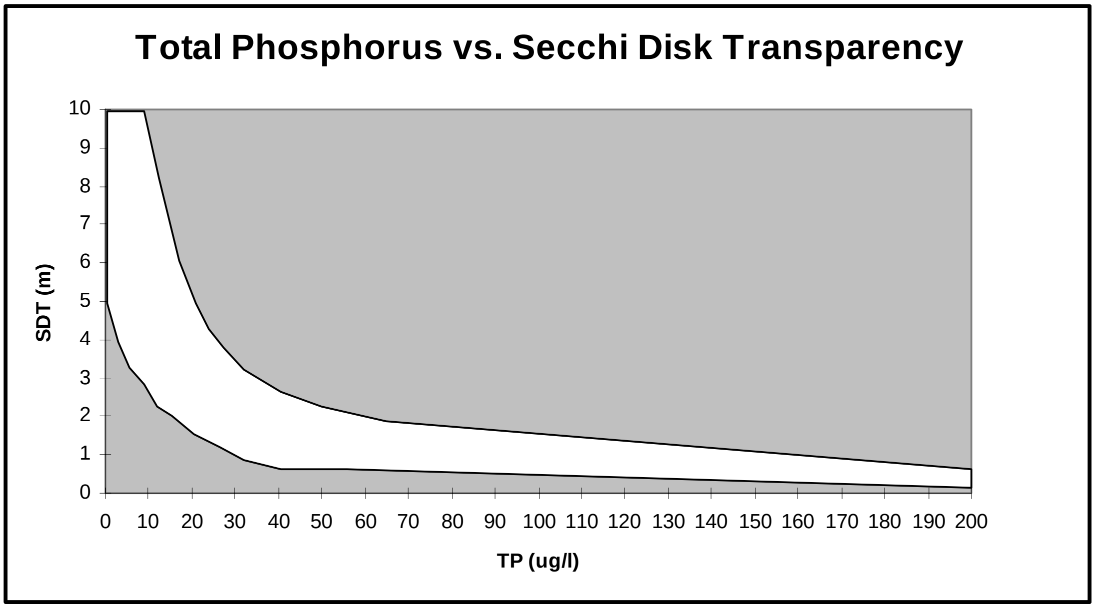


Figure 8. Expected Range of Water Clarity with Changing Phosphorus Concentration.

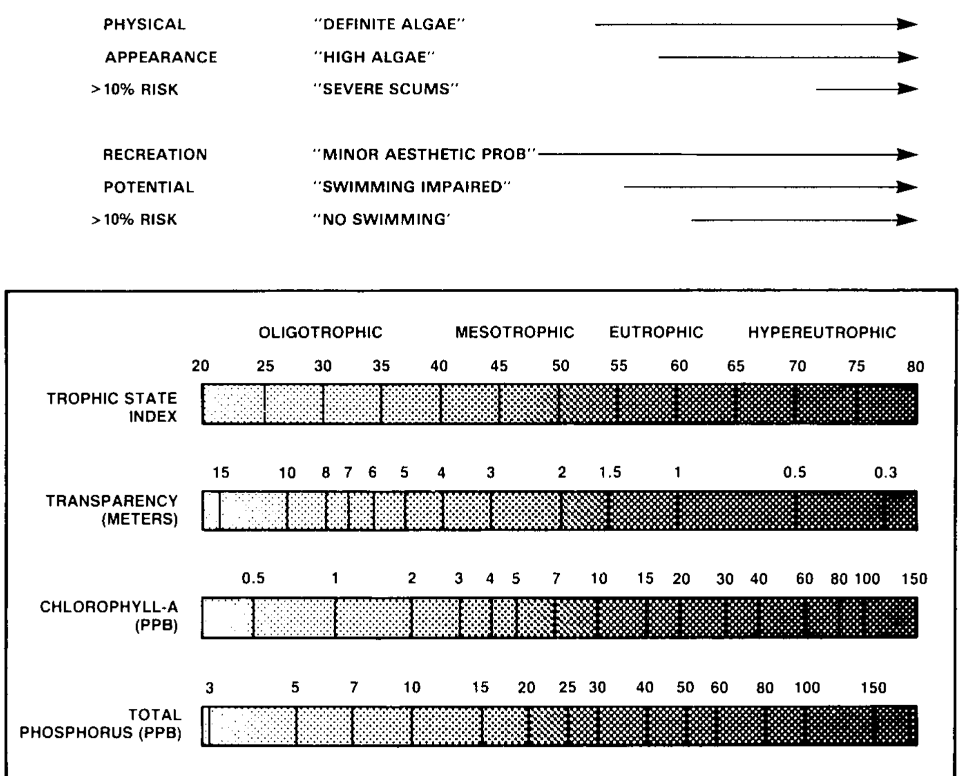


Figure 9. Carlson's Trophic State Index Related to Perceived Nuisance Conditions (Heiskary and Walker, 1987). **Lengths of arrows indicate range over which a greater than 10 percent probability exists that users will perceive a problem.**

TECHNIQUES TO MANAGE EUTROPHICATION AND AQUATIC PLANTS

Overview of Options

The GEIR and this Guide break up management options into two general categories: control of nutrients and control of aquatic plants. Control of nutrients is usually intended to reduce algal growth; it may prevent non-rooted vascular plant growth as well, but will not typically control rooted aquatic vegetation. Nutrient controls may occur in the watershed or in the lake, but if watershed controls are inadequate, in-lake controls will provide only temporary relief. Direct control of aquatic plants (vascular plants or algae) is often performed on a maintenance basis, but in some cases the community can be altered in more permanent ways.

One of the most effective ways to control algal populations is by limiting the nutrient supply to the lake, and thus limiting growth of algae. Phosphorus is the best nutrient to control, and the nutrient control options will deal primarily with phosphorus control. Even in cases where lakes are limited by nitrogen, phosphorus control is still the preferred method to control algae. In nutrient rich lakes, the growth of algae may be limited by light, and reduction in nutrient concentrations may not have a significant effect until the nutrient concentrations are lowered sufficiently to induce nutrient limitation.

One must identify the sources of nutrients before an effective control strategy can be determined. Once the relative importance of the sources of phosphorus is determined, one can examine the control techniques identified below for applicability and feasibility:

- Non-Point Source Management – control of diffuse nutrient sources from the watershed
- Point Source Management – control of point sources, usually piped discharges
- Hydraulic Controls – diversion, dilution, flushing, and hypolimnetic withdrawal strategies
- Phosphorus Inactivation – chemical binding of phosphorus to limit availability
- Artificial Circulation and Aeration – mixing and oxygen addition
- Dredging – removal of nutrient-laden sediments
- Bacterial Additives – encouraging uptake of nutrients by non-algal microbes
- Removal of Bottom Feeding Fish – elimination of major recyclers of nutrients

The needed or expected reduction in phosphorus loading should be modeled to predict the change in trophic status. In general, algal problems will be minimized at loadings less than Vollenweider's (1968) permissible level**,** which is a calculated value dependent mainly on the depth and hydraulic residence time of the lake. Yet algal abundance in response to nutrient loading is a probability distribution, not a threshold function. Consequently, algal blooms may be expected at some reduced frequency, even at fairly low nutrient levels, and lakes will not respond identically to changes in loading. Acceptable results might be achieved at loadings higher than the permissible level, but unacceptable conditions can be expected where loading exceeds Vollenweider's (1968) critical limit. Managers should be prepared to adjust strategies in response to resultant lake conditions; algal control through nutrient limitation is often an iterative process.

Additional ways to directly limit the density of algae may be needed on an interim or supplemental basis, and include the use of biocidal chemicals, dyes or biocontrol agents. Likewise, many aquatic vascular plants will not be controlled by nutrient reductions, and direct control techniques will be necessary. Direct rooted plant management options include physical, chemical and biological techniques as noted below:

- Drawdown - lowering of the water level to dry and freeze susceptible vegetation, with limited potential to control algal growth
- Harvesting - multiple methods of mechanical plant cutting, with or without removal, and algal collection

- Biological Control - biomanipulation, the practice of altering biological communities to control algae or macrophytes through biological interactions
- Benthic Barriers - placement of materials on the bottom of a lake to cover and impede the growth of macrophytes
- Herbicides and Algaecides - introduction of biocidal chemicals to directly kill vascular plants and/or algae
- Dyes and Covers - addition of coloring agents or sheet material to inhibit light penetration and reduce vascular plant and algae growths
- Dredging - removal of sediment and associated plants to inhibit growth
- Sonication – use of sound waves to disrupt and kill algal cells

In the case of nuisance species, especially introduced forms considered to be invasive, prevention is at least as important as management of existing infestations. Preventing the introduction of non-native plants is obviously the most desirable management option, but often this fails. One of the most active routes of introduction is the aquarium and landscaping trades; many of our greatest nuisance aquatic species can be traced to introductions by these commercial routes (Les, 2002). The need for laws and enforcement relating to such introductions remains great. This manual focuses on remediation for excessive macrophyte growths, and does not explicitly address approaches for prevention. However, as it is extremely difficult to truly eradicate introduced species, much greater emphasis is needed on controlling the undesirable spread of species by human actions.

A summary table of possible techniques for algae (and non-rooted vascular plant) control is presented in Table 3 and options for rooted plant control are summarized in Table 4, both adapted from Wagner (2001). All techniques have associated benefits and drawbacks, and those contemplating plant management should familiarize themselves with the following axioms for algae and vascular plant management:

<u>Axioms for the Control of Algae in Lakes</u>

1. Where light and nutrients are sufficient and toxic substances are limited, algae will grow

- Phosphorus >0.01 mg/L and nitrogen >0.3 mg/L can support blooms
- Phosphorus >0.05 mg/L and nitrogen >1.0 mg/L will usually support blooms
- Very little light is necessary for some species of algae to bloom; normal daylight is adequate except at very high algal densities
- Metals and some organic compounds are the primary toxicants for algae

2. One factor will control the abundance of any given alga, but that factor can vary over time and among algae

- Some blue-greens can fix nitrogen, but require elements not needed by other algae
- Succession of algae may be triggered by changing control factors
- Control of the whole algal community by one factor occurs at extremes (e.g., low P or high Cu)

3. Nutrient ratios are major determinants of the type of algae present

- N:P:Si ratio is most influential, but trace nutrients can have an effect as well
- Blue-greens which can fix N thrive at low N:P ratios, while most greens prefer high N:P ratios
- Diatoms require high Silica
- Carbon can be important at very high N and P
- Light can also be an important determinant of algal assemblage composition

4. Productivity and biomass are related but separate concepts

- Productivity is a growth process
- Biomass is the net result of growth and loss processes
- High productivity leads to high biomass if loss processes are not adequate to maintain balance

5. Diversity of algal adaptations may defeat controls other than maintaining low phosphorus
- N fixation by blue-greens minimizes N limitation
- Buoyancy regulation allows vertical movement
- Auxiliary pigments assist in low or high light habitats
- Heterotrophy can sustain some algae
- Anti-grazing mechanisms can minimize zooplankton impacts
- Copper resistance by some algae limits control options with algaecides

6. The most effective algal control is achieved through reduction of external and internal phosphorus loading
- P can be made to limit productivity most reliably
- Essential to determine relative magnitude of sources of P
- May require multiple techniques and extended timeframe

7. High grazing pressure yields the lowest algal biomass per unit of fertility
- Large-bodied, herbivorous, zooplankton (*Daphnia*) at high biomass can limit algal biomass
- Algal adaptation can overcome grazing pressure if nutrients are sufficient

8. Algaecides should only be used until growth processes can be controlled
- Algaecides can provide short-term control and can prevent blooms if applied at the proper time
- Algaecides rarely provide long term control and can have adverse side effects

<u>Axioms for the Control of Rooted Plants in Lakes</u>

1. In lighted areas with suitable sediments, plants will grow
- Light and substrate are critical factors
- A desire for no plants demands a maintenance program
- Management for a diverse native community is encouraged

2. No amount of watershed management will control an existing infestation
- Rooted aquatic plant growths are not controlled by clean water
- Increased water clarity may extend plant growth
- Watershed management complements in-lake management

3. Understanding plant biology and ecology is essential to control
- Native vs. non-native species differences exist
- Reproduction by seeds vs. vegetative propagation is important
- Monocotyledon vs. dicotyledon biology may affect results
- Light and nutrient needs vary substantially among plant groups

4. There is no "One Size Fits All" solution to plant problems
- Each situation is to some extent unique
- Adaptive strategies of plants require adaptive management
- Techniques can be applied in a wide range of levels and combinations

5. It is unusual to successfully manage all plants in a lake with one technique
- Variation in lake and plant features usually calls for multiple techniques
- Initial control and follow-up maintenance often require different approaches

6. Prevention is far less expensive than restoration

- Prevention costs are mainly associated with monitoring, regulation and small scale action
- Restoration costs typically involve expansive and repeated control efforts
- If restoration is achieved, additional prevention costs then apply

7. A regional focus is needed to protect the investment made in control

- Re-infestation from nearby lakes can reduce control longevity
- Control on a larger scale can be more efficient and economical
- Prevention measures are more effective on a regional scale

Table 3. Management Options for Control of Algae. (Adapted from Wagner 2001).

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
WATERSHED CONTROLS			
1) Management for nutrient input reduction	♦ Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake ♦ Essential component of algal control strategy where internal recycling is not the dominant nutrient source, and desired even where internal recycling is important	♦ Acts against the original source of algal nutrition ♦ Creates sustainable limitation on algal growth ♦ May control delivery of other unwanted pollutants to lake ♦ Facilitates ecosystem management approach which considers more than just algal control	♦ May involve considerable lag time before improvement observed ♦ May not be sufficient to achieve goals without some form of in-lake management ♦ Reduction of overall system fertility may impact fisheries ♦ May cause shift in nutrient ratios which favor less desirable algae
1a) Point source controls	♦ More stringent discharge requirements ♦ May involve diversion ♦ May involve technological or operational adjustments ♦ May involve pollution prevention plans	♦ Often provides major input reduction ♦ Highly efficient approach in most cases ♦ Success easily monitored	♦ May be very expensive in terms of capital and operational costs ♦ May transfer problems to another watershed ♦ Variability in results may be high in some cases
1b) Non-point source controls	♦ Reduction of sources of nutrients ♦ May involve elimination of land uses or activities that release nutrients ♦ May involve alternative product use, as with no phosphate fertilizer	♦ Removes source ♦ Limited or no ongoing costs	♦ May require purchase of land or activity ♦ May be viewed as limitation of “quality of life” ♦ Usually requires education and gradual implementation

Table 3 – continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
1c) Non-point source pollutant trapping	♦ Capture of pollutants between source and lake ♦ May involve drainage system alteration ♦ Often involves wetland treatments (detention/infiltration) ♦ May involve stormwater collection and treatment as with point sources	♦ Minimizes interference with land uses and activities ♦ Allows diffuse and phased implementation throughout watershed ♦ Highly flexible approach ♦ Tends to address wide range of pollutant loads	♦ Does not address actual sources ♦ May be expensive on necessary scale ♦ May require substantial maintenance
IN-LAKE PHYSICAL CONTROLS			
2) Circulation and destratification	♦ Use of water or air to keep water in motion ♦ Intended to prevent or break stratification ♦ Generally driven by mechanical or pneumatic force	♦ Reduces surface build-up of algal scums ♦ May disrupt growth of blue-green algae ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ May reduce internal loading of phosphorus	♦ May spread localized impacts ♦ May lower oxygen levels in shallow water ♦ May promote downstream impacts
3) Dilution and flushing	♦ Addition of water of better quality can dilute nutrients ♦ Addition of water of similar or poorer quality flushes system to minimize algal build-up ♦ May have continuous or periodic additions	♦ Dilution reduces nutrient concentrations without altering load ♦ Flushing minimizes detention; response to pollutants may be reduced	♦ Diverts water from other uses ♦ Flushing may wash desirable zooplankton from lake ♦ Use of poorer quality water increases loads ♦ Possible downstream impacts
4) Drawdown	♦ Lowering of water over autumn period allows oxidation, desiccation and compaction of sediments ♦ Duration of exposure and degree of dewatering of exposed areas are important ♦ Algae are affected mainly by reduction in available nutrients.	♦ May reduce available nutrients or nutrient ratios, affecting algal biomass and composition ♦ Opportunity for shoreline clean-up/structure repair ♦ Flood control utility ♦ May provide rooted plant control as well	♦ Possible impacts on non-target resources ♦ Possible impairment of water supply ♦ Alteration of downstream flows and winter water level ♦ May result in greater nutrient availability if flushing inadequate

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
5) Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering ♦ Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system ♦ Nutrient reserves are removed and algal growth can be limited by nutrient availability	♦ Can control algae if internal recycling is main nutrient source ♦ Increases water depth ♦ Can reduce pollutant reserves ♦ Can reduce sediment oxygen demand ♦ Can improve spawning habitat for many fish species ♦ Allows complete renovation of aquatic ecosystem	♦ Temporarily removes benthic invertebrates ♦ May create turbidity ♦ May eliminate fish community (complete dry dredging only) ♦ Possible impacts from containment area discharge ♦ Possible impacts from dredged material disposal ♦ Interference with recreation or other uses during dredging
5a) “Dry” excavation	♦ Lake drained or lowered to maximum extent practical ♦ Target material dried to maximum extent possible ♦ Conventional excavation equipment used to remove sediments	♦ Tends to facilitate a very thorough effort ♦ May allow drying of sediments prior to removal ♦ Allows use of less specialized equipment	♦ Rarely truly a dry operation; tends to be messy ♦ Eliminates most aquatic biota unless a portion left undrained ♦ Eliminates lake use during dredging
5b) “Wet” excavation	♦ Lake level may be lowered, but sediments not substantially exposed ♦ Draglines, bucket dredges, or long-reach backhoes used to remove sediment	♦ Requires least preparation time or effort, tends to be least cost dredging approach ♦ May allow use of easily acquired equipment ♦ May preserve aquatic biota	♦ Usually creates extreme turbidity ♦ Normally requires intermediate containment area to dry sediments prior to hauling ♦ May disrupt ecological function ♦ Disrupts many uses
5c) Hydraulic removal	♦ Lake level not reduced ♦ Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area ♦ Slurry is dewatered; sediment retained, water discharged	♦ Creates minimal turbidity and impact on biota ♦ Can allow some lake uses during dredging ♦ Allows removal with limited access or shoreline disturbance	♦ Often leaves some sediment behind ♦ Cannot handle coarse or debris-laden materials ♦ Requires sophisticated and more expensive containment area

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6) Light-limiting dyes and surface covers	♦ Creates light limitation	♦ Creates light limit on algal growth without high turbidity or great depth ♦ May achieve some control of rooted plants as well	♦ May cause thermal stratification in shallow ponds ♦ May facilitate anoxia at sediment interface with water
6.a) Dyes	♦ Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth ♦ Dyes remain in solution until washed out of system.	♦ Produces appealing color ♦ Creates illusion of greater depth	♦ May not control surface bloom-forming species ♦ May not control growth of shallow water algal mats ♦ Alters thermal regime
6.b) Surface covers	♦ Opaque sheet material applied to water surface	♦ Minimizes atmospheric and wildlife pollutant inputs	♦ Minimizes atmospheric gas exchange ♦ Limits recreational use
7) Mechanical removal	♦ Filtering of pumped water for water supply purposes ♦ Collection of floating scums or mats with booms, nets, or other devices ♦ Continuous or multiple applications per year usually needed	♦ Algae and associated nutrients can be removed from system ♦ Surface collection can be applied as needed ♦ May remove floating debris ♦ Collected algae dry to minimal volume	♦ Filtration requires high backwash and sludge handling capability for use with high algal densities ♦ Labor and/or capital intensive ♦ Variable collection efficiency ♦ Possible impacts on non-target aquatic life
8) Selective withdrawal	♦ Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels ♦ May be pumped or utilize passive head differential	♦ Removes targeted water from lake efficiently ♦ Complements other techniques such as drawdown or aeration ♦ May prevent anoxia and phosphorus build up in bottom water ♦ May remove initial phase of algal blooms which start in deep water ♦ May create coldwater conditions downstream	♦ Possible downstream impacts of poor water quality ♦ May eliminate colder thermal layer that supports certain fish ♦ May promote mixing of remaining poor quality bottom water with surface waters ♦ May cause unintended drawdown if inflows do not match withdrawal

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
9) Sonication	♦ Sound waves disrupt algal cells	♦ Supposedly affects only algae (new technique) ♦ Applicable in localized areas	♦ Uncertain effects on non-target organisms ♦ May release cellular toxins or other undesirable contents into water column
IN-LAKE CHEMICAL CONTROLS			
10) Hypolimnetic aeration or oxygenation	♦ Addition of air or oxygen at varying depth provides oxic conditions ♦ May maintain or break stratification ♦ Can also withdraw water, oxygenate, then replace	♦ Oxic conditions promote binding/sedimentation of phosphorus ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Build-up of dissolved iron, manganese, sulfide, ammonia and phosphorus reduced	♦ May accidentally disrupt thermal layers important to fish community ♦ Theoretically promotes supersaturation with gases harmful to fish ♦ Biota may become dependent on continued aeration
11) Algaecides	♦ Liquid or pelletized algaecides applied to target area ♦ Algae killed by direct toxicity or metabolic interference ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid elimination of algae from water column, normally with increased water clarity ♦ May result in net movement of nutrients to bottom of lake	♦ Possible toxicity to non-target species ♦ Restrictions on water use for varying time after treatment ♦ Increased oxygen demand and possible toxicity ♦ Possible recycling of nutrients
11a) Forms of copper	♦ Cellular toxicant, suggested disruption of photosynthesis, nitrogen metabolism, and membrane transport ♦ Applied as wide variety of liquid or granular formulations, often in conjunction with chelators, polymers, surfactants or herbicides	♦ Effective and rapid control of many algae species ♦ Approved for use in most water supplies	♦ Possible toxicity to aquatic fauna ♦ Ineffective at colder temperatures ♦ Accumulation of copper in system ♦ Resistance by certain green and blue-green nuisance species ♦ Rupturing of cells releases nutrients and toxins

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
11b) Synthetic organic herbicides	♦ Absorbed or membrane-active chemicals which disrupt metabolism ♦ Causes structural deterioration	♦ Used where copper is ineffective ♦ Limited toxicity to fish at recommended dosages ♦ Rapid action	♦ Non-selective in treated area ♦ Possible toxicity to aquatic fauna (varying degrees by dose and formulation) ♦ Time delays on water use
11c) Oxidants	♦ Disrupts most cellular functions, tends to attack membranes ♦ Applied most often as a liquid.	♦ Potential selectivity against blue-greens ♦ Moderate control of thick algal mats, used where copper alone is ineffective ♦ Rapid action	♦ Older formulations tended to have high toxicity to some aquatic fauna ♦ New formulations not well tested in the field yet
12) Phosphorus inactivation	♦ Typically salts of aluminum, iron or calcium are added to the lake, as liquid or powder ♦ Phosphorus in the treated water column is complexed and settled to the bottom of the lake ♦ Phosphorus in upper sediment layer is complexed, reducing release from sediment ♦ Permanence of binding varies by binder in relation to redox potential and pH	♦ Can provide rapid, major decrease in phosphorus concentration in water column ♦ Can minimize release of phosphorus from sediment ♦ May remove other nutrients and contaminants as well as phosphorus ♦ Flexible with regard to depth of application and speed of improvement	♦ Possible toxicity to fish and invertebrates, mainly by aluminum at low or high pH ♦ Possible release of phosphorus under anoxia (with Fe) or extreme pH (with Ca) ♦ May cause fluctuations in water chemistry, especially pH, during treatment ♦ Possible resuspension of floc in shallow areas ♦ Adds to bottom sediment, but typically an insignificant amount
13) Sediment oxidation	♦ Addition of oxidants, binders and pH adjusters to oxidize sediment ♦ Binding of phosphorus is enhanced ♦ Denitrification is stimulated	♦ Can reduce phosphorus supply to algae ♦ Can alter N:P ratios in water column ♦ May decrease sediment oxygen demand	♦ Possible impacts on benthic biota ♦ Longevity of effects not well known ♦ Possible source of nitrogen for blue-green algae

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
14) Settling agents	♦ Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too ♦ Lime, alum or polymers applied, usually as a liquid or slurry ♦ Creates a floc with algae and other suspended particles ♦ Floc settles to bottom of lake ♦ Re-application typically necessary at least once/yr	♦ Removes algae and increases water clarity without lysing most cells ♦ Reduces nutrient recycling if floc sufficient ♦ Removes non-algal particles as well as algae ♦ May reduce dissolved phosphorus levels at the same time	♦ Possible impacts on aquatic fauna ♦ Possible fluctuations in water chemistry during treatment ♦ Resuspension of floc possible in shallow, well-mixed waters ♦ Promotes increased sediment accumulation
15) Selective nutrient addition	♦ Ratio of nutrients changed by additions of selected nutrients ♦ Addition of non-limiting nutrients can change composition of algal community ♦ Processes such as settling and grazing can then reduce algal biomass (productivity can actually increase, but standing crop can decline)	♦ Can reduce algal levels where control of limiting nutrient not feasible ♦ Can promote non-nuisance forms of algae ♦ Can improve productivity of system without increased standing crop of algae	♦ May result in greater algal abundance through uncertain biological response ♦ May require frequent application to maintain desired ratios ♦ Possible downstream effects
IN-LAKE BIOLOGICAL CONTROLS			
16) Enhanced grazing	♦ Manipulation of biological components of system to achieve grazing control over algae ♦ Typically involves alteration of fish community to promote growth of large herbivorous zooplankton, or stocking with phytophagous fish	♦ May increase water clarity by changes in algal biomass or cell size distribution without reduction of nutrient levels ♦ Can convert unwanted biomass into desirable form (fish) ♦ Harnesses natural processes to produce desired conditions	♦ May involve introduction of exotic species ♦ Effects may not be controllable or lasting ♦ May foster shifts in algal composition to even less desirable forms

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
16.a) Herbivorous fish (not permitted in MA)	♦ Stocking of fish that eat algae	♦ Converts algae directly into potentially harvestable fish ♦ Grazing pressure can be adjusted through stocking rate	♦ Typically requires introduction of non-native species ♦ Difficult to control over long term ♦ Smaller algal forms may be benefited and bloom
16.b) Herbivorous zooplankton	♦ Reduction in planktivorous fish to promote grazing pressure by zooplankton ♦ May involve stocking piscivores or removing planktivores ♦ May also involve stocking zooplankton or establishing refugia	♦ Converts algae indirectly into harvestable fish ♦ Zooplankton response to increasing algae can be rapid ♦ May be accomplished without introduction of non-native species ♦ Generally compatible with most fishery management goals	♦ Highly variable response expected; temporal and spatial variability may be high ♦ Requires careful monitoring and management action on 1-5 yr basis ♦ Larger or toxic algal forms may be benefited and bloom
17) Bottom-feeding fish removal	♦ Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion	♦ Reduces turbidity and nutrient additions from this source ♦ May restructure fish community in more desirable manner	♦ Targeted fish species are difficult to eradicate or control ♦ Reduction in fish populations valued by some lake users (human/non-human)
18) Pathogens	♦ Addition of inoculum to initiate attack on algal cells ♦ May involve fungi, bacteria or viruses	♦ May create lakewide "epidemic" and reduction of algal biomass ♦ May provide sustained control through cycles ♦ Can be highly specific to algal group or genera	♦ Largely experimental approach at this time ♦ May promote resistant nuisance forms ♦ May cause high oxygen demand or release of toxins by lysed algal cells ♦ Effects on non-target organisms uncertain
19) Competition and allelopathy	♦ Plants may tie up sufficient nutrients to limit algal growth ♦ Plants may create a light limitation on algal growth ♦ Chemical inhibition of algae may occur through substances released by other organisms	♦ Harnesses power of natural biological interactions ♦ May provide responsive and prolonged control	♦ Some algal forms appear resistant ♦ Use of plants may lead to problems with vascular plants ♦ Use of plant material may cause depression of oxygen levels

Table 3 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
19a) Plantings for nutrient control	♦ Plant growths of sufficient density may limit algal access to nutrients ♦ Plants can exude allelopathic substances which inhibit algal growth ♦ Portable plant “pods” , floating islands, or other structures can be installed	♦ Productivity and associated habitat value can remain high without algal blooms ♦ Can be managed to limit interference with recreation and provide habitat ♦ Wetland cells in or adjacent to the lake can minimize nutrient inputs	♦ Vascular plants may achieve nuisance densities ♦ Vascular plant senescence may release nutrients and cause algal blooms ♦ The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes
19b) Plantings for light control	♦ Plant species with floating leaves can shade out many algal growths at elevated densities	♦ Vascular plants can be more easily harvested than most algae ♦ Many floating species provide valuable waterfowl food	♦ At the necessary density, floating plants likely to be a recreational nuisance ♦ Low surface mixing and atmospheric contact promote anoxia
19c) Addition of barley straw	♦ Input of barely straw can set off a series of chemical reactions which limit algal growth ♦ Release of allelopathic chemicals can kill algae ♦ Release of humic substances may bind phosphorus	♦ Materials and application are relatively inexpensive ♦ Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	♦ Success appears linked to uncertain and potentially uncontrollable water chemistry factors ♦ Depression of oxygen levels may result ♦ Water chemistry may be altered in other ways unsuitable for non-target organisms

Table 4. Management Options for Control of Rooted Aquatic Plants. (Adapted from Wagner, 2001).

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
PHYSICAL CONTROLS			
1) Benthic barriers	♦ Mat of variable composition laid on bottom of target area, preventing growth ♦ Can cover area for as little as several months or permanently ♦ Maintenance improves results ♦ Usually applied around docks, in boating lanes, and in swimming areas	♦ Highly flexible control ♦ Reduces turbidity from soft bottom sediments ♦ Can cover undesirable substrate ♦ Can improve fish habitat by creating edge effects	♦ May cause anoxia at sediment-water interface ♦ May limit benthic invertebrates ♦ Non-selective interference with plants in target area ♦ May inhibit spawning/feeding by some fish species
1.a) Porous or loose-weave synthetic materials	♦ Laid on bottom and usually anchored by weights or stakes ♦ Removed and cleaned or flipped and repositioned at least once per year for maximum effect	♦ Allows some escape of gases which may be generated underneath ♦ Panels may be flipped in place or removed for relatively easy cleaning or repositioning	♦ Allows some plant growth through pores ♦ Gas may still build up underneath in some cases, lifting barrier from bottom
1.b) Non-porous or sheet synthetic materials	♦ Laid on bottom and anchored by many stakes, anchors or weights, or by layer of sand ♦ Not typically removed, but may be swept or "blown" clean periodically	♦ Prevents all plant growth until buried by sediment ♦ Minimizes interaction of sediment and water column	♦ Gas build up may cause barrier to float upwards ♦ Strong anchoring makes removal difficult and can hinder maintenance
1.c) Improving sediment composition	♦ Sediments may be added on top of existing sediments or plants. ♦ Use of sand or clay can limit plant growths and alter sediment-water interactions. ♦ Sediments can be applied from the surface or suction dredged from below muck layer (reverse layering technique)	♦ Plant biomass can be buried ♦ Seed banks can be buried deeper ♦ Sediment can be made less hospitable to plant growths ♦ Nutrient release from sediments may be reduced ♦ Surface sediment can be made more appealing to human users ♦ Reverse layering requires no addition or removal of sediment	♦ Lake depth may decline ♦ Sediments may sink into or mix with underlying muck ♦ Permitting for added sediment difficult ♦ Addition of sediment may cause initial turbidity increase ♦ New sediment may contain nutrients or other contaminants ♦ Generally too expensive for large scale application

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
2) Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering/disposal ♦ Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system ♦ Plants and seed beds are removed and re-growth can be limited by light and/or substrate limitation	♦ Plant removal with some flexibility ♦ Increases water depth ♦ Can reduce pollutant reserves ♦ Can reduce sediment oxygen demand ♦ Can improve spawning habitat for many fish species ♦ Allows complete renovation of aquatic ecosystem ♦ May allow for growth of desirable species.	♦ Temporarily removes benthic invertebrates ♦ May create turbidity ♦ May eliminate fish community (complete dry dredging only) ♦ Possible impacts from containment area discharge ♦ Possible impacts from dredged material disposal ♦ Interference with recreation or other uses during dredging ♦ Usually very expensive
2.a) “Dry” excavation	♦ Lake drained or lowered to maximum extent practical ♦ Target material dried to maximum extent possible ♦ Conventional excavation equipment used to remove sediments	♦ Tends to facilitate a very thorough effort ♦ May allow drying of sediments prior to removal ♦ Allows use of less specialized equipment	♦ Eliminates most aquatic biota unless a portion left undrained ♦ Eliminates lake use during dredging
2.b) “Wet” excavation	♦ Lake level may be lowered, but sediments not substantially dewatered ♦ Draglines, bucket dredges, or long-reach backhoes used to remove sediment	♦ Requires least preparation time or effort, tends to be least cost dredging approach ♦ May allow use of easily acquired equipment ♦ May preserve most aquatic biota	♦ Usually creates extreme turbidity ♦ Tends to result in sediment deposition in surrounding area ♦ Normally requires intermediate containment area to dry sediments prior to hauling ♦ May cause severe disruption of ecological function ♦ Impairs most lake uses during dredging

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
2.c) Hydraulic (or pneumatic) removal	♦ Lake level not reduced ♦ Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area ♦ Slurry is dewatered; sediment retained, water discharged	♦ Creates minimal turbidity and limits impact on biota ♦ Can allow some lake uses during dredging ♦ Allows removal with limited access or shoreline disturbance	♦ Often leaves some sediment behind ♦ Cannot handle extremely coarse or debris-laden materials ♦ Requires advanced and more expensive containment area ♦ Requires overflow discharge from containment area
3) Dyes and surface covers	♦ Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting plant growth ♦ Dyes remain in solution until washed out of system. ♦ Opaque sheet material applied to water surface	♦ Light limit on plant growth without high turbidity or great depth ♦ May achieve some control of algae as well ♦ May achieve some selectivity for species tolerant of low light	♦ May not control peripheral or shallow water rooted plants ♦ May cause thermal stratification in shallow ponds ♦ May facilitate anoxia at sediment interface with water ♦ Covers inhibit gas exchange with atmosphere and restrict recreation ♦ Cannot be used in water bodies with an active outlet
4) Mechanical removal ("harvesting")	♦ Plants reduced by mechanical means, possibly with disturbance of soils ♦ Collected plants may be placed on shore for composting or other disposal ♦ Wide range of techniques employed, from manual to highly mechanized ♦ Application once or twice per year usually needed	♦ Highly flexible control ♦ May remove other debris ♦ Can balance habitat and recreational needs	♦ Possible impacts on aquatic fauna ♦ Non-selective removal of plants in treated area ♦ Possible spread of undesirable species by fragmentation ♦ Possible generation of turbidity
4.a) Hand pulling	♦ Plants uprooted by hand ("weeding") and preferably removed	♦ Highly selective technique	♦ Labor intensive ♦ Difficult to perform in dense stands ♦ Can cause fragmentation

4.b) Cutting (without collection)	♦ Plants cut in place above roots without being harvested	♦ Generally efficient and less expensive than complete harvesting	♦ Leaves root systems and part of plant for possible re-growth ♦ Leaves cut vegetation to decay or to re-root ♦ Not selective within applied area
4.c) Harvesting (with collection)	♦ Plants cut at depth of 2-10 ft and collected for removal from lake	♦ Allows plant removal on greater scale	♦ Limited depth of operation ♦ Usually leaves fragments which may re-root and spread infestation ♦ May impact lake fauna ♦ Limited selectivity within applied area ♦ More expensive than cutting
4.d) Rototilling	♦ Plants, root systems, and surrounding sediment disturbed with mechanical blades	♦ Can thoroughly disrupt entire plant	♦ Usually leaves fragments which may re-root and spread infestation ♦ May impact lake fauna ♦ Not selective within applied area ♦ Creates substantial turbidity ♦ More expensive than harvesting
4.e) Hydroraking	♦ Plants, root systems and surrounding sediment and debris disturbed with mechanical rake, part of material usually collected and removed from lake	♦ Can thoroughly disrupt entire plant ♦ Also allows removal of stumps or other obstructions	♦ Usually leaves fragments which may re-root and spread infestation ♦ May impact lake fauna ♦ Not selective within applied area ♦ Creates substantial turbidity ♦ More expensive than harvesting
5) Water level control	♦ Lowering or raising the water level to create an inhospitable environment for some or all aquatic plants ♦ Disrupts plant life cycle by dessication, freezing, or light limitation	♦ Requires only outlet control to affect large area ♦ Provides widespread control in increments of water depth ♦ Complements certain other techniques (dredging, flushing)	♦ Potential issues with water supply ♦ Potential issues with flooding ♦ Potential impacts to non-target flora and fauna

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
5.a) Drawdown	♦ Lowering of water over winter period allows desiccation, freezing, and physical disruption of plants, roots and seed beds ♦ Timing and duration of exposure and degree of dewatering are critical aspects ♦ Variable species tolerance to drawdown; emergent species and seed-bearers are less affected ♦ Most effective on annual to once/3 yr. basis	♦ Control with some flexibility ♦ Opportunity for shoreline clean-up/structure repair ♦ Flood control utility ♦ Impacts vegetative propagation species with limited impact to seed producing populations	♦ Possible impacts on contiguous emergent wetlands ♦ Possible effects on overwintering reptiles and amphibians ♦ Possible impairment of well production ♦ Reduction in potential water supply and fire fighting capacity ♦ Alteration of downstream flows ♦ Possible overwinter water level variation ♦ Possible shoreline erosion and slumping ♦ May result in greater nutrient availability for algae
5.b) Flooding	♦ Higher water level in the spring can inhibit seed germination and plant growth ♦ Higher flows which are normally associated with elevated water levels can flush seed and plant fragments from system	♦ Where water is available, this can be an inexpensive technique ♦ Plant growth need not be eliminated, merely retarded or delayed ♦ Timing of water level control can selectively favor certain desirable species	♦ Water for raising the level may not be available ♦ Potential peripheral flooding ♦ Possible downstream impacts ♦ Many species may not be affected, and some may be benefitted ♦ Algal nuisances may increase where nutrients are available
CHEMICAL CONTROLS			
6) Herbicides	♦ Liquid or pelletized herbicides applied to target area or to plants directly ♦ Contact or systemic poisons kill plants or limit growth ♦ Typically requires application every 1-5 yrs	♦ Wide range of control is possible ♦ May be able to selectively eliminate species ♦ May achieve some algae control as well ♦ May allow for more desirable plant growth	♦ Possible toxicity to non-target species ♦ Possible downstream impacts ♦ Restrictions of water use for varying time after treatment ♦ Increased oxygen demand from decaying vegetation ♦ Possible recycling of nutrients to allow other growths

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6.a) Forms of copper	♦ Contact herbicide ♦ Cellular toxicant, suspected membrane transport disruption ♦ Applied as wide variety of liquid or granular formulations, often in conjunction with polymers or other herbicides	♦ Moderately effective control of some submersed plant species ♦ More often an algal control agent	♦ Potentially toxic to aquatic fauna as a function of concentration, formulation, and ambient water chemistry ♦ Ineffective at colder temperatures ♦ Copper ion persistent; accumulates in sediments or moves downstream
6.b) Forms of endothall (7-oxabicyclo [2.2.1] heptane-2,3-dicarboxylic acid)	♦ Contact herbicide with limited translocation potential ♦ Membrane-active chemical which inhibits protein synthesis ♦ Causes structural deterioration ♦ Applied as liquid or granules	♦ Moderate control of some emersed plant species, moderately to highly effective control of floating and submersed species ♦ Limited toxicity to fish at typical MA dosages ♦ Rapid action	♦ Non-selective in treated area ♦ Potentially toxic to aquatic fauna (varying degrees by formulation) ♦ Time delays on use for water supply, agriculture and recreation
6.c) Forms of diquat (6,7-dihydropyrido [1,2-2',1'-c] pyrazinediium dibromide)	♦ Contact herbicide ♦ Absorbed by foliage but not roots ♦ Strong oxidant; disrupts most cellular functions ♦ Applied as a liquid, sometimes in conjunction with copper	♦ Moderate control of some emersed plant species, moderately to highly effective control of floating or submersed species ♦ Limited toxicity to fish at recommended dosages, low toxicity at typical MA doses ♦ Rapid action	♦ Non-selective in treated area ♦ Potentially toxic to zooplankton at high application rates ♦ Inactivated by suspended particles; ineffective in muddy waters
6.d) Forms of glyphosate (N-[phosphonomethyl glycine)	♦ Contact herbicide ♦ Absorbed through foliage, disrupts enzyme formation and function in uncertain manner ♦ Applied as liquid spray	♦ Moderately to highly effective control of emergent and floating plant species ♦ Can be used selectively, based on application to individual plants ♦ Rapid action ♦ Low toxicity to aquatic fauna at recommended dosages ♦ No time delays for use of treated water	♦ Non-selective in treated area ♦ Inactivation by suspended particles; ineffective in muddy waters ♦ Not for use within 0.5 miles of potable surface water intakes

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6.e) Forms of 2,4-D (2,4-dichlorophenoxyl acetic acid)	♦ Systemic herbicide ♦ Readily absorbed and translocated throughout plant ♦ Inhibits cell division in new tissue, stimulates growth in older tissue, resulting in gradual cell disruption ♦ Applied as liquid or granules, frequently as part of more complex formulations, preferably during early growth phase of plants	♦ Moderately to highly effective control of a variety of emergent, floating and submersed plant species ♦ Can achieve some selectivity through application timing and concentration ♦ Fairly fast action	♦ Potential toxicity to aquatic fauna, depending upon formulation and ambient water chemistry ♦ Time delays for use of treated water for agriculture and recreation ♦ Not for use in potable water supplies
6.f) Forms of fluridone (1-methyl-3-phenyl-5-[-3-{trifluoromethyl} phenyl]-4[IH]-pyridinone)	♦ Systemic herbicide ♦ Inhibits carotenoid pigment synthesis and impacts photosynthesis ♦ Best applied as liquid or granules during early growth phase of plants	♦ Can be used selectively, based on concentration ♦ Gradual deterioration of affected plants limits impact on oxygen level (BOD) ♦ Effective against several difficult-to-control species ♦ Low toxicity to aquatic fauna	♦ Impacts on non-target plant species possible at higher doses ♦ Extremely soluble and mixable; difficult to perform partial lake treatments ♦ Requires extended contact time
6.g Forms of triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid)	♦ Systemic herbicide, registration pending in MA at this time ♦ Readily absorbed by foliage, translocated throughout plant ♦ Disrupts enzyme systems specific to plants ♦ Applied as liquid spray or subsurface injected liquid	♦ Effectively controls many floating and submersed plant species ♦ Can be used selectively, more effective against dicot plant species, including many nuisance species ♦ Effective against several difficult-to-control species ♦ Low toxicity to aquatic fauna ♦ Fast action	♦ Impacts on non-target plant species possible at higher doses ♦ Restrictions on use of treated water for supply or recreation not yet certain for MA ♦ Registration not complete in MA at time of table preparation

Table 4 - continued

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
BIOLOGICAL CONTROLS			
7) Biological introductions	♦ Fish, insects or pathogens which feed on or parasitize plants are added to system to affect control ♦ The most commonly used organism is the grass carp, but the larvae of several insects have been used more recently, and viruses are being tested	♦ Provides potentially continuing control with one treatment ♦ Harnesses biological interactions to produce desired conditions ♦ May produce potentially useful fish biomass as an end product	♦ Typically involves introduction of non-native species ♦ Effects may not be controllable ♦ Plant selectivity may not match desired target species ♦ May adversely affect indigenous species
7.a) Herbivorous fish	♦ Sterile juveniles stocked at density which allows control over multiple years ♦ Growth of individuals offsets losses or may increase herbivorous pressure. Grass carp are illegal in Massachusetts.	♦ May greatly reduce plant biomass in single season ♦ May provide multiple years of control from single stocking ♦ Sterility intended to prevent population perpetuation and allow later adjustments	♦ May eliminate all plant biomass, or impact non-target species ♦ Funnels energy into algae ♦ Alters habitat ♦ May escape upstream or downstream ♦ Population control issues
7.b) Herbivorous insects	♦ Larvae or adults stocked at density intended to allow control with limited growth ♦ Intended to selectively control target species ♦ Milfoil weevil is best known, but still experimental	♦ Involves species native to region, or even targeted lake ♦ Expected to have no negative effect on non-target species ♦ May facilitate longer term control with limited management	♦ Population ecology suggests incomplete control likely ♦ Oscillating cycle of control and re-growth ♦ Predation by fish may complicate control ♦ Other lake management actions may interfere with success
7.c) Fungal/bacterial/viral pathogens	♦ Inoculum used to seed lake or target plant patch ♦ Growth of pathogen population expected to achieve control over target species	♦ May be highly species specific ♦ May provide substantial control after minimal inoculation effort	♦ Effectiveness and longevity of control not well known ♦ Infection ecology suggests incomplete control likely
7.d) Selective plantings	♦ Establishment of plant assemblage resistant to undesirable species ♦ Plants introduced as seeds, cuttings or whole plants	♦ Can restore native assemblage ♦ Can encourage assemblage most suitable to lake uses ♦ Supplements targeted species removal effort	♦ Largely experimental ♦ Nuisance species may eventually return assemblage ♦ Introduced species may become nuisances

Below is a template for the presentation of each management technique

NAME OF MANAGEMENT TECHNIQUE

Margin boxes provide places for photos, illustrations, and comments that may help readers better understand the technique and its use.

How it Works
Description of the technique, how it functions, and what one can expect from it.

Benefits
Explanation of desirable outcomes potentially accrued from the use of this technique. Note that listing does not guarantee that the potential benefit will be realized, and that the level of benefit may vary substantially among cases. Proper planning and implementation are required to gain listed benefits.

Detriments
Explanation of the undesirable impacts that could occur if this technique is used. Note that listing does not guarantee that such detriments will occur, as proper planning and implementation can eliminate many negative consequences. Some negative impacts may be unavoidable, however, and must be balanced with benefits if the technique is to be used.

This format is used for each management technique addressed in this manual.

Information for Proper Application
Listing of the data or analyses necessary to apply the technique in a way that maximizes benefit. Lack of such data may not negate the utility of the technique, but may compromise its value or shift the balance of benefits and detriments.

Factors Favoring the Use of this Technique
Brief explanation of conditions that suggest the technique would be appropriate and that the balance of benefits to detriments would be favorable. The list is generally written in a positive format; absence of the factor may indicate an unfavorable situation in some cases, while in others the lack of a favorable factor may have no negative consequences.

Performance Guidelines
Suggested limits, thresholds and factors that define appropriate use of the technique. This is an effort to define balance points for cost-benefit analysis and thresholds of acceptable risk, but is subjective. Any numerical values should not be construed to be regulatory standards or criteria unless so stated, but are offered for guidance purposes in planning management actions.

Photographs and graphics are by Ken Wagner unless otherwise noted

Possible Permits
Description of permits and approvals that may be necessary in Massachusetts to apply the technique. Listed permits may not be needed in all cases, as thresholds exist for many permits. However, potential applicants should investigate the need for any listed permit in each case.

Impacts Specific to the Wetlands Protection Act
Impacts, either beneficial or detrimental, on the eight specified interests of the WPA are listed and briefly explained.

Cost Considerations
Factors that affect costs and actual cost ranges or general rules from the literature or experience are provided. Recognize that cost can vary substantially among projects, even in what appear to be similar cases. Careful costing is recommended on a case by case basis, but estimates provided here will allow order of magnitude comparisons.

***NON-POINT SOURCE CONTROLS**: Source Management*

How it Works

Source management consists of techniques that eliminate or reduce the potential for pollutants (in this case nutrients) to be released from a source. The most reliable way to do this is to eliminate the source, but this may not be practical in many cases. Alternatively, methods to reduce the release of a pollutant may be instituted. Most source control is achieved through laws, statewide or local bylaws or ordinances that restrict product contents or use or limit activities within a watershed. Where a feasible alternative product exists or targeted land uses do not already exist in the watershed, this can be a very successful approach. Where education reveals both an environmental and economic value by source elimination, success may also be achieved. For example, as established lawns require very little added phosphorus, homeowners should be able to save money and protect water quality while maintaining lawns. However, the cost of no-phosphorus fertilizer is not less than phosphorus-rich brands, and a cultural shift is needed to get people to put water quality ahead of their lawns or their pocketbooks. Additional methods of nutrient source control include erosion prevention, pet waste collection, management of wildlife, and water quality-based zoning. Phosphorus and nitrogen load reductions are highly variable, but tend not to exceed 33% and are often <10%. Use of source controls to prevent loading before it ever starts is the most beneficial use of this approach.

Eliminating the sources of nutrients and other pollutants requires considerable up-front study and documentation of potential impact. It also requires much public education and a willingness to work with lawmakers to craft effective but fair laws.

Benefits

- Prevention, elimination or reduction of sources clearly reduces the potential nutrient load
- Costs can be minimal and are spread over the population
- Pollutants other than nutrients can be controlled by the same actions

Fertilized green lawns often translate into a fertilized green lake

Detriments

- Source controls are the first line of defense, but will rarely be successful as the only line of defense.
- Compliance may be difficult to track or enforce
- Urbanized or agricultural watersheds may contain many sources that cannot be eliminated or even substantially reduced

Information for Proper Application

- Knowledge of the portion of the load comprised by the targeted source(s)
- Education and compliance programs
- Regulatory jurisdiction and limitations
- Means to measure success

Uncovered exterior storage of fertilizers and pesticides represents an unnecessary risk

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is associated with NPS pollution
- Studies have demonstrated the impact of identifiable sources
- Jurisdiction can be claimed over areas of NPS contribution
- Zoning or other restrictions on uses of land or products are properly justified and consistent with applicable state and local laws

Performance Guidelines

- Establish an effective public process for involvement of all relevant parties
- Collect the data necessary to support the control effort
- Focus on education before new regulation
- Enforce existing regulations equitably
- Monitor at a scale appropriate to the control effort; demonstrate improvement on or from small parcels before seeking to document any overall change in the lake. Seek funding to facilitate an incentive program

Possible Permits

- None likely

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected by source controls.

Cost Considerations

- Variable but mostly low and internalized
- Assume $1-10/person for education or compliance effort

Non-Structural Source Controls include:

- **Land Purchase for Conservation Purposes**
- **Conservation Easements - Purchase of development or other use rights for land**
- **Zoning**
- **Watershed Protection Districts**
- **Aquifer Protection Districts**
- **Wetlands Protection Statutes**
- **National Pollutant Discharge Elimination System (NPDES)**
- **Household Hazardous Waste Collection**
- **Fertilization Limitations**
- **Lawn Waste Control**
- **Vehicle Cleaning Regulations**
- **Agricultural Management Planning**
- **Other Ordinances and Regulations Governing Activities on the Land or Water**
- **Education**

NON-POINT SOURCE CONTROLS:
Pollutant Trapping by Maintained Inlet Devices

How it Works

Deep sump catch basins equipped with hooded outlets can be installed as part of a storm water conveyance system. Deep sumps provide capacity for sediment accumulation and hooded outlets prevent discharge of floatables. Catch basins are usually installed as pre-treatment for other BMPs and are not generally considered adequate storm water treatment as a sole system. Volume and outlet configuration are key features that maximize particle capture, but it is rare that the finer fraction of the sediment/nutrient load (which contains most nutrients) is removed by these devices. As a consequence, phosphorus removal is normally about 1-20% and nitrogen removal is similar.

A number of more advanced chamber designs are available. These self-contained units include an initial settling chamber for sediment removal, typically have hooded internal passages to trap oil and other floatables, and often incorporate some form of outlet pool to control exit velocity. Several rely on a vortex design to enhance sediment removal, while others rely on filtering mechanisms to augment the settling process. Such systems are most applicable as pre-treatment for other BMPs, but can trap much of the particulate nutrient load and are generally well suited as retrofits for relatively small areas in developed watersheds. Installing these devices as off-line systems may enhance nutrient removal, but their more common use as on-line pre-treatment devices can be very beneficial.

Inlet devices are the first structural element in storm water management and are important to overall system function. However, inlet devices are rarely sufficient as the only element of a storm water management system.

Such devices must be maintained, with periodic clean-out as determined by experience with filling rate. Typically they must be cleaned once per year, with twice per year (spring/fall) cleaning maximizing performance. Street sweeping is not essential to device performance, but is often integral to pavement management where inlet devices are used as significant pollutant controls.

Benefits

- Traps up to 80% of solids with associated pollutants
- Removal of coarse settleables and floatables maximizes discharge aesthetics
- Greatly extends performance of downstream controls such as detention or infiltration
- Installation below grade minimizes impacts on land use

Detriments

- Up to 90% of nutrients are dissolved or associated with the 20% smallest solids that are not removed by these traps
- Failure to maintain devices may result in no removal or clogging and flooding
- Generally inadequate as the sole control mechanism

Information for Proper Application

- Proper device size and attributes for expected load and cleaning frequency
- Monitoring to assess effectiveness and any need for adjustment

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is documented to be associated with coarse particulate NPS pollution.

Advanced grease and grit trap (Vortechnics)

- Studies have demonstrated the impact of identifiable storm water sources (e.g., piped runoff)
- Water associated with NPS inputs is important to lake hydrology
- Sizing and pollutant removal functions have been properly calculated
- Additional controls (e.g., detention, infiltration) are planned and can be enhanced by this approach

Street sweeper

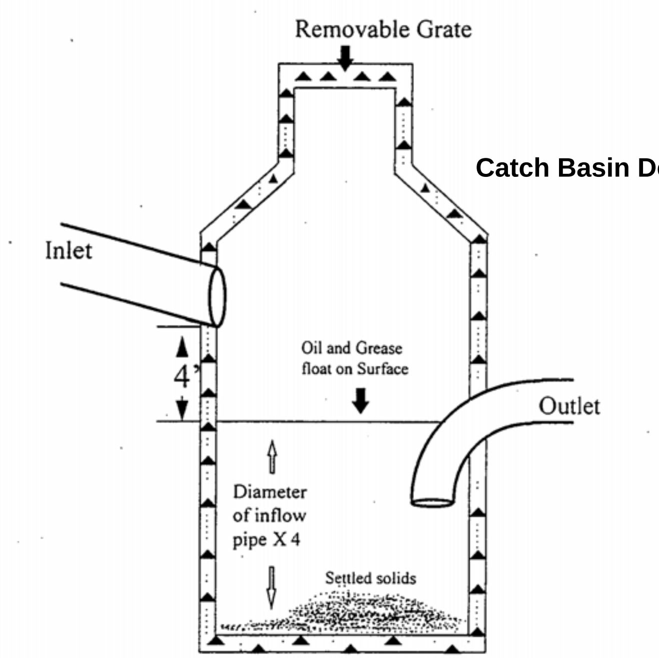
Performance Guidelines
- Collect the data necessary to demonstrate the problem and potential for improvement
- Design the system to meet demonstrated needs
- Develop a storm water management plan in which inlet devices are one element; do not expect inlet devices to solve all storm water problems
- Develop a maintenance plan
- Monitor at a scale appropriate to demonstrating results

Catch basin cleaner

Possible Permits
- None likely

Impacts Specific to the Wetlands Protection Act
All interests of the WPA are either benefited or unaffected.

Cost Considerations
Costs tend to range from a low of around $3000 for simple deep sump catch basins to a high of $30,000 for larger advanced basins with swirl concentrators, filters, multiple chambers, or other special controls. Catch basin cleaning tends to cost $30-100 per basin on a contract basis, depending on the number of basins cleaned. Purchase of street sweepers or catch basin cleaners can represent an expense in excess of $100,000 each, plus maintenance and operation costs.



Catch Basin Design

NON-POINT SOURCE CONTROLS: *Pollutant Trapping by Buffers and Swales*

How it Works

Buffer strips are areas of grass or other dense vegetation that separate a waterway from an intensive land use. These vegetated strips allow overland flow to pass through vegetation that filters out some percentage of the particulates and decreases the velocity of the storm water. Particulate settling and infiltration of water often occurs as the storm water passes through the vegetation. Buffer strips need to be at least 25 ft wide before any appreciable benefit is derived, and superior removal requires a width >100 ft. This can create land use conflicts, but creative planting and use of buffer strips can be a low cost, low impact means to minimize inputs to the aquatic environment. Removal of phosphorus and nitrogen varies substantially (20-90%), with averages in the vicinity of 30% but greater removal achievable with proper design.

Substantial buffer

Swales are engineered ditches that provide detention and infiltration while transporting runoff to a planned discharge point. Use of dense vegetation and stone or wood check dams within the confines of a channel designed to handle substantial flows of runoff can slow water velocity, allow particulate nutrients to settle, and provide infiltration of a substantial fraction of the dissolved nutrient load. Less removal may occur during higher flows, but such flows do not often carry more of the total nutrient load than smaller storms in most watersheds as a consequence of the first flush phenomenon. Swales may be adequate for nutrient removal if large and long enough, but are more effective as pre-treatment devices before discharge to detention systems. Phosphorus removal is also highly variable (0-70%) with typical average removal at about 30%. Nitrogen removal averages about 25%.

Minimal buffer

Benefits

- Passively removes nutrients without long detention of flow
- Relatively simple to build and maintain
- Can blend aesthetically into the landscape
- May provide substantial habitat value as well as pollutant removal

Lack of buffer

Detriments

- Requires substantial land area
- Steep slopes will limit removal potential
- Maintenance may reduce effectiveness until vegetation re-grows

Photographs on this page were provided by L. Gaherty of the BRPC.

Information for Proper Application

- Climatic and drainage area data to provide estimate of maximum hydrologic loading
- Water quality data with separation of particulate and dissolved fractions, to allow estimation of needed width or length
- Ground slopes, soil types, and planned vegetative cover to allow removal estimation
- Monitoring to assess effectiveness and any need for adjustment

Factors Favoring the Use of this Technique

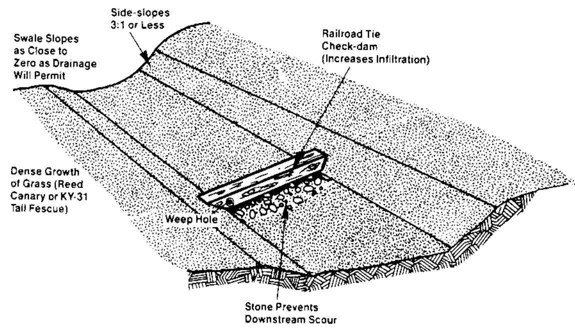
- A substantial portion of the P and/or N load is associated with NPS pollution

- Studies have demonstrated the impact of identifiable sources
- Water associated with NPS inputs is important to lake hydrology
- Sizing and pollutant removal functions have been properly calculated
- Land is available for placement of BMPs

Swale

Performance Guidelines

- Collect the data necessary to demonstrate the problem and potential for improvement
- Design buffers and swales to meet demonstrated needs; remember habitat and aesthetic functions as well as water quality benefits
- Use only native species in planting programs
- Seek funding to provide an incentive program
- Monitor at a scale appropriate to demonstrating results



Swale Design (after Schueler et al., 1992)

Possible Permits

- None likely unless natural wetland resources are involved

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected, with the possible exception of groundwater quality protection if infiltration occurs in the buffer or swale.

Cost Considerations

Often very inexpensive to build and maintain, but maximum performance may require occasional cleaning and replanting. May cost as much as a few dollars per square foot of buffer (exclusive of any land purchase costs) and $25-50 per linear foot of swale with velocity barriers and infiltration capacity.

Elements of a proper buffer (provided by L. Gaherty of the BRPC)

NON-POINT SOURCE CONTROLS: *Pollutant Trapping by Detention*

How it Works

Detention ponds are basins that are designed to hold a portion of storm water runoff for at least 12-24 hours and preferably longer. Pollutant removal is accomplished mainly through settling and biological uptake, although incorporation of infiltration capacity can add substantial adsorptive capacity as well. Design features are extremely varied and depend on pollutant removal goals, regional climate, and localized site conditions. Detention facilities can be large ponds with multiple forms of aquatic habitat or small "rain gardens". Wet detention ponds are more effective than dry detention ponds as the latter have a greater risk of sediment re-suspension and generally do not provide adequate soluble pollutant removal. Dry detention ponds have less potential to support mosquitoes and provide greater detention capacity per unit cost. Although potentially very effective, the land requirement is typically large; the area should be at least 2% of the drainage area it serves, and preferably as much as 7% of that area.

Length to width ratio can be an important feature of detention systems, with a L:W ratio of 2:1 often applied. Outlet configuration can also make a big difference; graduated outlets that allow more water to exit as the water level rises are often needed to ensure flood protection, while filtration berms are used to hold back fine solids and hooded overflows are used to trap floatables. Addition of coagulants can enhance removal of dissolved nutrients and colloidal solids. Removal rates for phosphorus vary widely with design features and the nature of the load, with average values of 30-65% reported. Nitrogen removal tends to be somewhat lower, with averages in the 30-40% range.

Benefits

- Provides flood protection as well as water quality enhancement
- Generally passive removal with limited maintenance needs
- Can provide habitat value and blend aesthetically with landscape

Dry detention basin

Detriments

- Requires substantial land area
- Construction problems are common in areas of high ground water or abundant bedrock
- Wet ponds may become mosquito breeding areas

Information for Proper Application

- Climatic and drainage area data to provide estimate of variability in hydrologic loading
- Water quality data with separation of particulate, colloidal and dissolved fractions, to allow estimation of needed detention time and supplemental features (e.g., plantings, outlet features, polymer addition)
- Soil types, ground water depth and related data for construction planning
- Monitoring to assess effectiveness and any need for adjustment

Wet detention basin

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is associated with NPS pollution
- Studies have demonstrated the impact of identifiable sources
- Water associated with NPS inputs is important to lake hydrology
- Sizing and pollutant removal functions have been properly calculated

- Land is available for placement of the detention system
- Detention capacity is available to hold a substantial portion of the targeted runoff
- Detention and/or infiltration will not cause local flooding problems, wet basements, or structural damage

Performance Guidelines

- Collect the data necessary to demonstrate the problem and potential for improvement
- Design the system to meet demonstrated needs; consider flood prevention and water quality enhancement, providing appropriate capacity and rate of through-flow
- Develop a maintenance plan
- Monitor at locations appropriate to demonstrating results

Outlet structure for detaining a range of flows

Possible Permits

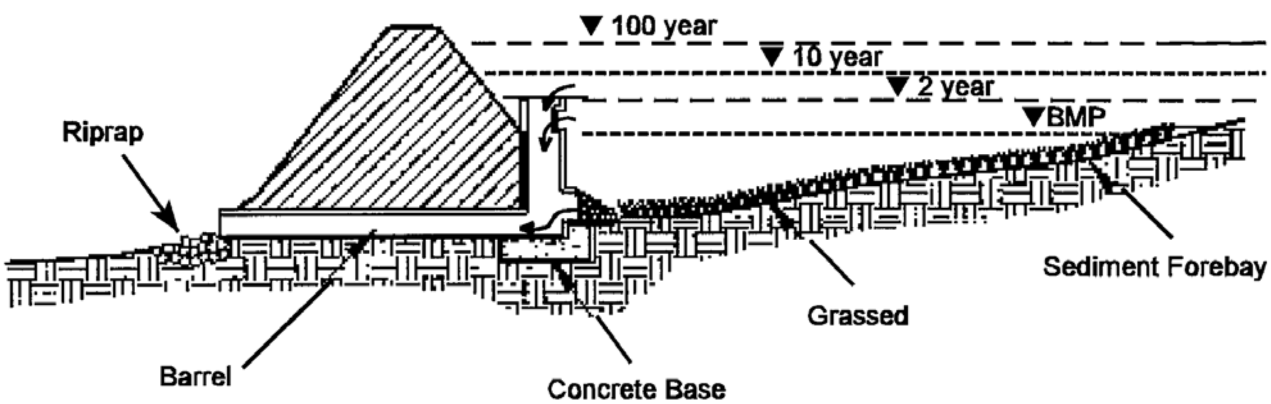
- NPDES permit from EPA under special circumstances
- WPA permit if natural wetland resources are involved

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected, with the possible exception of groundwater quality protection if infiltration occurs in the detention area.

Cost Considerations

Costs will vary with size, depth and special features, with typical values of $10-30 per cubic yard of capacity. On an areal basis, costs of $50,000-200,000 per acre could be expected, with an expected depth of at least 3 ft.



Detention Basin Design (after USEPA, 1999)

NON-POINT SOURCE CONTROLS:
Pollutant Trapping by Infiltration

How it Works
Water quality response to runoff has been clearly linked to the portion of the watershed that is impervious. While natural surfaces such as clay soil, muck soils, and exposed rock are functionally impervious, human derived surfaces such as roads, parking lots, driveways and roofs are major sources of runoff in developing watersheds. Once imperviousness exceeds 10% of the watershed area, water quality problems are often observed, and at levels in excess of 25%, water quality impairment almost always occurs. Imperviousness can be minimized by narrowing roadways, limiting development footprints, and incorporating porous pavement wherever feasible. Removal rates vary, but average close to 50% for phosphorus and 60% for nitrogen when infiltration is facilitated.


Leaching catch basins

Infiltration systems may include trenches, basins or dry wells, and involve the passage of water into the soil or through an artificial medium such as a constructed berm. Particles are filtered by the soil matrix and many soluble compounds are adsorbed to soil particles. Such systems require sufficient storage capacity to permit the gradual infiltration of runoff into suitable soils or through the constructed medium. Pre-treatment of the runoff removes larger particles before filtration, thereby aiding in the prevention of infiltration system failure due to clogging and sediment accumulation. Phosphorus removal is maximized by infiltration, but dissolved forms of nitrogen may be only minimally affected. Removal rates for phosphorus tend to be moderate to high, with averages of 60-70%. Despite limited effectiveness for dissolved nitrogen, total nitrogen removal rates are moderate, with averages near 50%. Variability is high, however, as a function of local conditions and design.


Leaching trench

Site constraints such as shallow depth to groundwater or bedrock and poorly drained soils often limit the effective use of infiltration, so detailed knowledge of the site is essential when planning infiltration facilities. In sites with suitable conditions, off-line infiltration systems are generally preferred. One key to successful infiltration is providing adequate pre-infiltration settling time or other treatment to remove particles that could clog the interface at which infiltration occurs. Another key is having sufficient runoff detention capacity to allow delivery of runoff to the infiltration surface at a rate that maximizes performance. Both key factors can be met by combining adequate detention facilities with infiltration systems.

Benefits
- High removal based on multiple processes in soil or artificial media
- Removes many contaminants besides nutrients
- Can be used to minimize runoff and maximize ground water recharge
- Can include underground leaching to minimize surficial land use


Filtration berm

Detriments
- Poor removal of dissolved nitrogen in most cases
- May contaminate ground water if pollutants (like dissolved N) are mobile
- Requires substantial land area; may interfere with surface uses if not subterranean

- May require substantial detention capacity or not work at all if soils are not sufficiently permeable
- May raise localized groundwater table; possible issues for structures
- May clog if not adequately maintained; pretreatment of influent often necessary for optimal performance

Information for Proper Application

- Soil conditions and groundwater table elevation, to evaluate efficacy of infiltration and determine design criteria
- Drainage area and climatic data to estimate range of expected loading
- Water quality data for evaluating possible impacts on groundwater
- Monitoring to assess effectiveness and any need for adjustment

Permanent leaching basin

Temporary leaching basin

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is associated with NPS pollution
- Studies have demonstrated the impact of identifiable sources
- Sizing and pollutant removal functions have been properly calculated
- Land is available for placement of infiltration facilities
- Detention capacity is available to hold excess runoff until it can be infiltrated
- Infiltration will not cause local flooding problems, wet basements, or structural damage
- Infiltration will not cause groundwater quality deterioration

Performance Guidelines

- Collect the data necessary to demonstrate the problem and potential for improvement
- Design the system to meet demonstrated needs; provide trapping for solids that may clog system and appropriate storage capacity for expected infiltration rate
- Evaluate possible groundwater impacts; adhere to Massachusetts Stormwater Policy
- Develop a maintenance plan
- Monitor at locations appropriate to demonstrating results

Possible Permits

- Groundwater Discharge Permit from DEP

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected, with the possible exception of groundwater quality protection. The Massachusetts Storm Water Policy governs pre-treatment needs for infiltration scenarios and should be consulted.

Cost Considerations

Infiltration system costs vary with size and local site conditions. Simple leaching catch basins can be installed for $5000-10,000 each, while leaching trenches will tend to cost more (around $30,000 for a small system handling a few acres). Elaborate systems with back-up detention may cost considerably more. Leaching detention basins will cost about the same as a regular detention basin if the soils are suitable or could be up to twice as expensive if soil modification is needed. Maintenance needs may be substantial, including annual or semi-annual inspection and cleaning as warranted.

NON-POINT SOURCE CONTROLS:
Pollutant Trapping by Constructed Wetlands

How it Works

Detention systems tend to be created wetlands, but design features that combine open water and emergent wetlands tend to provide superior nutrient removal. These systems maximize pollutant removal through vegetative filtration, nutrient uptake, soil binding, bacterial decomposition, and enhanced settling. Much of the effectiveness of the treatment is related to microbial action; the plants are more the substrate than the active pollutant removers, but removal rates are higher in the presence of plants. Wetland systems are suitable for on-line or off-line treatment, but maintenance of adequate hydrology with off-line systems is necessary to support the complete wetland features that maximize effectiveness.

Constructed treatment wetlands can function effectively in cold environments, mainly as a function of subsurface flow and related microbial uptake, adsorption, and filtration processes. Presence of aerobic and anaerobic conditions in sequential portions of the system is essential to reduction in nitrogen through sequential oxidation and reduction of nitrogen forms to convert organic forms to nitrogen gas. There are many details of design that affect performance, with multi-chamber, high detention time systems with both surface and subsurface flow providing the highest nutrient removal rates. Decay of vegetation may raise nutrient export at times. Phosphorus removal is therefore highly variable, but averages 55-65%. Nitrogen removal is also highly variable, but averages close to 40%.

Benefits

- Combines features of emergent wetlands, ponds, and groundwater for maximum pollutant removal
- Can be installed in areas with high groundwater table
- May provide supplemental habitat value
- Relatively low maintenance needs

There are many types of wetlands, both natural and created. Successful design of wetlands for storm water treatment benefits from a clear understanding of treatment goals and knowledge of wetland functions and processes.

Detriments

- Some seasonal component to removal efficiency, although subsurface flow can offset this in many cases
- May have net release of nutrients during hydraulic washout after decay periods
- May act as breeding ground for mosquitoes

Information for Proper Application

- Soil conditions and groundwater table elevation, to evaluate efficacy of wetland maintenance and determine design criteria
- Drainage area and climatic data to estimate range of expected loading
- Water quality data for evaluating possible impacts on groundwater and special design needs for maximizing pollutant removal
- Monitoring to assess effectiveness and any need for adjustment

Constructed wetland

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is associated with NPS pollution
- Studies have demonstrated the impact of identifiable sources
- Sizing and pollutant removal functions have been properly calculated
- Land is available for placement of wetlands
- Detention capacity is available to hold a substantial portion of the targeted runoff

- Detention and/or infiltration will not cause local flooding problems, wet basements, or structural damage
- Infiltration will not cause groundwater quality deterioration
- Maximum nitrogen removal is desired

Performance Guidelines

- Collect the data necessary to demonstrate the problem and potential for improvement
- Design the wetland to meet demonstrated needs; utilize multiple wetland processes; consider flood prevention and water quality enhancement, providing appropriate capacity and rate of through-flow
- Remember habitat and aesthetics in design, and use only native species in planting programs
- Develop a maintenance plan
- Monitor at locations appropriate to demonstrating results

Possible Permits

- Groundwater Discharge Permit from DEP

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected, with the possible exception of groundwater quality protection if infiltration occurs in the wetland.

Cost Considerations

Wetland creation can be very inexpensive if local site conditions favor wetness, but considerable design effort and careful construction are needed to maximize performance. Costs will be similar to those of detention basins ($50,000-200,000/acre), with potential additional planting costs. Multi-chamber designs that facilitate nitrification/denitrification will be most effective yet most expensive.

Constructed wetland

Constructed wetland forebay for a lake

Constructed wetland with multiple chambers (provided by D. Lowry of ENSR)

NON-POINT SOURCE CONTROLS:
Pollutant Trapping by Agricultural Best Management Practices

How it Works

The spatial and temporal features of planting, coupled with the actual crops chosen, can greatly affect the movement of nutrients off farm fields. Cover crops stabilize soils, and may be used as interim cover or as a supplemental crop in association with plants that grow up through the cover crop to form another layer above it. Interspersing of crops can create buffer zones such that potential nutrient losses facilitated by harvest of one crop are trapped by the other. The basic philosophy of the planting plan is to minimize bare soil and create buffer zones that have economic as well as ecological value.

The pattern of plowing on a farm can be a great aid to minimizing the movement of nutrients. Conservation tillage involves contouring, terracing, and related approaches that minimize the peak velocity attained by runoff and maximize infiltration of rainwater. Coupled with an effective planting plan, the quantity of runoff generated from the field can be greatly reduced; this translates into reduced nutrient loading to area waterways.

Feed crops

Livestock operations have the potential to contribute nutrient loads that overshadow most other sources, and represent a health hazard as well. Manures are of special concern as they are relatively high in nutrients and attempts to meet nitrogen requirements by application of manure may result in losses of phosphorus to surface waters. Handling manure in a manner that limits interaction with precipitation and incorporation into runoff is essential to protecting aquatic habitats. Manure application should be kept as far away as possible from streams and lakes and the application of manure should be avoided during winter months when frozen soils result in large losses in runoff. Covered feeding areas, manure collection systems, covered storage, and proper spreading on farm fields or disposal by other means are all necessities of best management for livestock facilities. Studies suggest alum and other chemical additives may reduce phosphorus leaching from manure. Conversion of manure to energy is a novel approach now being advanced.

Cranberry production is large in MA, and these operations are usually associated with lakes. While bogs use water to irrigate and most apply fertilizers and pesticides, the impact of these activities on downstream lakes is not certain. Current impacts on lakes from cranberry bogs tend to be linked to the fall harvest for wet-pick bogs and to periodic flushing (usually a post harvest through spring event) of all bogs. Water discharged from bogs, if not detained or otherwise treated, may carry large amounts of particulate nutrients into the receiving waters, often a lake or tributary to a lake. Dissolved phosphorus in anoxic winter discharges may be high. Nitrogen is usually in short supply in bogs, and concentrations of readily available nitrogen tend to be low. Microbial processes in lakes may recycle the bog inputs and eventually increase lake fertility. The key factor appears to be the volume of discharge relative to the volume of the lake, with larger relative volumes having greater potential impact.

Livestock operations

Overall reduction in nutrient loading is difficult to predict, given the wide range of agricultural activities, local site conditions, and BMP options. Major reductions (>50%) have been realized from manure handling improvements, but substantial reductions from crop management practices also appear possible. Localized monitoring is essential to tracking progress.

Benefits
- Can minimize soil loss and associated economic cost
- Can minimize fertilizer costs
- May provide health benefits as well as nutrient loading reduction

Farm with indication of contour planting

Detriments
- Generally has unfavorable short-term cost-benefit balance from farmer's perspective, unless supporting public funds are available
- Soil capacity for phosphorus from manure spreading is quickly exhausted, leading to a need for new and large disposal areas

Information for Proper Application
- Soil nutrient needs, to assess fertilizer needs or adsorptive capacity
- Farming plan, to ensure that BMPs have minimum impact on productivity
- Climatic information and local drainage pattern, to evaluate key sites/periods
- Ongoing monitoring to assess impacts and additional management needs

Cranberry harvest

Factors Favoring the Use of this Technique
- A substantial portion of the P and/or N load is associated with NPS pollution
- Studies have demonstrated the impact of identifiable sources
- Sizing and pollutant removal functions have been properly calculated
- Land is available for placement of BMPs
- Cooperation of farmers
- Agricultural assistance funding is available

Performance Guidelines
- Collect the data necessary to demonstrate the problem and potential for improvement
- Seek involvement from farmers and farm agencies in selecting BMPs; develop a clear understanding of the agricultural operation before specifying BMPs
- Apply BMPs to meet demonstrated needs; focus on soil, nutrient and pesticide mobility
- Seek funding to provide an incentive program
- Develop a maintenance plan
- Monitor at locations appropriate to demonstrating results

Given the financial constraints faced by most farmers and the food-producing value of agriculture, successful agricultural BMP implementation often depends upon understanding the agricultural operation and finding funding support for capital improvements that benefit the farm as well as the lake.

Possible Permits
- None likely unless wetland resources are involved

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected.

Cost Considerations

Costs are highly variable in accordance with the type of farming, need for controls, and local site conditions. Manure handling and storage systems often cost on the order of $100,000 for a typical dairy heard or other livestock operation in MA. Procedural controls like conservation tillage or planting plans may carry minimal cost.

NON-POINT SOURCE CONTROLS:
Pollutant Trapping by Managing Septic Systems

How it Works

Most on-site domestic sewage treatment consists of either the older cesspool (single chamber, open bottom pit type, no longer in construction) or the newer septic tank with leaching field or chamber (conventional septic systems). Most septic systems consist of a subsurface chambered tank where scum and settleable solids are removed from the liquid by gravity separation and a subsurface drain system where the clarified liquid effluent percolates into the soil. Regular inspection of the system is recommended, with pumping as experience dictates or according to calculations based on the number of people served and the size of the tank.

For conventional septic systems, the management techniques are detailed in Title 5 of the State Environmental Code 310 CMR 15.00 et. sec. For any new septic systems, the leach field must have a minimum setback of 50 feet from surface waters. To protect resources, additional restrictions on septic systems may be imposed by local ordinance.

Phosphorus is removed to a substantial degree in both the septic tank and the leachfield, owing to chemical reactions that tend to convert phosphorus into particulate forms. Even beyond the leaching field or chamber, soils adsorb phosphorus at high rates. Removal rates may be only 20-50% in the actual septic system, but removal rates >90% are expected through soil adsorption in most cases. Where the system is in fractured rock or compacted soil with fissures, high removal rates may not be realized. Likewise, where system failure results in breakout of septic effluent at the ground surface, or the soil capacity for phosphorus adsorption is exhausted, removal of phosphorus will be severely reduced. The phosphorus load to a lake from septic systems requires careful evaluation, however; do not assume high loading.

Septic system leachfield being installed

Even a properly sited, well-maintained, conventional septic system will release a substantial amount of nitrogen into the ground. Physical and chemical soil processes do little to reduce discharge concentrations, which may exceed 50 mg/L. Site limitations and the inability of conventional septic systems to capture more than about 10% of the nitrogen load has fostered a variety of alternative systems. Advanced on-site wastewater disposal systems may be applied in cases where a septic system fails and/or the site cannot accommodate a conventional system due to size or performance needs. There are many approved alternate technologies for septic systems in Massachusetts.

Septic system pump-out

Many advanced systems are designed to remove nitrogen, with removal rates >50% and sometimes approaching 90%. Few advanced systems have a demonstrated ability to remove significantly more phosphorus than conventional systems, although some are being tested. Some systems are designed to enhance infiltration in low permeability sites, but all focus on achieving better overall effluent quality.

Tight tanks are an older alternative that eliminates the leaching function of on-site wastewater disposal and necessitate more frequent pump-out and hauling to an approved septage disposal site, usually a wastewater treatment facility operated by a municipality or regional authority.

Benefits

- Properly designed, constructed and maintained septic systems minimize phosphorus input to lakes
- Advanced on-site wastewater disposal systems can minimize phosphorus and nitrogen inputs to lakes
- Tight tanks eliminate discharge to the groundwater or lake

Detailed D/F studies (those involving direct measurement of in-seepage quality) indicate limited impacts from septic systems on most lakes (range of 0-25% of total P load, with a mean of 6-8%). Septic systems should be managed for long-term successful operation, but it should not be assumed that they are major sources of phosphorus without supporting data.

Detriments

- Conventional septic systems provide minimal nitrogen removal
- Conventional septic systems do not function well where the groundwater table is high (<4-6 ft below leachfield elevation)
- On-site wastewater disposal systems depend upon soil adsorption of phosphorus for much of the removal function; leachfields are eventually exhausted, leading to inputs to lakes
- Maintenance is not required by state law or most local ordinances, and no individual effluent limitations are applied

Information for Proper Application

- Careful investigation that documents the importance of septic system inputs on lake conditions
- Local soil and groundwater conditions to allow proper siting and design
- Use levels (number of people, presence of dishwashers, garbage grinders, and other conveniences) to allow proper design
- Means to measure success

Conventional septic systems are potentially large contributors of nitrogen, as little nitrogen is removed by the system or the soil into which effluent is discharged. Advanced designs can provide greater removal at increased cost.

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is associated with septic systems
- Studies have demonstrated the impact of septic systems on the lake
- Sizing and pollutant removal functions have been properly calculated
- Required changes are properly justified and consistent with applicable state and local laws

Performance Guidelines

- Collect the data necessary to demonstrate the problem and potential for improvement
- Design systems or rehabilitation programs to meet demonstrated needs; match available designs to water quality goals
- Adhere to Title V regulations in the design and construction of septic systems
- Develop an inspection and maintenance plan
- Monitor at locations appropriate to demonstrating results

Possible Permits

- Title V compliance through DEP

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected by improved management of on-site wastewater disposal systems.

Cost Considerations

A conventional septic system will typically cost on the order of $10,000-15,000, with increased costs if local site conditions are problematic. Advanced systems tend to be more expensive, often in the range of $20,000-30,000 or even higher.

POINT SOURCE CONTROLS

How it Works

Point source pollution is defined as originating from a pipe or other distinct conveyance under federal regulations. Originally intended to deal with wastewater treatment discharges from industrial or municipal operations, the definition of a point source was extended in 1990 to include storm water discharges where the delivery was an observable pipe, ditch, swale, curb cut, or other delivery device that could be construed as meeting the federal definition. Certain activities, such as concentrated animal feedlot operations (CAFOs), have also been classified as point sources in this manner. Point source discharges are governed by the National Pollutant Discharge Elimination System, or NPDES. Many states have been authorized to administer this program, but Massachusetts is still governed by the federal program and does not issue NPDES permits itself. The DEP is involved in NPDES issues, however, and provides considerable guidance on meeting federal requirements.

Wastewater treatment

Although industry and other activities may have point source discharges of pollutants, most of the nutrient sources are from municipal WWTFs. The current thrust of WWTF permitting emphasizes meeting effluent concentrations that will protect lakes with reasonable dilution. Domestic wastewater enters a WWTF with P in excess of 3 mg/L and sometimes as high as 15 mg/L. N levels can exceed 40 mg/L, with values up to 70 mg/L not uncommon. Wastewater treatment in Massachusetts involves primary and secondary treatment and in some cases, tertiary treatment. Primary treatment involves the settling out of suspended solids in sedimentation tanks. Secondary treatment usually involves a biological component to oxidize and convert organic wastes, sometimes with chemical addition that reduces P levels. Resulting P concentrations can be as low as 0.3 mg/L, but are more often >1 mg/L and often as high as 3-4 mg/L. N levels of 10-15 mg/L are common, with concern directed toward the fraction of the N load that is present as toxic un-ionized ammonia. Well-functioning secondary treatment WWTFs tend to convert nearly all ammonia/ammonium to nitrate. However, nutrient levels from even the best secondary treatment facilities are well in excess of desirable levels in lakes.

Wastewater point source discharge

Advanced waste treatment, or tertiary treatment, usually involves the removal of phosphorus and/or nitrogen. Phosphorus compounds are most often removed by coagulation with chemicals, sometimes with an additional filtering step. Dissolved air flotation (DAF) can also greatly reduce P concentrations, but is more commonly used in drinking water treatment than wastewater situations. Achievement of concentrations <0.5 mg/L is routinely possible through tertiary treatment, with targets set as low as 0.1 mg/L in some cases and current research aimed at achieving P concentrations of 0.01 to 0.02 mg/L. However, with a target lake P level of <0.02 mg/L and preferably <0.01 mg/L, WWTF inputs currently require substantial dilution to avoid eutrophication impacts on lakes.

There are many methods to remove nitrogen compounds, including ammonia stripping by air and nitrification-denitrification in biological reactors. Other advanced treatment methods that protect lakes include adsorption of residual organic and color compounds on activated carbon and the use of reverse osmosis and electrodialysis to remove dissolved solids. Wetland treatment has become popular for nutrient control as a polishing step in WWTFs, and some WWTFs are based mainly on biological activity as a mainstay of wastewater treatment.

Note that storm water that is conveyed through any type of drainage system is defined by the EPA as a point source and subject to NPDES permits. The most salient provision of the NPDES program for storm water is the requirement for a Storm water Pollution Prevention Plan (SWPPP), which is a site- and activity-specific management guide for minimizing impacts on runoff from the site. The emphasis is on prevention of pollution, not treatment or remediation. The SWPPP includes provision for managing potential pollutants stored or used on site, limiting exposure of potentially polluting activities to precipitation and runoff, and measures for responding to spills, leaks, or other releases. Monitoring provisions are industry-specific and not overly stringent, but the whole process is a major step toward minimizing contamination of runoff and documenting that effort.

In some cases inflows to wastewater treatment plants are combined with urban storm water flow. This is most often a result of underdesign of conveyance systems in the face of expanding user populations, with combined manholes for easy access to both sanitary and storm sewers being the primary point of mixing. This situation leads to excess hydraulic loading to the drainage system and/or WWTF during storms that may result in untreated or incompletely treated wastes being discharged to streams or lakes. Separating these Combined Sewer Systems (CSS) to avoid Combined Sewer Overflow (CSO) has been emphasized by the EPA and DEP for about two decades now, and substantial progress has been made.

Drainage inlets typically lead to pipes that become stormwater point source discharges

One less well-known point source that has become a problem in Massachusetts is drinking water treated to comply with anti-corrosion provisions of the federal Safe Drinking Water Act of 1996. The most common chemical used to inhibit corrosion in distribution pipes is calcium phosphate, with concentrations of P in excess of 1 mg/L in many cases and sometimes as high as 5 mg/L, not much different than secondary treated sewage! Blowdown from boilers or hydrants, discharged directly to storm water drainage systems, or leaks from water mains can provide a substantial input of P to downstream lakes. Use of potable water for make-up water in smaller ponds and swimming facilities can actually cause an algal bloom. Alternatives to calcium phosphate, such as a variety of silicates, are available but more expensive.

Management of point sources generally falls into the same categories as for non-point sources: source management and pollutant trapping. Source management includes bans on phosphorus in detergents and a variety of pretreatment requirements for businesses that might otherwise contribute excessive amounts of oils, metals or other contaminants of special concern. Pollutant trapping is a function of the treatment process, with tertiary treatment necessary to remove enough nutrients to protect lakes.

Storm water point source discharge

Source management for storm water point sources is essential to improving discharge quality in nearly all cases. Nutrient removal from storm water by treatment will depend on the BMPs applied, with removal rates typically in the 30-60% range. Source management for wastewater treatment facilities is only essential to the extent that it protects the treatment process, with improved treatment providing the greatest reduction in nutrient loading. Actual removal rates for phosphorus average 10% for primary, 20-40% for secondary, and 80-99% for tertiary. For nitrogen, removal rates average 5-10% for primary, 10-30% for secondary, and 50-90% for tertiary.

Benefits

- Control of centralized wastewater collection and treatment can result in a major reduction in loading
- Improved treatment can remove many contaminants as well as nutrients
- Storm water management has great potential for reduced nutrient loading

Detriments

- Discharge of even the “cleanest” treated wastewater may still contain excessive concentrations of nutrients
- Centralized wastewater discharge localizes a potentially major impact and may affect hydrology of contributing watershed areas

Unless dilution by the receiving water is very high (>1000X), tertiary treatment of domestic wastewater is necessary to achieve a phosphorus level that will not harm downstream lakes. Where dilution is low (<10X), impacts may be unavoidable with current technology and discharge to surface waters.

Information for Proper Application

- An accurate nutrient budget that demonstrates the importance of the point source(s) in determining lake quality
- Water quality data for influent that supports treatment design
- Hydrologic data for receiving waters to evaluate dilution effects
- Source analysis for storm water point sources, to allow minimization of impacts on runoff quality
- Ongoing monitoring to assess impacts and additional management needs

Factors Favoring the Use of this Technique

- A substantial portion of the P and/or N load is associated with point source pollution
- Studies have demonstrated the impact of identifiable discharges on the lake
- Water associated with point sources is important to lake hydrology
- Pollutant removal expected from source management or treatment upgrade has been properly calculated and is achievable
- Jurisdiction can be claimed over point sources

Performance Guidelines

- Collect the data necessary to demonstrate the problem and potential for improvement
- Meet all requirements of the NPDES program; seek to establish permit limits that meet water quality goals, but with recognition of other pollutant sources to the target lake
- Design the treatment system or upgrade to meet demonstrated needs; match treatment processes to water quality goals
- Monitor the effluent in accordance with NPDES requirements and at locations appropriate to demonstrating results

Possible Permits

- NPDES permit from EPA, with input from DEP

Impacts Specific to the Wetlands Protection Act

All interests of the WPA are either benefited or unaffected.

Cost Considerations

Costs of source control tend to be nominal and internalized, as with substituting products or ingredients to avoid high nutrient content. Some source controls carry significant cost, as with moving possible contaminants into covered storage, but such action will limit liability on numerous fronts. Cost of treatment upgrade is usually substantial ($5-10 million) and carries significant operational costs as well ($100,000-$1 million/yr), in proportion to the volume of water treated.

***HYDRAULIC CONTROLS**: Dilution and Flushing*

How it Works

Lake waters that have low concentrations of an essential nutrient are unlikely to exhibit algal blooms. While it is preferable to reduce nutrient loads to the lake, it is possible to lower (dilute) the concentration of nutrients within the lake by adding sufficient quantities of nutrient-poor water from some additional source. High amounts of additional water, whether low in nutrients or not, can also be used to flush algae out of smaller, linear impoundments faster than they can reproduce.

When water low in phosphorus is added to the inflow, the actual phosphorus load will increase, but the mean phosphorus concentration should decrease. Dilution or flushing washes out algal cells, but since the reproductive rate for algae is high (blooms form within days to a few weeks), only extremely high flushing rates will be effective without a significant dilution effect. A flushing rate of 10 to 15% of the lake volume per day is appropriate to minimize algal biomass build-up.

Outlet structures and downstream channels must be capable of handling the added discharge for this approach to be feasible. Qualitative downstream impacts must also be considered. Water used for dilution or flushing should be carefully monitored prior to use in the lake. Application of this technique is most often limited by the lack of an adequate supply of low nutrient water.

Benefits

- Reduces algal biomass without reducing nutrient loading
- May provide improved downstream habitat or recreational opportunity through elevated flows

Dilution with "clean" water

Detriments

- Diverts water from other uses
- May cause flooding if downstream channel is incapable of handling enough flow
- Will not work with many isolated coves

Information for Proper Application

- Accurate hydrologic and nutrient budgets to allow evaluation of potential benefits
- Assessment of probable in-lake effects and an evaluation of downstream impacts
- Reliability of source water
- Routing information for new water source
- Monitoring program to track changes in detention time, nutrient levels and water clarity

Flushing of Moses Lake, WA did improve conditions

Factors Favoring the Use of this Technique

- Actual reduction in nutrient inputs from identifiable sources is not practical, either for technical or jurisdictional reasons
- Water level fluctuation will not differ greatly from pre-treatment conditions
- Adequate water of a suitable quality is available for dilution or flushing
- Downstream problems with water quantity or quality will not be caused

Performance Guidelines

- Develop reliable hydrologic and nutrient budgets and evaluate probable outcomes of dilution or flushing

- Determine impacts of diverting water for use in dilution or flushing
- Determine possible effects on stratification and related habitat in the lake
- Determine possible downstream effects of increased flow
- Design delivery system and any necessary maintenance program
- Control in-lake water level; avoid unnatural fluctuations
- Conduct dilution or flushing mainly during the summer
- Monitor quality of incoming, in-lake, and outgoing water

The primary factor limiting the application of dilution is a consistent source of "clean" (low nutrient) water.

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 Permit through DEP may be required for structural alterations in Great Ponds
- Dam Safety Permit may be required through DCR
- Rerouting of water in excess of 100,000 gpd may require a permit under the Water Management Act through DEP
- Possible 401 WQ permit through the DEP, but jurisdiction will depend upon which other permits are required and funding sources
- Possible NPDES permitting through EPA/DEP, depending on water quality of discharge.

Successful flushing requires a resultant detention time of less than about two weeks on a consistent basis during the growing season. This technique is primarily limited by reliability of water supply for this purpose.

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Variable (depends on location of supply relative to discharge and detention time)
- Protection of groundwater supply – Neutral, unless there is a discharge to groundwater, in which case the impact could be beneficial or detrimental
- Flood control - Neutral (added flow must remain within tolerance limits for lake and downstream receiving waters)
- Storm damage prevention – Neutral (added flow must remain within tolerance limits for lake and downstream receiving waters)
- Prevention of pollution - Benefit in the lake (water quality enhancement) and possibly downstream
- Protection of land containing shellfish - Possible benefit through water quality enhancement in the lake and possible detriment with any downstream flow problems
- Protection of fisheries - Benefit (water quality enhancement), but possible detriment through reduced fertility and possible benefit or detriment downstream through flow changes
- Protection of wildlife habitat – Benefit (water quality enhancement), but possible detriment through reduced fertility and possible downstream benefit or detriment through flow changes

Cost Considerations

The cost of dilution and flushing varies mainly with the volume and availability of water. If a nearby upstream source of clean water could be diverted to a lake by gravity, or if a short canal can be constructed to provide a connection to a larger stream or river, the costs may be limited. Purchase of public water for this purpose will likely be very expensive. Expect $500-2500/acre/yr for application of these techniques, inclusive of permitting and monitoring, when a source of water is readily available. Costs may rise to $5,000-25,000/acre/yr if water is purchased, piped and/or pumped.

HYDRAULIC CONTROLS: *Diversion*

How it Works

Diversion is simply the re-routing of a discharge to avoid a sensitive resource, discharging instead to an alternative receiving water, typically downstream of the original discharge location or in another drainage basin. Diverting water from a lake may make sense if the associated nutrient load is undesirable and the loss of the hydrologic load will not have undue negative impacts. Ideally, diversion involves a small amount of water with a large amount of nutrients in it. Diversion is most often practiced in association with wastewater or storm water discharges to lakes with adequate alternative water supplies. It suffers from the philosophical drawback of sending contaminated water elsewhere without addressing the source of nutrients, and may be difficult to permit, but it can be a very effective means of reducing nutrient inputs to a lake targeted for management.

Benefits

- Eliminates significant loads of nutrients
- Minimal long-term expense expected once gravity diversion complete

Detriments

- Removes a source of water to the lake
- Relocates impact elsewhere

Information for Proper Application

- Accurate hydrologic and nutrient budgets to allow evaluation of potential benefits
- Assessment of probable in-lake effects and an evaluation of downstream impacts
- Routing information for new discharge location
- Monitoring program to track changes in detention time, nutrient levels and water clarity in the target lake
- Monitoring program to assess impacts of new discharge location

South Pond in East Brookfield normally flows into North Pond, but during storm events the flow can reverse, adding high nutrient water to South Pond. A moveable gate was installed at the interbasin connector with North Pond. When inflows to North Pond are high, this gate is lowered and prevents poor quality water from entering South Pond. Measurable water quality improvement was observed in <2 years.

Factors Favoring the Use of this Technique

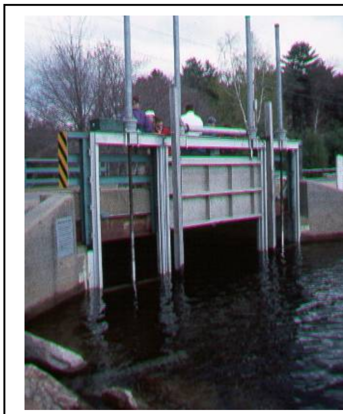
- A substantial portion of the P and/or N load is associated with sources that can be diverted
- Studies have demonstrated the impact of the targeted discharge on the lake
- Water associated with sources to be diverted is not important to lake hydrology; water level fluctuation will not differ greatly from pre-treatment conditions
- Downstream problems with water quantity or quality will not be caused.

Performance Guidelines

- Develop reliable hydrologic and nutrient budgets and evaluate probable impacts of diversion on lake and any stream upstream of diversion
- Determine possible effects of diversion downstream of discharge
- Design diversion system and any necessary maintenance program; avoid flooding and erosion problems downstream of discharge
- Monitor quality of water in the lake and downstream of discharge

Possible Permits

- WPA permit through local Conservation Commission/DEP



South Pond flow control gate

- Review by NHESP (further action if protected species are present)
- Chapter 91 Permit through DEP may be required for structural alterations in Great Ponds
- Dam Safety Permit may be required through DCR
- Rerouting of water in excess of 100,000 gpd may require a permit under the Water Management Act through DEP
- 404 permit through the Corps of Engineers
- 401 WQ permit through the DEP
- NPDES permitting through EPA/DEP

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Variable (depends on location of supply relative to discharge)
- Protection of groundwater supply – Neutral, unless there is a discharge to groundwater, in which case the impact could be detrimental
- Flood control – Most likely neutral (diverted flow must remain within tolerance limits for receiving waters)
- Storm damage prevention – Neutral (diverted flow must remain within tolerance limits for receiving waters)
- Prevention of pollution - Benefit in the lake (water quality enhancement), but possibly detrimental downstream (possible poor quality discharges)
- Protection of land containing shellfish - Possible benefit through water quality enhancement in the lake and possible detriment with any downstream water quality degradation
- Protection of fisheries - Benefit (water quality enhancement), but possible detriment through reduced fertility and possible detriment downstream with any water quality degradation
- Protection of wildlife habitat – Benefit (water quality enhancement), but possible detriment through reduced fertility

Cost Considerations

The cost of diversion varies greatly among cases, but is rarely inexpensive. The cost is primarily based on the required distance for transport and associated construction costs. If the water must be treated prior to discharge, that cost should also be included. Estimates for diversion of various wastewater discharges in Massachusetts have exceeded $5 million; these diversions were not implemented, in favor of improved treatment. Diverting storm drains may be a more economic approach if technical and permitting difficulties can be overcome.

Diversion of secondary treated sewage effluent from Dennisville Lake in NJ in about 1980 dramatically improved conditions within a decade

***HYDRAULIC CONTROLS**: Selective Withdrawal*

How it Works

For recreational lake management, the intent of selective withdrawal is usually to remove the poorest quality water from the lake, which is normally the water at the bottom of the lake unless an intense surface bloom of algae is underway. It is desirable to discharge water at a rate that prevents anoxia near the sediment-water interface, resulting in both improved lake conditions and an acceptable discharge quality. This can be accomplished in impoundments with small hypolimnia and/or large inflows. In most lake management cases, however, selective withdrawal will involve waters of poor quality and treatment may be necessary before discharge downstream.

Where phosphorus has accumulated in the hypolimnion through release from the sediments, selective discharge of hypolimnetic waters prior to fall turnover can reduce effective phosphorus loading. However, unless late summer inflows are substantial, this may result in a considerable drawdown of the lake level. Where a drawdown is planned, selective discharge may increase the benefit. Often an outlet structure must be retrofitted to facilitate selective withdrawal, but the one-time capital cost confers permanent control with minimal operation and maintenance costs.

Selective withdrawal for water supply means locating the intake at the depth where water quality is most advantageous for the intended use. It can be used in any system where vertical water density gradients are sufficiently stable, but is most often applied to more strongly stratified lakes. For potable water use of productive lakes, the choice is often between high algae concentrations in the epilimnion and high iron and/or manganese in the hypolimnion. Intakes located near the thermocline sometimes get both high algae and high metals. A choice of intake depths is preferred, allowing adjustment of intake depth in accordance with the best available water quality. For cooling water supply, cold hypolimnetic withdrawal is preferred, as long as it does not contain high levels of corrosive sulfides.

Benefits

- Removes poor quality water before it mixes with upper water layer; ideally prevents development of poor quality water
- Uses expected outflow in a more beneficial manner
- Can provide benefits for downstream coldwater fishery

Detriments

- May cause unintended drawdown
- May disrupt stratification
- May result in downstream discharge of poor quality water

Information for Proper Application

- Accurate hydrologic and nutrient budgets to allow evaluation of potential benefits and limitations
- Detailed knowledge of system morphometry and thermal structure to allow assessment of appropriate withdrawal depth
- Assessment of probable in-lake effects and downstream impacts
- Adequacy of inflow to keep the lake water budget in balance, in order to avoid an unintended water level decrease
- Drawdown plans, if hypolimnetic withdrawal is to be used in conjunction with this technique
- Outlet plans to facilitate design of withdrawal port
- Monitoring program to assess quality of discharged water, quality of water remaining in the lake, and stability of lake water level and stratification

Results for 17 lakes with 1 to 10 years of hypolimnetic withdrawal indicate that reduced epilimnetic phosphorus concentrations did result, presumably leading to lowered algal biomass. However, concerns over summer drawdown, disruption of stratification, and downstream water quality must all be addressed in a successful program.

In some large western reservoirs, hypolimnetic discharges constitute a major outflow and are responsible for maintenance of very productive downstream coldwater fisheries.

Factors Favoring the Use of this Technique
- ♦ A substantial portion of the P and/or N load is associated with sources that can be preferentially discharged
- ♦ Studies have demonstrated the impact of hypolimnetic load on the lake
- ♦ Water level fluctuation will not differ greatly from pre-treatment conditions
- ♦ Downstream problems with water quantity or quality will not be caused.
- ♦ Actual reduction in nutrient inputs from identifiable sources is not practical, either for technical or jurisdictional reasons

Performance Guidelines
- ♦ Develop reliable hydrologic and nutrient budgets and evaluate probable outcomes of selective withdrawal
- ♦ Determine possible effects on stratification and related habitat in the lake
- ♦ Determine possible downstream effects of increased flow and altered water quality
- ♦ Design withdrawal system and any necessary maintenance program
- ♦ Avoid lowered water level as a consequence of selective withdrawal (unless permitted as part of a drawdown)
- ♦ Avoid contravention of downstream water quality standards due to discharge
- ♦ Conduct selective withdrawal mainly during the summer and fall
- ♦ Monitor quality of in-lake and outgoing water

Selective withdrawal can be accomplished with a subsurface pipe. Head pressure derived from the difference between the water surface elevation and the discharge elevation forces water into the pipe at the inlet end (set in deeper water), even when the discharge elevation is higher than the inlet elevation.

Possible Permits
- ♦ WPA permit through local Conservation Commission/DEP
- ♦ Review by NHESP (further action if protected species are present)
- ♦ Chapter 91 Permit through DEP may be required for Great Ponds
- ♦ Dam Safety Permit may be required through DCR
- ♦ Possible 404 permit through the Corps of Engineers
- ♦ Possible 401 WQ permit through the DEP
- ♦ Possible NPDES permitting through EPA/DEP

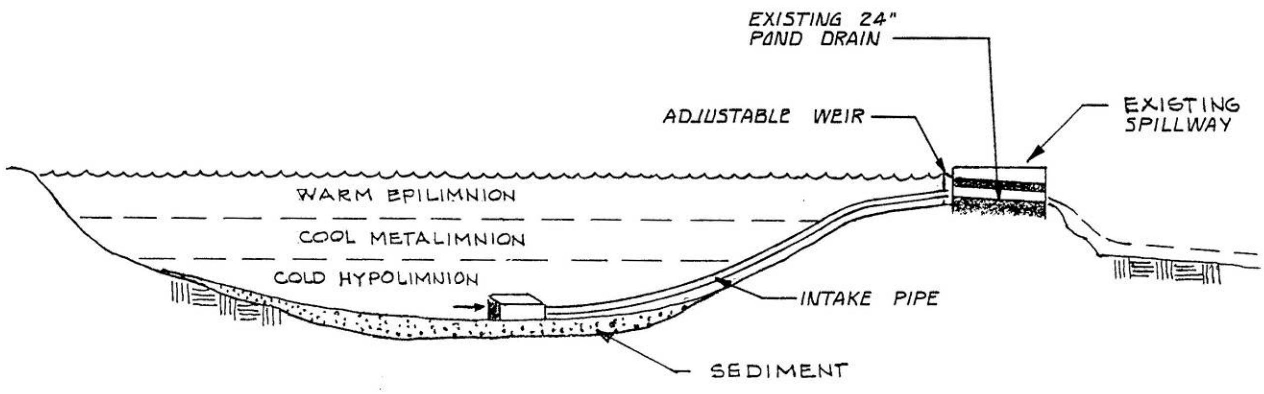
Subsurface withdrawal pipe

Impacts Specific to the Wetlands Protection Act
- ♦ Protection of public and private water supply – Variable (depends on location of supply relative to discharge or depth of intake)
- ♦ Protection of groundwater supply – Neutral, unless there is a discharge to groundwater, in which case the impact could be detrimental
- ♦ Flood control - Neutral (discharge must remain within tolerance limits for lake and downstream receiving waters)
- ♦ Storm damage prevention – Neutral (discharge must remain within tolerance limits for lake and downstream receiving waters)
- ♦ Prevention of pollution - Benefit in the lake (water quality enhancement), but possibly detrimental downstream (possible poor quality discharges)
- ♦ Protection of land containing shellfish - Possible benefit through water quality enhancement in the lake and possible detriment with any downstream water quality degradation

- Protection of fisheries - Benefit (water quality enhancement), but possible detriment through reduced fertility and possible detriment downstream with any water quality degradation
- Protection of wildlife habitat – Benefit (water quality enhancement), but possible detriment through reduced fertility

Cost Considerations

Installation costs for withdrawal pipes typically range between $10,000 and $50,000, although higher costs are certainly possible if major outlet reconstruction is needed. Costs for treating the discharge could be substantial, but treatment has consisted mainly of aeration by passive means at limited capital and operational cost. A cost of <$100 per acre is suggested where structures are in place and no major downstream impacts are expected. The cost may rise to $1000-3000/acre where structural alterations and/or treatment of discharged water become necessary.



Subsurface Withdrawal Design

PHOSPHORUS INACTIVATION

How it Works

The release of phosphorus stored in lake sediments can be so extensive in some lakes and reservoirs that algal blooms persist even after incoming phosphorus has been significantly lowered. Phosphorus precipitation by chemical complexing removes phosphorus from the water column and can control algal abundance until the phosphorus supply is replenished. Inactivation of phosphorus in surficial lake sediments can greatly reduce the release of phosphorus from those sediments, minimizing the internal load. It is essentially an "anti-fertilizer" treatment. This technique is most effective after nutrient loading from the watershed is sufficiently reduced, as it acts only on existing phosphorus reserves, not new ones added post-treatment. In-lake treatments are used when studies indicate that the primary source of the phosphorus is internal (recycled from lake sediments). Such nutrient control generally does not reduce macrophyte abundance, but can control algal growths.

The three most common treatments for lakes employ salts of aluminum, iron, or calcium compounds. Nitrate treatments are very rare and are used to enhance phosphorus binding to natural iron oxides in sediments. For the aluminum, iron and calcium treatments, the typical compounds used include aluminum sulfate ($Al_2(SO_4)_3\,xH_2O$), sodium aluminate ($Na_2Al_2O_4\,xH_2O$), iron as ferric chloride ($FeCl_3$)or ferric sulfate ($Fe_2(SO_4)_3$), and calcium as lime ($Ca(OH)_2$) or calcium carbonate ($CaCO_3$). Additional forms of aluminum are becoming more common.

Inactivators are applied to the surface or subsurface, in either solid or liquid form, normally from a boat or barge. These compounds dissolve and form hydroxides, $Al(OH)_3$, $Fe(OH)_3$, or in the case of calcium, carbonates such as calcite ($CaCO_3$). These minerals form a floc that can remove particulates, including algae, from the water column within minutes to hours and precipitate reactive phosphates. Reactions continue at the surface-water interface, binding phosphorus that could otherwise be released from the sediment. Because aluminum and iron added as sulfates or chlorides dissolve to form acid anions along with the formation of the desired hydroxide precipitates, the pH will tend to decrease in low alkalinity waters unless basic salts such as sodium aluminate or lime are also added. Conversely, calcium is usually added as carbonates or hydroxides that tend to raise pH.

Alum application

The various floc minerals behave very differently under high or low dissolved oxygen and they also differ in their response to changes in pH. Because of its ability to continue to bind phosphorus under the widest range of pH and oxygen levels, aluminum is usually the preferred phosphorus inactivator. Other binders are applied under specific conditions that favor their use, but not as commonly as aluminum.

Good candidate lakes for this procedure are those that have had external nutrient loads reduced to an acceptable level and have been shown, through a D/F study, to have a high internal phosphorus load (release from sediment). High natural alkalinity is also desirable to provide buffering capacity. Highly flushed impoundments are usually not good candidates because of an inability to limit phosphorus inputs. Treatment of lakes with low doses of alum may effectively remove phosphorus from the water column, but may be inadequate to provide long-term control of phosphorus release from lake sediments. High doses are needed to effectively bind phosphorus in the upper few inches of sediment and retard release.

Alum application

Low doses of aluminum (1-5 mg/L) can be used to strip phosphorus out of the water column with limited effects on pH or other water quality variables, even in many poorly buffered waters. Mixing with aeration systems can increase treatment efficiency and lower the necessary dose. Aluminum doses in excess of 50 g/m^2 may be needed to thoroughly inactivate sediment phosphorus reserves and maximize treatment longevity. Areal doses (g/m^2) convert to volumetric doses (g/m^3 or mg/L) simply by dividing the areal dose by the water depth in meters. Doses around 10 mg/L are typically applied to storm water discharges, and current efforts in storm water management focus on capturing the floc in detention areas prior to discharge to the lake or stream.

Floc formation

Iron salts are very sensitive to dissolved oxygen levels. Under oxic conditions the ferric hydroxide floc is stable at normal pH conditions (pH>5). Under anoxic conditions, however, the iron in ferric hydroxide is reduced to soluble ferrous iron (Fe^{+2}) and the floc dissolves, releasing the adsorbed phosphorus. Therefore, while iron acts as a natural binder in well-oxygenated systems, loss of oxygen in eutrophic lakes may disrupt this natural phosphorus inactivation process. Inactivation of phosphorus by iron will become very ineffective where anoxia is so strong that sulfate reduction occurs. In such cases, iron is preferentially bound by sulfides released as hydrogen sulfide, leaving little iron to bind with phosphorus. Consequently, iron is only used in well-aerated systems with naturally low iron levels, but may be the inactivator of choice as a supplement to an aeration system. Iron is generally not toxic at levels applied to lakes.

Common application rates for stripping phosphorus from the water column range from 1 to 20 mg/L, while the range for inactivating surficial sediments is about 10 to 150 g/m^2. Without use of a buffer solution, dose is determined by the amount of inactivator that can be added without causing an undesirable pH level.

The stability of calcite is highly sensitive to pH, calcium, and carbonate concentrations. Consequently, treatment with calcium is effective only if pH is maintained at a relatively high level (8 or above). Such pH levels are found naturally only in the Berkshire region where elevating the pH by chemical addition to facilitate calcium effectiveness may have many adverse impacts on natural systems adjusted to lower pH. Calcium is more commonly used in alkaline lakes regions, such as Alberta, Canada, and has not been applied in Massachusetts or the northeastern USA except on a pilot basis.

Nitrate treatments such as $Ca(NO_3)_2$ neither precipitate nor inactivate phosphorus directly. Nitrates are injected directly into the surface sediments as a 'sediment oxidation' treatment, which in this case refers to maintaining a high redox (reduction-oxidation) potential and thus maintaining the stability of natural iron oxides in the sediments. That is, nitrate is broken up to yield oxygen before iron oxides, by preference of the active bacteria. Thus nitrates act indirectly to enhance and stabilize the ability of natural iron oxides to bind phosphorus in the sediments. In this manner, nitrate treatment is analogous to hypolimnetic aeration by providing an alternative source of oxygen. This approach is not commonly practiced anywhere and has never been tried in Massachusetts.

Floc formation during treatment should be visible, and a floc layer up to perhaps 3 inches deep will accumulate on the bottom afterward, but within a month this layer will have merged with the surficial sediments and adds minimal solid material to the lake.

Benefits

- Rapid removal of available phosphorus from the water column
- Minimized internal loading of phosphorus
- Potential removal of a variety of other contaminants and algae

Detriments

- Potential for damage to aquatic life at depressed or elevated pH

- Limited longevity of effects if external loading is significant

Information for Proper Application

- An accurate nutrient budget that includes a detailed analysis of internal sources of phosphorus
- Sediment testing for available sediment phosphorus
- Recent information on pH and alkalinity at all depths to properly predict potential changes in pH and to minimize impacts
- Knowledge of lake oxygen regime and biotic components is helpful in planning treatments
- An accurate depth map of the lake is required to properly evaluate dosing
- In addition to jar tests to establish doses and ratios of chemicals, toxicity tests with a sensitive fish species may be desirable
- Monitoring of pH, alkalinity and any biotic reactions is appropriate during treatment, with follow-up monitoring if any deviations from the expected range are detected
- Estimates of effectiveness should be made for lake recovery in terms of total phosphorus levels and Secchi disk transparency.
- For deep lakes, hypolimnetic dissolved phosphorus concentration should decrease dramatically and should be checked.

Factors Favoring the Use of this Technique

- A substantial portion of the P load is associated with sediment sources within the lake
- Studies have demonstrated the impact of internal loading on the lake.
- External P load has been controlled to the maximum practical extent or is documented to be small; historic loading may have been much greater than current loading
- Inactivation of phosphorus in the water column is expected to provide interim relief from algal blooms and turbidity while a prolonged watershed management program is conducted to reduce external loading
- The lake is well buffered or buffering can be augmented to prevent major changes in pH during treatment
- Assays indicate no toxic effects during simulated treatment
- Where iron is to be used as an inactivator, oxygen is adequate at the bottom to maintain iron-phosphorus bonds
- Where calcium is to be used as an inactivator, normal background pH is high enough to maintain calcium-phosphorus bonds
- Where nitrate is to be used to alter redox potential and limit P release, nitrate can be effectively injected into the sediment without major release to the water column

Concentrations of reactive aluminum (AL^{+3}) are strongly influenced by pH. Aluminum is toxic to fish at levels of 100 to 200 ug/L at pH of < 6.0 and >7.5, typically via gill membranes. The "safe" level of dissolved reactive aluminum is considered to be 50 ug/L, but these are not sharp thresholds.

Toxicity can be avoided by properly buffering inactivator additions, treating repeatedly at a lower dose, treating parts of the lake sequentially, or by injecting the inactivator into the bottom waters during stratification.

Performance Guidelines

- Develop reliable phosphorus budget that demonstrates magnitude of internal loading
- Determine dose necessary to inactivate targeted phosphorus (water column or sediment)
- Determine chemicals to be used; consider oxygen regime and minimize shift in pH unless naturally outside range of 6.0 to 8.0 SU
- Secure appropriate access for equipment and chemicals; adhere to materials handling regulations in the transfer of chemicals to application equipment
- For larger lakes, treat non-contiguous sections of the lake on sequential days
- For higher doses of aluminum, split treatment to yield calculated in-lake aluminum level <10 mg/L on any day

- In pH sensitive lakes with anoxic hypolimnia, consider injecting aluminum at or below the thermocline during stratification
- Monitor phosphorus, the inactivator compound, pH, alkalinity, water clarity, algae, zooplankton, benthic invertebrates and fish before, during and after treatment as appropriate to determine impacts to sensitive resources.

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Permit to Apply Chemicals from DEP
- Possible 401 WQ permit through the DEP

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality improvement)
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control - Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution - Benefit (water quality enhancement)
- Protection of land containing shellfish - Possible benefit through water quality enhancement in the lake and possible detriment by direct toxicity unless treatment is properly buffered
- Protection of fisheries - Possible benefit through water quality enhancement in the lake and possible detriment by direct toxicity unless treatment is properly buffered, plus possible detriment through reduced fertility
- Protection of wildlife habitat – Benefit (water quality enhancement), but possible detriment through reduced fertility

Bioassays for fish impact prevention

The most serious impact is the possibility for fish or invertebrate kills following treatment in low alkalinity lakes, but such impacts are preventable. Minimal adverse impacts are expected to either surface or groundwater supplies. Aluminum, iron and calcium are commonly added in water and wastewater treatment facilities with no significant adverse impacts (and generally a marked improvement in water quality).

Cost Considerations

Aluminum treatment costs typically range from $500-$1,000/acre, with the areal cost decreasing for larger treatments, unbuffered treatments, and lesser monitoring requirements. Higher cost may result from extreme controls and monitoring, as with the 2001 Ashumet Pond treatment. Costs for iron treatments are similar to those for alum treatment; the chemical is less expensive to purchase but higher doses are recommended. However, iron is best applied in conjunction with aeration systems, so total project cost is likely to be substantially higher. Calcium costs are slightly less expensive than alum, especially in hard water lakes where this technique is most likely to be applied. The cost is estimated at about $200/acre. Nitrate application to sediments is an expensive treatment, typically on the order of $5,000-10,000/acre.

ARTIFICIAL CIRCULATION

How it Works

Whole lake circulation is a technique for management of algae that tends to affect nutrient levels. The central process is the introduction of more oxygen, intended to limit internal recycling of phosphorus, thereby controlling algae. Other important processes may apply as well, however. Circulation strategies increase turbulence and minimize stratification. Whole lake artificial circulation is also referred to as destratification or whole lake aeration. Thermal stratification and features of lake morphometry such as coves create stagnant zones that may be subject to loss of oxygen, accumulation of sediment, or algal blooms. Artificial circulation minimizes stagnation and can eliminate thermal stratification or prevent its formation. Movement of air or water is normally used to create the desired circulation pattern in shallow (<20 ft) lakes, and this has been accomplished with surface aerators, bottom diffusers, and water pumps (Figure 10). Algae may simply be mixed more evenly in the available volume of water in many cases, but turbulence, changing light regime and altered water chemistry can cause shifts in algal types and reduce biomass.

Fountain aerator

Stratification is broken or prevented in deeper lakes through the injection of compressed air into lake water from a diffuser at the lake bottom (Figure 11a). The rising column of bubbles, if sufficiently powered, will produce lake-wide mixing at a rate that eliminates temperature differences between top and bottom waters. The use of air as the mixing force also provides some oxygenation of the water, but the efficiency and magnitude of this transfer are generally low. In some instances, wind driven pumps have been used to move water. For air mixed systems, the general rule is that an air flow rate of 1.3 cubic feet per minute per acre of lake (9.2 $m^3/min/km^2$) will be needed to maintain a mixed system. However, there are many factors that could require different site specific air flow rates, and undersizing of systems is the greatest contributor to failure for this technique.

Bubble row from submerged diffuser pipe

Algal blooms are sometimes controlled by destratification through one or more of the following processes:

- Introduction of dissolved oxygen to the lake bottom may inhibit phosphorus release from sediments, curtailing this internal nutrient source.
- In light-limited algal communities, mixing to the lake's bottom will increase the time a cell spends in darkness, leading to reduced photosynthesis and productivity.
- Rapid circulation and contact of water with the atmosphere, as well as the introduction of carbon dioxide-rich bottom water during the initial period of mixing, can increase the carbon dioxide content of water and lower pH, leading to a shift from blue-green algae to less noxious green algae.
- Turbulence can neutralize the advantageous buoyancy mechanisms of blue-green algae and cause a shift in algal composition to less objectionable forms such as diatoms.
- When zooplankton that consume algae are mixed throughout the water column, they are less vulnerable to visually feeding fish. If more zooplankters survive, their consumption of algal cells may also increase.

Artificial circulation can prevent winterkills of fish in eutrophic lakes that become anoxic during the winter. On a smaller scale, artificial circulation can be used to prevent ice formation around docks or other structures. The technique is also used to maintain acceptable water quality in drinking reservoirs as the oxic conditions created by the circulation reduce concentrations of nuisance substances such as hydrogen sulfide, ammonia, iron and manganese. For these types of problems artificial circulation has been very successful.

If circulation provides increased oxygen to a low oxygen system, oxic chemical reactions may reduce phosphorus availability and control algal growth where sufficient P-binders are present. Otherwise, this technique depends upon physical disruption and light limitation associated with mixing to control algae. Blue-greens are especially susceptible to such disruption, but most green algae and diatoms are not negatively affected. Surface scums may be avoided, but algal biomass may not decline.

Benefits

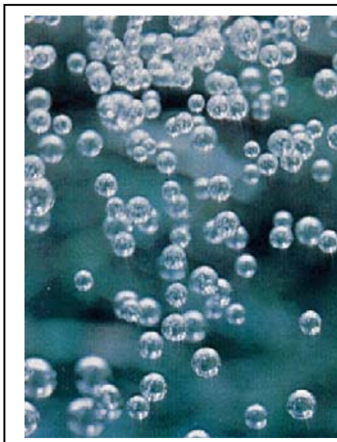
- ♦ Increases mixing and decreases stagnation; may control algae by multiple means, and will at least spread out the algal biomass
- ♦ Increases oxygen levels and enhances habitat accordingly
- ♦ Increases die-off rate of bacteria

Detriments

- ♦ Mixing may distribute previously localized undesirable substances throughout the lake
- ♦ May resuspend sediment and increase turbidity if not carefully controlled
- ♦ May increase algal growth in some cases

Information for Proper Application

- ♦ An accurate nutrient budget with a detailed analysis of internal P sources
- ♦ Data related to each of the five possible control mechanisms (oxygenation/P inactivation, light limitation, pH/carbon source adjustment, buoyancy disruption, and enhanced grazing) should be analyzed and evaluated in terms of potential algal control. Specifically,
  - a. Is there anaerobic release of phosphorus that can be mitigated by oxygenation of deep waters?
  - b. Is the mixing zone deep enough to promote light limitation of algae?
  - c. Is there a large amount of carbon dioxide in the bottom waters that could be mixed to the surface to favor the growth of non-blue-green algae?
  - d. Is mixing predicted to counteract the buoyancy advantage of blue-greens over other algae?
  - e. Will a dark, oxygenated refuge be created for zooplankton?
- ♦ Reliable estimate of the oxygen demand that must be met by the system
- ♦ Reliable estimate of the amount of air necessary to mix/destratify the lake
- ♦ Lake morphometry data that facilitates choice of aerator type and placement of aerators for maximum effectiveness
- ♦ Location and details of compressor and power source
- ♦ Monitoring to track oxygen and nutrient levels after implementation
- ♦ Monitoring to track water clarity and algal types and quantity



Bubbles from submerged diffuser (provided by R. Geney of GES)

Factors Favoring the Use of this Technique

- ♦ A substantial portion of the P load is associated with anoxic sediment sources within the lake
- ♦ Studies have demonstrated the impact of internal loading on the lake
- ♦ External P load has been controlled to the maximum practical extent or is documented to be small; historic loading may have been much greater than current loading
- ♦ Hypolimnetic or sediment oxygen demand is high (>500 $mg/m^2/day$)

- In addition to phosphorus management, control of other reduced compounds such as hydrogen sulfide, ammonia, manganese and iron, is desired
- Adequate phosphorus inactivators are present for reaction upon addition of oxygen
- Shoreline space for a compressor or pump is available where access is sufficient, power is available, and noise impacts will be small
- The lake is bowl shaped, or at least not highly irregular in bathymetry (few separate basins and isolated coves)
- Long-term application of the technique is accepted
- Coldwater fishery habitat is limited or not a concern

The power and spatial arrangement of aerators are very important factors in determining the extent and evenness of circulation. Underpowering or overspacing can lead to "dead zones" while overpowering and underspacing may resuspend bottom sediment.

Performance Guidelines

- Determine goals for circulation; if oxygenation is desired, oxygen demand must be determined; if destratification is desired, necessary mixing force must be determined
- Properly size equipment; avoid over- or underpowering
- Properly place equipment; avoid over- or underspacing
- Develop a maintenance plan for equipment
- Operate equipment in accordance with management goals to achieve temporal or spatial results as planned
- Monitor temperature and oxygen as indicators of mixing and aeration, and other water quality or biological variables as necessary to evaluate success

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 Permit through DEP may be required for Great Ponds

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality enhancement)
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control - Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution - Benefit (water quality enhancement)
- Protection of land containing shellfish - Benefit (water quality enhancement) with rare detriment by water quality variability induced by whole lake circulation
- Protection of fisheries - Benefit (water quality enhancement) with possible detriment by water quality variability and loss of coldwater habitat induced by whole lake circulation
- Protection of wildlife habitat – Benefit (water quality enhancement)

Adverse impacts to the eight interests of the Wetland Protection Act are not expected with the exception that in rare cases deleterious substances like hydrogen sulfide or ammonia may be circulated to the surface and cause temporary adverse impacts to fish and wildlife. In general, aeration is expected to improve habitat for fish and other organisms in lakes with anoxic hypolimnia, but artificial circulation can reduce or eliminate coldwater habitat for trout.

Cost Considerations

Costs include the initial purchase and installation of the pumps, pipes and diffusers as well as annual maintenance costs and annual electricity costs. Capital costs range from about $200 to $3,000/ac, while annual costs usually range from $50 to $800/ac. Actual costs depend on the amount of air required, which is related to lake area. The estimated range of cost for 20 years of application at a hypothetical 100-acre lake is $70,000 to $400,000.

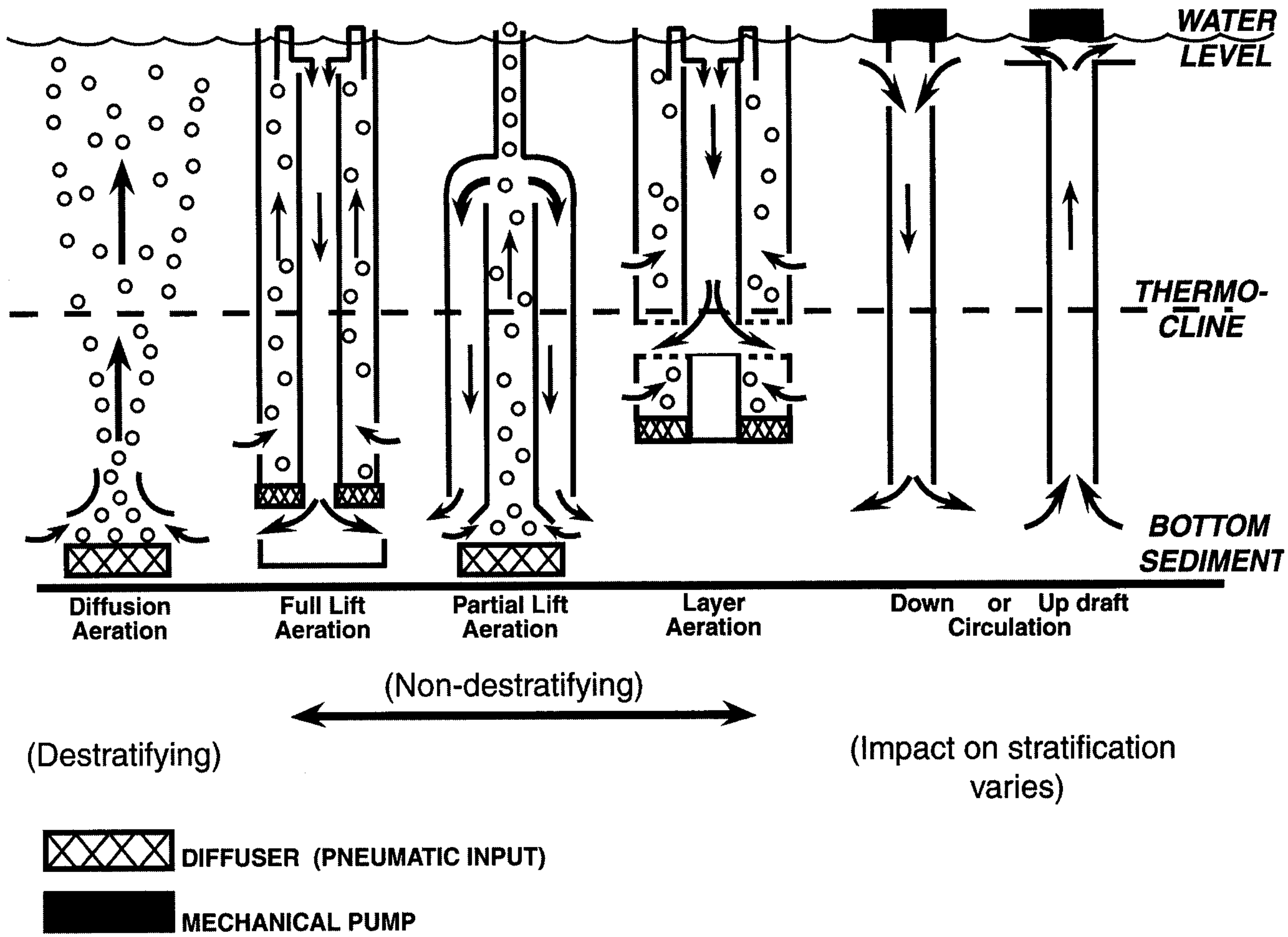
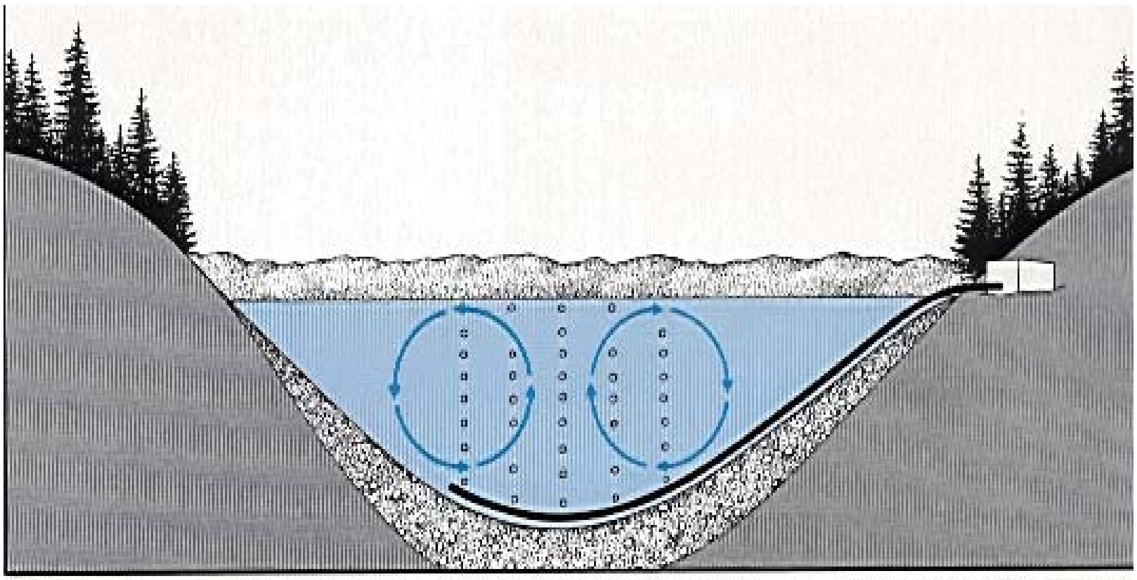
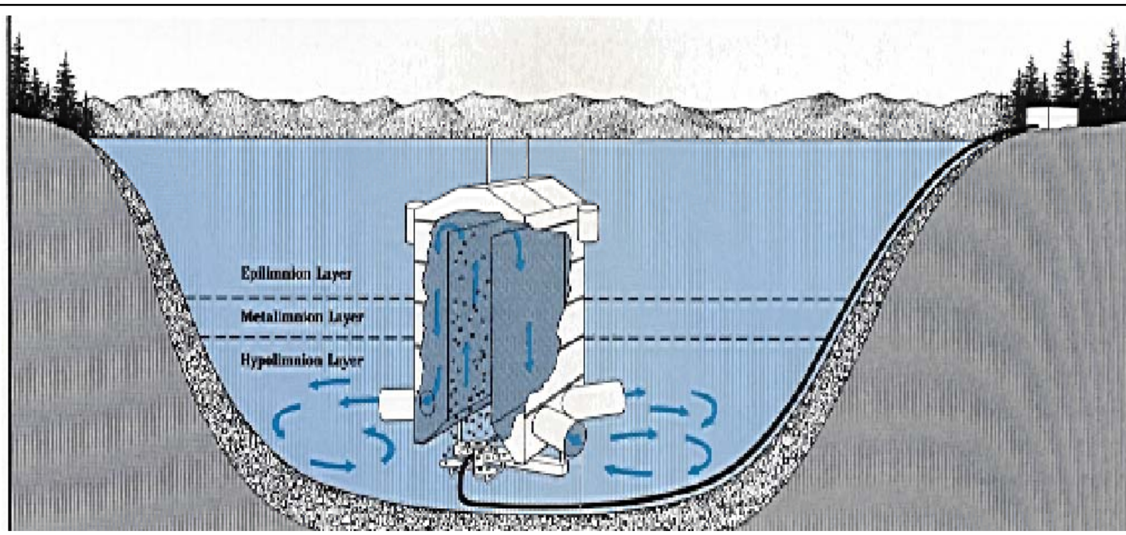


Figure 10. Methods of Artificial Circulation and Aeration (from Wagner, 2001)



A. Destratifying aeration (provided by R. Geney of GES)



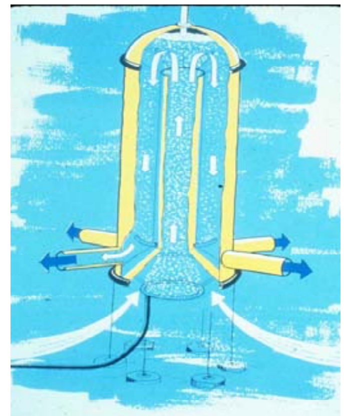
B. Non-destratifying (hypolimnetic) aeration (provided by R. Geney of GES)

Figure 11. Destratifying (A) and Non-destratifying (B) Aeration

HYPOLIMNETIC AERATION

How it Works

Hypolimnetic aeration is a technique for management of algae through control of nutrient levels. The central process is the introduction of more oxygen, intended to limit internal recycling of phosphorus, thereby controlling algae. Hypolimnetic aeration typically uses an air compressor as described for whole lake circulation, but in this case the upward plume is controlled to avoid mixing with the epilimnetic waters, and thus thermal stratification of the lake is maintained (Figure 10). The maintenance of stratification is often desirable as it maintains coldwater fish habitat and reduces transport of nutrients from the hypolimnion into the epilimnion where they may stimulate further algal blooms.



Hypolimnetic aerator (provided by R. Geney of GES)

Aeration puts air into the aquatic system, increasing oxygen concentration by transfer from gas to liquid and generating a controlled mixing force. The oxygen transfer function is used to prevent hypolimnetic anoxia (Figure 11b). By keeping the hypolimnion from becoming anoxic during stratification, aeration should minimize the release of phosphorus, iron, manganese and sulfides from deep bottom sediments and decrease the build-up of undecomposed organic matter and oxygen-demanding compounds (e.g., ammonium). Hypolimnetic aeration can also increase the volume of water suitable for habitation by zooplankton and fish, especially coldwater forms. Pure oxygen can be used in place of air to maximize oxygen transfer at an increased cost.

A full lift hypolimnetic aeration approach moves hypolimnetic water to the surface, aerates it, and replaces it in the hypolimnion. Bringing the water to the surface can be accomplished with electric or wind-powered pumps, but is most often driven by pneumatic force (compressed air). Return flow to the hypolimnion is generally directed through a pipe to maintain separation of the newly aerated waters from the surrounding epilimnion. To provide adequate aeration, the hypolimnetic volume should be pumped and oxygenated at least once every 60 days.

Layer aeration system (provided by R. Kortman of ECS)

Another hypolimnetic aeration system is the partial lift system, in which air is pumped into a submerged chamber in which exchange of oxygen is made with the deeper waters. The newly oxygenated waters are released back into the hypolimnion without destratification. A shoreline site for a housed compressor is needed, but the aeration unit itself is submerged and does not interfere with lake use or aesthetics.

An alternative approach involves a process called layer aeration. Water can be oxygenated by full or partial lift technology, but by combining water from different (but carefully chosen) temperature (and therefore density) regimes, stable oxygenated layers can be formed anywhere from the upper metalimnetic boundary down to the bottom of the lake. Each layer acts as a barrier to the passage of phosphorus, reduced metals and related contaminants from the layer below. Each layer is stable as a consequence of thermally mediated differences in density. The whole hypolimnion may be aerated, or any part thereof, to whatever oxygen level is deemed appropriate for the designated use. Maintenance of a highly oxidized layer for water supply will call for more oxygen than providing a refuge for zooplankton or fish.

The mechanism of phosphorus control exercised through hypolimnetic aeration is the maintenance of high oxygen and limitation of phosphorus release from sediments. Out of the processes listed for artificial circulation, the only other applicable mechanism for hypolimnetic aeration is provision of a zooplankton refuge, potentially increasing grazing potential. To successfully aerate a hypolimnion, the continuous oxygen demand of the sediments must be met, and experience dictates that the oxygen input needs to be about twice the measured oxygen demand. This demand may be reduced over time under aeration, but is unlikely to be eliminated.

Oligotrophic lakes typically have oxygen demands <250 mg/m^2/day, while eutrophic lake values are >550 mg/m^2/day; values of 2000 to 4000 mg/m^2/day have been measured in hypereutrophic lakes.

Benefits

- Reduces release of phosphorus from the sediment and accumulation in the hypolimnion without eliminating stratification
- Reduces hypolimnetic accumulations of iron, manganese, ammonium and hydrogen sulfide
- Increases hypolimnetic oxygen levels and enhances habitat accordingly

Detriments

- Theoretically possible to induce gas bubble disease in fish, but not a documented occurrence

Information for Proper Application

- Data requirements for this type of nutrient control include an accurate nutrient budget with a detailed analysis of internal sources of phosphorus
- The most critical information for designing an aeration system is the oxygen demand that must be met by the system; calculations and related interpretation for design purposes are best performed by experienced professionals
- Lake morphometry and stratification data are needed to facilitate choice of aerator features and placement of aerators for maximum effectiveness
- Location and details of compressor and power source are needed

Oxygen demand is normally calculated from actual data for the lake. For stratified lakes, the hypolimnetic oxygen demand (HOD, often a function of sediment oxygen demand, or SOD) can be calculated as the difference in oxygen levels at the time stratification formed and one or more points in time later during stratification. However, measurements obtained when the oxygen levels are <2 mg/L are deceiving, as oxygen consumption is not linear and will decline markedly as oxygen supply declines.

Factors Favoring the Use of this Technique

- A substantial portion of the P load is associated with anoxic sediment sources within the lake
- Studies have demonstrated the impact of internal loading on the lake.
- External P load has been controlled to the maximum practical extent or is documented to be small; historic loading may have been much greater than current loading
- Hypolimnetic or sediment oxygen demand is high (>500 mg/m^2/day)
- In addition to phosphorus management, control of other reduced compounds such as hydrogen sulfide, ammonia, manganese and iron, is desired
- Adequate phosphorus inactivators are present for reaction upon addition of oxygen
- Shoreline space for a compressor or pump is available where access is sufficient, power is available, and noise impacts will be small
- The lake is bowl shaped, or at least not highly irregular in bathymetry (few separate basins and isolated coves)
- Long-term application of the technique is accepted
- Coldwater fishery habitat is abundant or an important goal

Performance Guidelines

- Determine oxygen demand to be counteracted
- Properly size equipment; avoid over- or underpowering
- Properly place equipment; avoid over- or underspacing
- Develop a maintenance plan for equipment
- Operate equipment in accordance with management goals to achieve temporal or spatial results as planned
- Monitor temperature and oxygen as indicators of mixing and aeration, and other water quality or biological variables as necessary to evaluate success

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 Permit through DEP may be required for Great Ponds

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality enhancement)
- Protection of groundwater supply – Neutral (no significant interaction).
- Flood control - Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution - Benefit (water quality enhancement)
- Protection of land containing shellfish - Benefit (water quality enhancement)
- Protection of fisheries - Benefit (water quality enhancement)
- Protection of wildlife habitat – Benefit (water quality enhancement)

Cost Considerations

Costs can be standardized on a per kg oxygen basis as approximately \$2.50/kg O_2 with operating costs of \$0.072/ kg O_2. Assuming a need to counteract an oxygen demand of 500 to 2000 mg/m^2/day for 120 days per year, this suggests a capital cost of roughly \$750 to \$3,000/acre and an annual operational cost of \$55 to \$220/acre. Shape and depth of the lake will affect costs, with deep, single basin lakes requiring the simplest and least expensive systems.

DRAWDOWN

How it Works

Drawdown is a process whereby the water level is lowered by gravity, pumping or siphoning and held at that reduced level for some period of time, typically several months and usually over the winter. Drawdown can provide control of plant species that overwinter in a vegetative state, and oxidation of sediments may result in lower nutrient levels with adequate flushing. Drawdowns also provide flood control and allow access for nearshore clean ups and repairs to structures. The ability to control the water level in a lake is affected by area precipitation pattern, system hydrology, lake morphometry, and the outlet structure. The base elevation of the outlet or associated subsurface pipe(s) will usually set the maximum drawdown level, while the capacity of the outlet to pass water and the pattern of water inflow to the lake will determine if that base elevation can be achieved and maintained. In some cases, sedimentation of an outlet channel or other obstructions may control the maximum drawdown level.

Several factors affect the success of drawdown with respect to plant control. While drying of plants during drawdowns may provide some control, the additional impact of freezing is substantial, making drawdown a more effective strategy during late fall and winter. However, a mild winter or one with early and persistent snow may not provide the necessary level of drying and freezing. The presence of high levels of groundwater seepage into the lake may mitigate or negate destructive effects on target submergent species by keeping the area moist and unfrozen. The presence of extensive seed beds may result in rapid re-establishment of previously occurring plant species, some of which may be undesirable. Recolonization from nearby areas may be rapid, and the response of macrophyte species to drawdown is quite variable.

Aside from direct impact on target plants, drawdown can also indirectly and gradually affect the plant community by changing the substrate composition in the drawdown zone. If there is sufficient slope, finer sediments will be transported to deeper waters, leaving behind a coarser substrate. If there is a thick muck layer present in the drawdown zone, there is probably not adequate slope to allow its movement. However, where light sediment has accumulated over sand, gravel or rock, repetitive drawdowns can restore the coarse substrate and limit plant growths.

The actual conduct of a drawdown involves facilitating more outflow than inflow for several weeks or months. After the target water level is reached, outflow is roughly matched to inflow to maintain the drawdown for the desired period, usually at least a month and often up to 3 months, usually over the winter. At a time picked to allow refill before any undesirable spring impacts can occur, outflow is reduced (although it should not be eliminated) and "excess" inflow causes the water level to rise. In some cases, refill is commenced after an inch or two of ice forms, ripping up plants and bottom material. This "extreme disturbance" approach has been applied where sediments will not dewater sufficiently to provide the level of freezing and desiccation desired, but impacts have not been studied extensively.

Despite the apparent simplicity of the concept of drawdown, proper conduct of a drawdown to maximize effectiveness and minimize adverse side effects necessitates that many considerations be addressed (Table 5). Expected response of target species (Table 6) is of particular importance when plant control is the major goal.

Benefits

- Kills vegetative portions of plants by drying, freezing, or physical disturbance
- Increases plant species richness in many cases
- Allows sediment oxidation and compaction, with potential reduction of sediment oxygen demand, sediment volume, and available nutrient content
- May reduce fine sediments in drawdown zone, creating coarser peripheral substrate and enhancing plant control and habitat for some organisms
- Provides protection from ice damage to shoreline and associated structures
- Facilitates access for shoreline clean–up, sediment removal, and structural maintenance
- Provides flood storage capacity

Drawdown

Drawdown: after many years, rocks have become the dominant nearshore substrate

Detriments

- Will not kill seeds or other non-vegetative overwintering propagules, and may stimulate increased seed germination
- Nutrient release during exposed sediment oxidation may fuel increased algal production if not flushed from system before next growing season
- Will reduce available water for supplies, and may impair nearby shallow well production
- May strand and harm minimally mobile aquatic fauna (such as molluscs)
- Concentration of fish in smaller volume may harm some populations through predation or oxygen stress particularly in warmer months
- Fish may not be able to reach spawning areas during drawdown
- May expose and harm hibernating reptiles and amphibians
- May restrict access and cover for aquatic mammals and birds
- Limits human access where peripheral sediments are soft
- Although largely dormant in winter, hydrologically connected wetlands may experience some changes in species composition and relative abundance if dewatering occurs

Drawdown: refill at this stage may rip plants and stumps from the bottom

Drawdown: access provided for swimming area maintenance

The disadvantages of drawdown are linked to reduced areal coverage by water and lowered water volume and elevation. Water supply from the lake or wells may be impaired, and species that depend upon the exposed area may be harmed. Changes in exposed sediment features may affect water quality after refill. Downstream resources may be impacted as well. Repeated drawdown may result in the invasion of plants that are resistant to drawdowns, some of which may be nuisance species. Failure to refill the lake in time for spring spawning may affect fish populations. None of these impacts may be manifest, and various mitigative means may avoid or minimize them. However, it is difficult to predict the ecological impact to many non-target organisms, due largely to the lack of published information and site-specificity of many possible impacts.

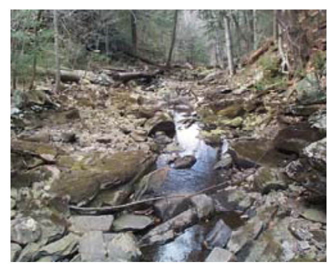
Information for Proper Application

The listing of key considerations provided in Table 5 indicates the extensive data needs for proper implementation of this technique. Key needs include:

- Detailed hydrology and lake morphometry to allow estimates of drawdown and refill times under the range of potential conditions
- Knowledge of outlet features essential to releasing and holding water
- Maps of aquatic macrophytes and expected area of exposure
- Evaluation of sediment types and slopes in expected drawdown zone
- Biological surveys of populations perceived to be at risk from drawdown
- Assessment of downstream channel configuration and resources, to facilitate planning to minimize adverse impacts
- Local well depths or water supply intake elevations
- A carefully crafted monitoring program to track water levels and outflow, and to assess potential impacts, positive and negative

Drawdown pipe (left) usurps flow from normal outlet (right)

Excessive downstream flow from a discharge to achieve drawdown



Inadequate downstream flow during refill after drawdown

Factors Favoring the Use of this Technique

- The lake periphery is dominated by undesirable species that are susceptible to drying and freezing
- Drawdown can be achieved by gravity outflow via an existing outlet structure, or such a structure can be established for a reasonable cost
- Drawdown can reach a depth that impacts enough of the targeted plants to make a difference for recreational interests and habitat enhancement
- Areas to be exposed have sediments and slopes that promote dewatering
- Drawdown and refill can be accomplished within a few weeks under typical flow conditions and without causing downstream flows outside the natural range
- Drawdown can be timed to avoid key migration and spawning periods for non-target organisms
- Populations of molluscs or other nearshore-dwelling organisms of limited mobility are not significant
- The lake is not used for water supply and nearby wells are deep
- Flood storage capacity generated by drawdown prevents downstream flood impacts
- The downstream channel and associated resources will not be impacted by fluctuating flows expected during drawdown and refill periods
- Shoreline structures are prone to ice damage

Performance Guidelines

- Determine susceptibility of target plants to drawdown
- Evaluate potential risks to non-target flora and fauna
- Limit drawdown to 3 ft or contact the MDFG for assistance in evaluating impacts of greater drawdown
- Commence drawdown after the beginning of November

- Achieve the target drawdown depth by the beginning of December; target a drawdown rate of <3 inches/day
- Achieve full lake status by the beginning of April
- Keep outflow during drawdown below a discharge equivalent to 4 cfs per square mile of watershed; once the target water level is achieved, match outflow to inflow to the greatest extent possible, maintaining a stable water level
- Keep outflow during refill above a discharge equivalent to 0.5 cfs per square mile of watershed
- Conduct a monitoring program that includes water level, flow, water clarity, winter oxygen, the plant community, and representative sensitive faunal populations
- After target species are controlled, evaluate the potential to move to an every other or every third year drawdown schedule

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Potential detriment (if adequate water for supply is not maintained), but can be neutral in some cases with proper management
- Protection of groundwater supply – Potential detriment (if lowered lake level lowers groundwater), but can be neutral (if adequate groundwater level is maintained or there is no significant interaction)
- Flood control – Benefit (flood storage potential increased)
- Storm damage prevention – Benefit (flood storage potential increased), but possible detriment as exposed areas may be subject to potentially damaging storm impacts
- Prevention of pollution – May provide benefit (water quality enhancement) or detriment (water quality deterioration), but impacts generally limited
- Protection of land containing shellfish – Detriment (shellfish potentially exposed), but impacts may be neutral in some cases, and shellfish habitat may be improved overall
- Protection of fisheries - Potential detriment by temporary habitat loss, potential benefit by habitat improvement (may have benefit and detriment to different species in same lake from same drawdown)
- Protection of wildlife habitat - Potential detriment by temporary habitat loss for completely aquatic species and impact on muskrat and beaver lodges, potential benefit by habitat improvement (may have benefit and detriment to different species in same lake from same drawdown)

Cost Considerations

Drawdown is a relatively inexpensive lake management technique, if the means to conduct a drawdown are present. Where an outlet structure facilitates drawdown, the cost may be as little as what is required to obtain permits, open and close the discharge structure, and monitor. If pumps are required to lower the water level, the drawdown will be more expensive. It is unusual to alter a dam for less than $100,000, but if the structure already supports water level control, costs of $3,000 to $10,000 per year would be a reasonable expectation for permitting and monitoring. Where protected species are present, permitting may be difficult and monitoring and mitigation costs can escalate.

Table 5. Key Considerations for Drawdown

Reasons for Drawdown
Access to structures for maintenance or construction – note that other permits may apply
Access to sediments for removal (dredging) – additional permits apply
Flood control – a major late winter benefit, but minimally available in spring with regulatory refill date
Prevention of ice damage to shoreline and structures – control of late winter water level needed
Sediment compaction – only if sediments dewater sufficiently
Rooted plant control – for species that rely on vegetative forms to overwinter

Necessary Drawdown Planning Information
Target level of drawdown – depth of water lost
Pond bathymetry – detailed contours for calculation exposed area
Area to be exposed – area of sediment at water depth < target depth, plus ice contact zone
Volume to remain – quantity of water available for habitat and supply during drawdown
Timing and frequency of drawdown – initiation/duration and whether annual or less frequent event
Outlet control features – method for controlling outflow
Climatological data – frequency of sub-freezing weather, precipitation and snow cover data
Normal range of outflow – maximum, minimum and average over expected time of drawdown
Outflow during drawdown and refill – provisions for downstream flow control (high and low)
Time to drawdown or refill – rate of water level change, number of days to achieve target level

In-Lake and Downstream Water Quality
Possible change in nutrient levels – any expected increases due to oxidation of sediments
Possible change in oxygen levels – any expected increase through oxidation or decrease under ice
Possible change in pH levels – any expected shift due to interactions with smaller volume
Other water quality issues – any expected changes as a function of drawdown

Water Supply
Use of lake water as a supply – dependence on water availability and impact of drawdown
Presence/depths of supply wells – potential for supply impairment
Alternative water supplies – options or supplying water to impacted parties
Emergency response system – ability to detect and address supply problems during drawdown
Downstream flow restrictions – maintenance of appropriate flows for downstream habitat and uses

Sediments
Particle size distribution (or general sediment type) – dewatering potential
Solids and organic content – dewatering potential, nutrient content
Potential for sloughing – potential for coarse sediment to be exposed in drawdown zone
Potential for shoreline erosion – threat of erosive impacts to bank resources
Potential for dewatering and compaction – possibility of sediment alteration and depth increase
Potential for odors – emissions from exposed area
Access and safety considerations – issues for use of lake during drawdown

Flood Control
Anticipated storage needs – ability to meet needs with target drawdown
Flood storage gained – volume available to hold incoming runoff
Effects on peak flows – dampening effect on downstream velocities and discharge

Table 5 (continued). Key Considerations for Drawdown

Protected Species
Presence of protected species – NHESP designated species may require special protection
Potential for impact – assessment of possible damage to protected populations
Possible mitigative measures – options for avoiding adverse impacts

In-lake Vegetation
Composition of plant community – details of species present and susceptibility to drawdown
Areal distribution of plants – mapping of plant locations relative to drawdown impact zone
Plant density – quantity of plants present
Seed-bearing vs. vegetative propagation – drawdown will only control vegetative propagators
Impacts to target and non-target species – analysis of which species will be impacted

Vegetation of Connected Wetlands
Composition of plant community – details of species present and susceptibility to drawdown
Areal distribution of plants – mapping of plant locations relative to drawdown impact zone
Plant density – quantity of plants present
Temporal dormancy of key species – potential for seasonal impacts
Anticipated impacts – analysis of likely effects of drawdown

Macroinvertebrates, Fish and Wildlife
Composition of fauna – types of animals present
Association with areas to be exposed – when and how drawdown zone is used on a regular basis
Breeding and feeding considerations – use of drawdown for breeding or food on intermittent basis
Expected effects on target and non-target species – analysis of likely faunal impacts

Downstream Resources
Erosion or flooding potential – susceptibility to impacts from varying flow
Possible habitat alterations – potential for impacts
Water quality impacts – potential for alteration
Direct biotic impacts – possible scour or low flow effects on biota
Recreational impacts – effects on downstream recreational uses
Supply impacts – effects on downstream supply uses

Access to the Pond
Alteration of normal accessibility – issues for seasonal use of pond by humans and wildlife
Possible mitigation measures – options for minimizing impacts

Associated Costs
Structural alteration to facilitate drawdown by gravity – expense for any needed changes to outlet
Pumping or alternative technology – operational expense for pumped or siphoned outflow
Monitoring program – cost of adequate tracking of drawdown and assessment of impacts

Other Mitigating Factors
Monitoring program elements – may be very lake specific and vary over years
Watershed management needs – additional actions beyond drawdown may be warranted
Ancillary project plans (dredging, shoreline stabilization) – additional actions may require separate planning and permitting

Table 6. Anticipated Response of Some Aquatic Plants to Winter Drawdown (After Cooke et al., 1993).

	Change in Relative Abundance		
	Increase	No Change	Decrease
Acorus calamus (sweet flag)	E		
Alternanthera philoxeroides (alligator weed)	E		
Asclepias incarnata (swamp milkweed)			E
Brasenia schreberi (watershield)			S
Cabomba caroliniana (fanwort)			S
Cephalanthus occidentalis (buttonbush)	E		
Ceratophyllum demersum (coontail)			S
Egeria densa (Brazilian Elodea)			S
Eichhornia crassipes (water hyacinth)		E/S	
Eleocharis acicularis (needle spikerush)	S	S	S
Elodea canadensis (waterweed)	S	S	S
Glyceria borealis (mannagrass)	E		
Hydrilla verticllata (hydrilla)	S		
Leersia oryzoides (rice cutgrass)	E		
Myrica gale (sweetgale)		E	
Myriophyllum spp. (milfoil)			S
Najas flexilis (bushy pondweed)	S		
Najas guadalupensis (southern naiad)			S
Nuphar spp. (yellow water lily)			E/S
*Nymphaea odorata (*water lily)			S
Polygonum amphibium (water smartweed)		E/S	
Polygonum coccineum (smartweed)	E		
Potamogeton epihydrus (leafy pondweed)	S		
Potamogeton robbinsii (Robbins' pondweed)			S
Potentilla palustris (marsh cinquefoil)			E/S
Scirpus americanus (three square rush)	E		
Scirpus cyperinus (wooly grass)	E		
Scirpus validus (great bulrush)	E		
Sium suave (water parsnip)	E		
Typha latifolia (common cattail)	E	E	
Zizania aquatic (wild rice)		E	

E=emergent growth form; S=submergent growth form (includes rooted species with floating leaves); E/S=emergent and submergent forms

CONVENTIONAL DRY DREDGING

How it Works

Dredging involves the removal of sediment. Conventional dry, conventional wet, and hydraulic/ pneumatic dredging are each addressed separately here, as planning and impact considerations vary substantially. Dredging is perhaps best known for increasing depth, but dredging can be an effective lake management technique for the control of excessive algae and invasive growth of macrophytes. The management objectives of a sediment removal project are usually to deepen a shallow lake for boating and fishing, or to remove nutrient rich sediments that can cause algal blooms or support dense growths of rooted macrophytes.

Control of rooted aquatic vascular plants is achieved by either the removal of substrate hospitable for their growth or by deepening the area enough to create a light limitation on plant growth (although note that invasives such as milfoil can grow in waters up to 30 feet deep with adequate light). The release of algae-stimulating nutrients from lake sediments can be controlled by removing layers of enriched materials. This can reduce internal loading and suppress algal production if internal sources are the dominant nutrient source. Even where incoming nutrient loads remain high, dredging can reduce benthic mat formation and related problems with filamentous green and blue-green algae, as these forms may initially depend on nutrient-rich substrates for nutrition. Dredging also removes the accumulated seed bed established by many vascular plants and the resting cysts deposited by a variety of algae. Dry, wet and hydraulic methods are illustrated in Figure 12.

Dry dredging involves partially or completely draining the lake and removing the exposed bottom sediments with a bulldozer or other conventional excavation equipment and trucking it away. Projects involving silts, sands, gravel and larger obstructions where water level can be controlled favor conventional, dry methodology. Although ponds rarely dry to the point where equipment can be used without some form of support (e.g., railroad tie mats or gravel placed to form a road), excavating under "dry" conditions allows very thorough sediment removal and a complete restructuring of the pond bottom. The term "dry" may be a misnomer in many cases, as organic sediments will not dewater sufficiently to be moved like upland soils. Dry dredging may resemble a large-scale excavation of pudding, and the more the material is handled, the more liquid it becomes.

Dry dredging with conventional excavation equipment (provided by C. Carranza of BEC)

Control of inflow to the lake is critical during dry excavation. For dry excavation, water can often be routed through the lake in a sequestered channel or pipe, limiting interaction with disturbed sediments. Water added from upstream or directly from precipitation will result in solids content rarely in excess of 50% and often as low as 30%. Consequently, some form of containment area is needed before material can be used productively in upland projects. Where there is an old gravel pit or similar area to be filled, one-step disposal is facilitated, but most projects involve temporary and permanent disposal steps.

A properly conducted dredging program removes accumulated sediment from a lake and effectively sets it back in time, to a point prior to significant sedimentation. Partial dredging projects are possible and may be appropriate depending upon management goals, but for maximum benefit it is far better to remove all "soft" sediment. Failed dredging projects are common, and failure can almost always be traced to insufficient consideration of the many factors that govern dredging success (Table 7).

Dry dredging: removal to "hard" bottom (provided by C. Carranza of BEC)

Benefits
- ♦ Deepening of the lake for many purposes, including increased flood or water supply storage, improved recreational uses, enhanced pollutant trapping effectiveness, and dilution of nutrient loads
- ♦ Control of rooted plants if a depth (light) or substrate limitation is imposed
- ♦ Reduced algal mat formation by reduced nutrient supply and elimination of resting cysts
- ♦ Reduced planktonic algal abundance if internal loading is an important nutrient source and enough sediment is removed
- ♦ Removal of toxic substances or other unwanted materials accumulated in the sediment
- ♦ Reduced sediment-water interactions, with potential improvement in water quality
- ♦ Complete removal of soft sediments in any target area or even "overdredging" to removal of sand or gravel is facilitated by dry dredging

Sediment core: dark organic matter on top of a clay base

Detriments
- ♦ All possible impacts of drawdown, as the lake is lowered to facilitate dry dredging
- ♦ Loss of most biological components of the drained portion of the lake through physical disturbance
- ♦ Potential for downstream turbidity if throughflow is not controlled
- ♦ Peripheral land disruption for access by equipment
- ♦ Upland area must be provided for sediment disposal, with temporary alteration
- ♦ Contaminated sediments potentially subject to many restrictions on disposal

Information for Proper Application
Table 7 lists the many considerations applicable to a dredging project. Key factors include:
- ♦ Sediment quality, which will determine disposal options and cost
- ♦ Sediment quantity, which determines disposal volume needs and greatly affects cost
- ♦ Ability to control the lake level, which affects choice of dredging method
- ♦ Sensitive biological resources, which affects project goals and permitting
- ♦ Monitoring to track system recovery and overall project impacts

When dredging for rooted plant control, it is important to know how deep the water must be to establish a light limitation on plant growth. For northern lakes, the depth to which plants will grow can be estimated as:
Log MDC=0.79 logSD +0.25
where MDC= Maximum Depth of Colonization and SD= Secchi Depth, both in meters.

Factors Favoring the Use of this Technique
- ♦ There is a distinct need for increased depth in the lake
- ♦ Studies have demonstrated the impact of internal loading on the lake
- ♦ Studies have demonstrated the presence of contaminants that are impacting lake biota or uses
- ♦ Rooted plants and algal mats dependent on the soft sediments are impairing recreation and habitat value
- ♦ Habitat is degraded to the extent that a complete restructuring is desirable
- ♦ Partial drawdown or sequestering of the dredged area can be performed to limit impacts to aquatic species
- ♦ Sediments are "clean", based on Massachusetts regulatory thresholds
- ♦ Suitable and sufficient containment and disposal areas are available close to the lake Performance Guidelines

- Address the many considerations for dredging provided in Table 7; pay particular attention to sediment quality and quantity and disposal arrangements
- Design the dredging project with local conditions in mind; address water level and flow control, appropriate equipment, access and staging areas, material dewatering and transport for disposal
- Excavate in accordance with all permits
- Achieve a depth (light) or substrate (hard bottom) limitation if control of plant growth is a project goal; usually this involves removal of all soft sediment or achievement of a water depth in excess of 10 ft
- Remove sediment to expose a low nutrient layer if reduction of internal loading is a project goal; usually this involves removal of all soft sediment
- Restore or rehabilitate all access, temporary containment, and final disposal areas
- Monitor downstream flows and water quality during dry dredging
- Monitor recovery of lake biota and in-lake conditions relative to project goals (e.g., depth increase, plant control, water quality enhancement)

Possible Permits

- MEPA review
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 permit through DEP may be required for Great Ponds
- 404 permit through the Corps of Engineers
- 401 WQ permit through the DEP
- Solid Waste permit for sediment disposal through DEP
- Possible Dam Safety permit through DCR

Dry dredging containment area - full

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality improvement); may also affect water quantity by uncapping springs and seepage areas. Short-term limitation on available water is possible during dredging
- Protection of groundwater supply – Generally neutral (no significant interaction), although uncapping of springs and seepage areas may increase interaction. Possible adverse impacts below containment area if contaminants leach
- Flood control – Generally neutral (no significant interaction), although greater depth could be an asset if drawdown is later practiced for flood control. Possible short-term benefit or detriment during dredging, depending upon flow controls applied
- Storm damage prevention – Generally neutral (no significant interaction), although greater depth could be an asset if drawdown is later practiced for damage control. Possible short-term benefit or detriment during dredging, depending upon flow controls applied
- Prevention of pollution – Expected benefit (water quality enhancement), although short-term detriment is possible if flows contact disturbed sediment

Lake drawn down for “dry” dredging

- Protection of land containing shellfish – Possible long-term benefit through water quality enhancement, but potential short-term detriment by direct removal and lack of water
- Protection of fisheries - Possible long-term benefit through water quality and physical habitat enhancement, but short-term detriment by habitat loss during dry dredging
- Protection of wildlife habitat – Expected long-term benefit (water quality enhancement, invasive plant control), but possible short-term detriment by habitat loss during dry dredging

Impacts to interests of the Wetlands Protection Act from a specific dredging project are highly dependent upon site-specific features and project design.

Cost Considerations

Because the cost varies depending on the volume of material removed, costs are usually expressed per cubic yard (cy) of material removed. Generally, the larger the project, the smaller the cost per cubic yard. The proper way to estimate dredging costs is to consider each element of the project, which may vary dramatically among projects. The total cost can be divided by the total yardage to get a cost per cubic yard, but this may not be especially meaningful in estimating other dredging projects. With that caveat in mind, a typical range of costs for dry dredging projects in recent years is $8 to $25/cy, with $15/cy suggested as a rough estimator for considering the general magnitude of a project under initial consideration. It is important, however, to develop a more careful estimate during further project planning, and many smaller projects (<50,000 cy) have incurred costs in excess of $30/cy. Total cost can be reduced if the dredged material is clean enough to be sold as a soil amendment. Recovery of more than $1/cy is unusual, however. In some cases, contractors have wanted the material in the lake, or more likely the sand and gravel under the muck in the lake, and were willing to perform dry dredging at a much reduced cost. Income from excavation should not be assumed, however, unless a firm agreement is in hand. As part of a major overhaul of a lake, dredging is often accompanied by other management actions such as storm water treatment, construction of recreational amenities or fish habitat enhancement. These associated improvements add to overall project cost but are not specifically part of the dredging project cost estimated here.

Dry dredging: excavation of dry lake bed (provided by C. Carranza of BEC)

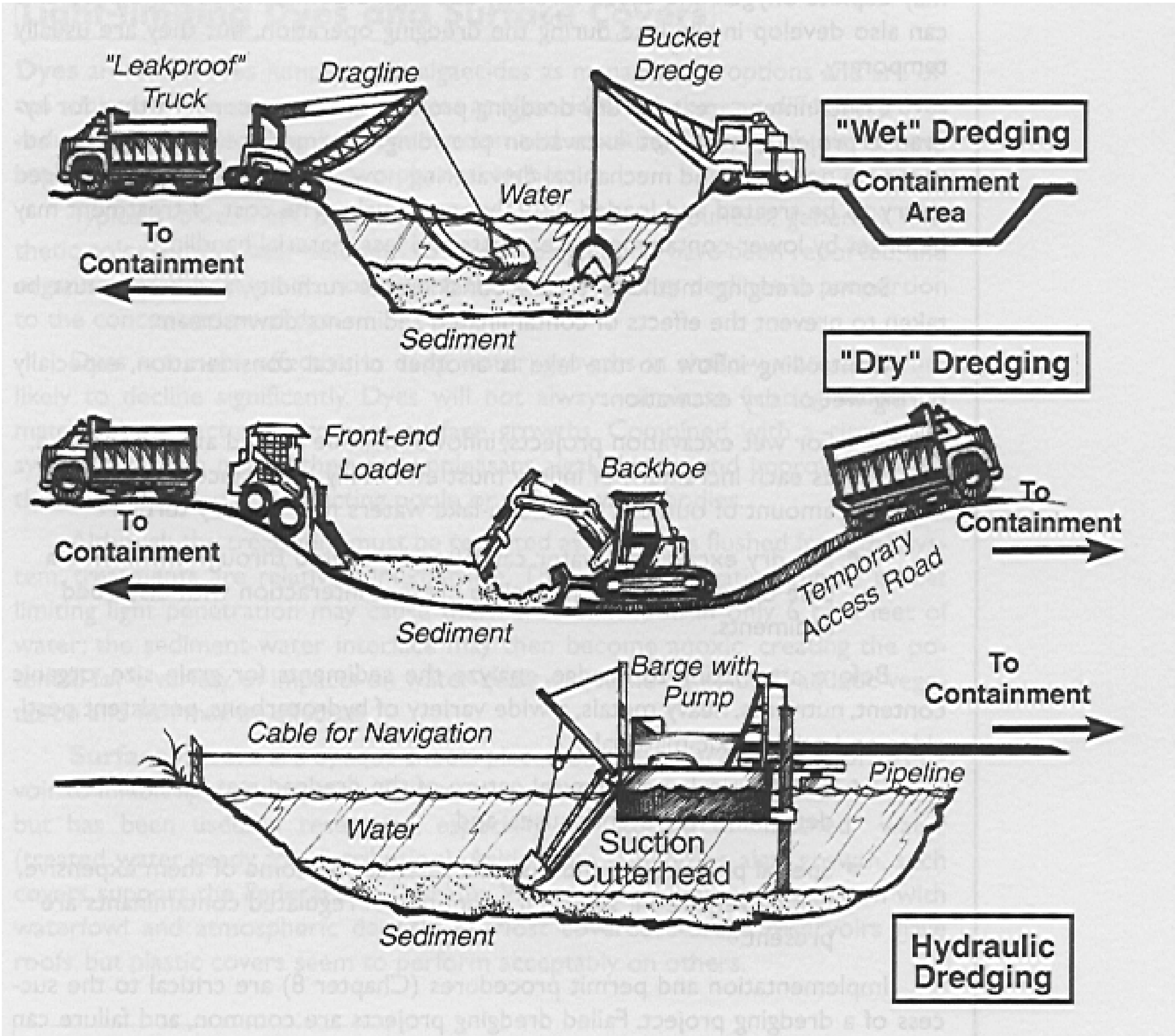


Figure 12. Wet, Dry and Hydraulic Dredging Approaches (from Wagner, 2001).

Table 7. Key Considerations for Dredging

Reasons For Dredging:
Increased depth/access
Removal of nutrient reserves
Control of aquatic vegetation
Alteration of bottom composition
Habitat enhancement
Reduction in oxygen demand

Volume Of Material To Be Removed:
In-situ volume to be removed
Distribution of volume among sediment types
Distribution of volume over lake area (key sectors)
Bulked volume (see below)
Dried volume (see below)

Nature of Underlying Material To Be Exposed:
Type of material
Comparison with overlying material

Dewatering Capacity of Sediments:
Dewatering potential
Dewatering timeframe
Methodological considerations

Protected Resource Areas:
Wetlands
Endangered species
Habitats of special concern
Species of special concern
Regulatory resource classifications

Equipment Access:
Possible input and output points
Land slopes
Pipeline routing
Property issues

Potential Disposal Sites:
Possible containment sites
Soil conditions
Necessary site preparation
Volumetric capacity
Property issues
Long term disposal options

Existing and Proposed Bathymetry:
Existing mean depth
Existing maximum depth
Proposed distribution of lake area over depth range
Proposed mean depth
Proposed maximum depth
Proposed distribution of area over depth range

Physical Nature of Material To Be Removed:
Grain size distribution
Solids and organic content
Settling rate
Bulking factor
Drying factor
Residual turbidity

Chemical Nature of Material To Be Removed:
Metals levels
Petroleum hydrocarbon levels
Nutrient levels
Pesticides levels
PCB levels
Other organic contaminant levels
Other contaminants of concern (site-specific)

Flow Management:
System hydrology
Possible peak flows
Expected mean flows
Provisions for controlling water level
Methodological implications

Relationship To Lake Uses:
Impact on existing uses during project
Impact on existing uses after project
Facilitation of additional uses

Dredging Methodologies:
Hydraulic (or pneumatic) options
Wet excavation
Dry excavation

Table 7 (continued). Key Considerations for Dredging

Applicable Regulatory Processes:
MEPA review (Environmental Notification Form)
Environmental impact reporting (EIR if needed)
Wetlands Protection Act (Order of Conditions)
Dredging permits (Chapter 91)
Aquatic structures permits (Chapter 91)
Drawdown notification (to DFWELE)
Water Management Act (diversion/use permits)
Clean Water Act Section 401 (WQ certification)
Clean Water Act Section 404 (USACE wetlands)
Dam safety/alteration permit (DCR)
Waste disposal permit (DEP)
Discharge permits (NPDES, USEPA/DEP)

Removal Costs:
Engineering and permitting costs
Construction of containment area
Equipment purchases
Operational costs
Contract dredging costs
Ultimate disposal costs
Monitoring costs
Total cost divided by volume to be removed

Uses Or Sale Of Dredged Material:
Possible uses
Possible sale
Target markets

Other Mitigating Factors:
Necessary watershed management
Ancillary project impacts
Economic setting
Political setting
Sociological setting

CONVENTIONAL WET DREDGING

How it Works

Dredging involves the removal of sediment. Conventional dry, conventional wet, and hydraulic/ pneumatic dredging are each addressed separately here, as planning and impact considerations vary substantially. Dredging is perhaps best known for increasing depth, but dredging can be an effective lake management technique for the control of excessive algae and invasive growth of macrophytes. The management objectives of a sediment removal project are usually to deepen a shallow lake for boating and fishing, or to remove nutrient rich sediments that can cause algal blooms or support dense growths of rooted macrophytes.

Control of rooted aquatic vascular plants is achieved by either the removal of substrate hospitable for their growth or by deepening the area enough to create a light limitation on plant growth. The release of algae-stimulating nutrients from lake sediments can be controlled by removing layers of enriched materials. This can reduce internal loading and suppress algal production if internal sources are the dominant nutrient source. Even where incoming nutrient loads remain high, dredging can reduce benthic mat formation and related problems with filamentous green and blue-green algae, as these forms may initially depend on nutrient-rich substrates for nutrition. Dredging also removes the accumulated seed bed established by many vascular plants and the resting cysts deposited by a variety of algae. Dry, wet and hydraulic methods are illustrated in Figure 12.

Wet dredging may involve a partial drawdown, especially to avoid downstream flow of turbid water, but sediment will be excavated from areas overlain by water. Sediment will be very wet, often only 10 to 30% solids unless sand and gravel deposits are being removed. Clamshell dredges, draglines, and other specialized excavation equipment are used in what most people would consider a very messy operation. Excavated sediment must usually be deposited in a bermed area adjacent to the pond or into other water-holding structures until dewatering can occur. This approach is most often practiced when water level control is limited. Aside from small ponds, this technique is applicable to ocean harbors, and has been practiced in Boston and New Bedford.

Conventional wet dredging methods create considerable turbidity, and steps must be taken to prevent downstream mobilization of sediments and associated contaminants. For wet excavation projects, inflows must normally be routed around the lake, as each increment of inflow must be balanced by an equal amount of outflow, and the in-lake waters may be very turbid. It should be noted, however, that more recent bucket dredge designs greatly limit the release of turbid water and have been approved for use in potentially sensitive aquatic settings such as Boston Harbor.

A properly conducted dredging program removes accumulated sediment from a lake and effectively sets it back in time, to a point prior to significant sedimentation. Partial dredging projects are possible and may be appropriate depending upon management goals, but for maximum benefit it is far better to remove all “soft” sediment. Failed dredging projects are common, and failure can almost always be traced to insufficient consideration of the many factors that govern dredging success (Table 7).

Benefits

- Deepening of the lake for many purposes, including increased flood or water supply storage, improved recreation, enhanced pollutant trapping effectiveness and dilution of nutrient loads
- Control of rooted plants if a depth (light) or substrate limitation is imposed
- Reduced algal mat formation by reduced nutrient supply and elimination of resting cysts
- Reduced planktonic algal abundance if internal loading is an important nutrient source and enough sediment is removed
- Removal of toxic substances or other unwanted materials accumulated in the sediment
- Reduced sediment-water interactions, with potential improvement in water quality

Detriments

- All possible impacts of drawdown, if the lake is lowered to any appreciable extent
- Loss of many biological components of the lake through physical disturbance and high turbidity
- Potential for downstream turbidity if outflow is not controlled
- Peripheral land disruption for access by equipment
- Upland area must be provided for sediment disposal, with temporary alteration
- Contaminated sediments potentially subject to many restrictions on disposal
- Potentially incomplete dredging as a consequence of not being able to visually appraise underwater sediment conditions and high suspended solids levels that may form a thin muck layer upon settling

Information for Proper Application

Table 7 lists the many considerations applicable to a dredging project. Key factors include:

- Sediment quality, which will determine disposal options and cost
- Sediment quantity, which determines disposal volume needs and greatly affects cost
- Ability to control the lake level, which affects choice of dredging method
- Sensitive biological resources, which affects project goals and permitting
- Monitoring to track system recovery and overall project impacts

Clamshell dredge used in wet dredging operations (provided by the Lake Michigan Federation)

Factors Favoring the Use of this Technique

- There is a distinct need for increased depth in the lake, but water level cannot be lowered and controlled to facilitate dry dredging, or water level must be maintained for other uses
- Studies have demonstrated the impact of internal loading on the lake
- Studies have demonstrated the presence of contaminants that are impacting lake biota or uses
- Rooted plants and algal mats dependent on the soft sediments are impairing recreation and habitat value
- Habitat is degraded to the extent that a complete restructuring is desirable
- Sequestering of the dredged area can be performed to limit impacts to aquatic species
- Sediments are “clean”, based on Massachusetts regulatory thresholds
- Suitable and sufficient containment and disposal areas are available close to the lake

Performance Guidelines

- Address the many considerations for dredging provided in Table 8; pay particular attention to sediment quality and quantity and disposal arrangements
- Design the dredging project with local conditions in mind; address flow control, appropriate equipment, access and staging areas, material dewatering and transport for disposal
- Excavate in accordance with all permits
- Achieve a depth (light) or substrate (hard bottom) limitation if control of plant growth is a project goal; usually this involves removal of all soft sediment or achievement of a water depth in excess of 10 ft
- Remove sediment to expose a low nutrient layer if reduction of internal loading is a project goal; usually this involves removal of all soft sediment
- Restore or rehabilitate all access, temporary containment, and final disposal areas
- Monitor in-lake water quality during wet dredging
- Monitor downstream flows and water quality during wet dredging

- Monitor recovery of lake biota and in-lake conditions relative to project goals (e.g., depth increase, plant control, water quality enhancement)

Possible Permits

- MEPA review
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 permit through DEP may be required for Great Ponds
- 404 permit through the Corps of Engineers
- 401 WQ permit through the DEP
- Solid Waste permit for sediment disposal through DEP
- Possible Dam Safety permit through DCR
- Possible NPDES permitting through EPA/DEP

Wet dredging is usually performed in smaller water bodies or small sections of larger water bodies, where water level cannot be lowered for physical or regulatory reasons but increased depth is needed.

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality improvement); may also affect water quantity by uncapping springs and seepage areas. Short-term limitation on available water is possible during dredging
- Protection of groundwater supply – Generally neutral (no significant interaction), although uncapping of springs and seepage areas may increase interaction. Possible adverse impacts below containment area if contaminants leach
- Flood control – Generally neutral (no significant interaction), although greater depth could be an asset if drawdown is later practiced for flood control. Possible short-term benefit or detriment during dredging, depending upon flow controls applied
- Storm damage prevention – Generally neutral (no significant interaction), although greater depth could be an asset if drawdown is later practiced for damage control. Possible short-term benefit or detriment during dredging, depending upon flow controls applied
- Prevention of pollution – Expected benefit (water quality enhancement), although short-term detriment is possible during unsequestered wet dredging due to turbidity generation
- Protection of land containing shellfish – Possible long-term benefit through water quality enhancement, but potential short-term detriment by direct removal or water quality impacts
- Protection of fisheries – Possible long-term benefit through water quality and physical habitat enhancement, but potential short-term detriment by water quality impairment during wet dredging
- Protection of wildlife habitat – Expected long-term benefit (water quality enhancement, invasive plant control), but possible short-term detriment by water quality impairment during wet dredging

Impacts to interests of the Wetlands Protection Act from a specific dredging project are highly dependent upon site-specific features and project design.

Cost Considerations

As cost depends on the volume of material removed, costs are usually expressed per cubic yard (cy) of material removed. Generally, the larger the project, the smaller is the cost per cubic yard. The proper way to estimate dredging costs is to consider each element of the project, which may vary dramatically among projects. The total cost can be divided by the total yardage to get a cost per cubic yard, but this may not be especially meaningful in estimating other dredging projects. With that caveat in mind, a typical range of costs for wet dredging projects in recent years is \$15 to \$25/cy, with \$20/cy suggested as a rough estimator for considering the general magnitude of a project under initial consideration. It is important, however, to develop a more careful estimate during further project planning, as much higher costs are possible as a function of site-specific conditions. Resale of dredged material or allowing access to sand and gravel under muck deposits can reduce costs, but such income should not be assumed unless a firm agreement is in hand.

HYDRAULIC OR PNEUMATIC DREDGING

How it Works

Dredging involves the removal of sediment. Conventional dry, conventional wet, and hydraulic/ pneumatic dredging are each addressed separately here, as planning and impact considerations vary substantially. Dredging is perhaps best known for increasing depth, but dredging can be an effective lake management technique for the control of excessive algae and invasive growth of macrophytes. The management objectives of a sediment removal project are usually to deepen a shallow lake for boating and fishing, or to remove nutrient rich sediments that can cause algal blooms or support dense growths of rooted macrophytes.

Control of rooted aquatic vascular plants is achieved by either the removal of substrate hospitable for their growth or by deepening the area enough to create a light limitation on plant growth. The release of algae-stimulating nutrients from lake sediments can be controlled by removing layers of enriched materials. This can reduce internal loading and suppress algal production if internal sources are the dominant nutrient source. Even where incoming nutrient loads remain high, dredging can reduce benthic mat formation and related problems with filamentous green and blue-green algae, as these forms may initially depend on nutrient-rich substrates for nutrition. Dredging also removes the accumulated seed bed established by many vascular plants and the resting cysts deposited by a variety of algae. Dry, wet and hydraulic methods are illustrated in Figure 12.

Hydraulic dredging: dredge in background with buoyed pipeline

A more advanced form of wet dredging, hydraulic dredging usually involves a suction type of dredge that has a cutter head. Agitation combined with suction removes the sediments as a slurry containing approximately 15-20% solids by volume, although this may increase to as high as 30 to 40% in some cases or be as low as 5% with especially watery sediments in difficult areas. This slurry is typically pumped to a containment area in an upland setting where the excess water can be separated from the solids by settling (with or without augmentation). The supernatant water can be released back to the lake or some other waterway. The containment area for a hydraulic dredging project is usually a shallow diked area that is used as a settling basin. The clarified water may be treated with flocculation and coagulation techniques to further reduce the suspended solids in the return water.

Hydraulic dredging: large cutterhead barge

Hydraulic dredging is normally favored for removal of large amounts of highly organic sediments with few rocks, stumps or other obstructions and where water level control is limited. This type of project does require a containment area to be available where removed sediments are separated from water, and may involve secondary removal of the dried sediment from the containment area for ultimate disposal elsewhere. Usually the containment area is not far from the lake, but a slurry can be pumped multiple miles along a suitable route with booster pumps.

Hydraulic dredging: working in dense plant growths

Innovations in polymers and belt presses for sediment dewatering have reached the point where hydraulically dredged slurry can be treated as it leaves the lake to the extent necessary to load it directly onto trucks for transport to more remote sites. Solids content of the resultant material is still too low for many uses without further drying or mixing with sand, but the need for a large containment area can be avoided with this technology. The cost of coagulation and mechanical dewatering may be at least partially offset by savings in containment area construction and ultimate material disposal. Likewise, pumping the slurry into geo-tubes (engineered filter bags) can also enhance dewatering in a limited space.

Pneumatic dredging, in which air pressure is used to pump sediments out of the lake at a higher solids content (50 to 70%) has not yet been performed in Massachusetts or surrounding states. This would seem to be a highly desirable approach, given containment area limitation in many cases and more rapid drying with higher solids content. However, few of these dredges are operating within North America, and there is little freshwater experience upon which to base a review. Considerations are much like those for hydraulic dredging.

Hydraulic dredging containment area - empty

A properly conducted dredging program removes accumulated sediment from a lake and effectively sets it back in time, to a point prior to significant sedimentation. Partial dredging projects are possible and may be appropriate depending upon management goals, but for maximum benefit it is far better to remove all "soft" sediment. Failed dredging projects are common, and failure can almost always be traced to insufficient consideration of the many factors that govern dredging success (Table 7).

Hydraulic dredging containment area – full

Benefits

- Deepening of the lake for many purposes, including increased flood or water supply storage, improved recreational uses, enhanced pollutant trapping effectiveness, and dilution of nutrient loads
- Control of rooted plants if a depth (light) or substrate limitation is imposed
- Reduced algal mat formation by reduced nutrient supply and elimination of resting cysts
- Reduced planktonic algal abundance if internal loading is an important nutrient source and enough sediment is removed
- Removal of toxic substances or other unwanted materials accumulated in the sediment
- Reduced sediment-water interactions, with potential improvement in water quality
- Less disruption of biological components of the aquatic system and less impact on peripheral land than for conventional excavation approaches

Hydraulically dredged slurry deposition

All photos on this page provided by J. Walsh of BEC

Detriments

- Upland area must be provided for sediment disposal, with temporary alteration
- Contaminated sediments potentially subject to many restrictions on disposal
- Loss of many biological components of the lake through physical disturbance and high turbidity
- Potentially incomplete dredging as a consequence of not being able to visually appraise underwater sediment conditions and high suspended solids levels that may form a thin muck layer upon settling
- Less effective than conventional excavation approaches where there are obstructions such as boulders, stumps or underwater structures

Information for Proper Application

Table 7 lists the many considerations applicable to a dredging project. Key factors include:

- Sediment quality, which will determine disposal options and cost
- Sediment quantity, which determines disposal volume needs and greatly affects cost
- Obstructions or other factors that limit access to soft sediments by the hydraulic dredge
- Containment area features and routing of the slurry to the containment area
- Discharge location and water quality for supernatant from the containment area
- Monitoring to track system recovery and overall project impacts

Factors Favoring the Use of this Technique

- There is a distinct need for increased depth in the lake
- Studies have demonstrated the impact of internal loading on the lake
- Studies have demonstrated the presence of contaminants that are impacting lake biota or uses
- Rooted plants and algal mats dependent on the soft sediments are impairing recreation and habitat value
- Significant biological resources remain and warrant protection during dredging
- Sediment is largely muck, and rocks, stumps and other obstructions are minimal
- Sediments are "clean", based on Massachusetts regulatory thresholds
- Suitable and sufficient containment and disposal areas are available close to the lake

Hydraulically dredged sediment after drying

Comparison of influent (left) to effluent (right) from containment area

Performance Guidelines

- Address the many considerations for dredging provided in Table 8; pay particular attention to sediment quality and quantity and disposal arrangements
- Design the dredging project with local conditions in mind; address flow control, appropriate equipment, access and staging areas, material dewatering and transport for disposal
- Excavate in accordance with all permits
- Achieve a depth (light) or substrate (hard bottom) limitation if control of plant growth is a project goal; usually this involves removal of all soft sediment or achievement of a water depth in excess of 10 ft
- Remove sediment to expose a low nutrient layer if reduction of internal loading is a project goal; usually this involves removal of all soft sediment
- Restore or rehabilitate all access, temporary containment, and final disposal areas
- Monitor containment area discharge quality during hydraulic dredging
- Monitor downstream flows and water quality during hydraulic dredging
- Monitor recovery of lake biota and in-lake conditions relative to project goals (e.g., depth increase, plant control, water quality enhancement)

Possible Permits

- MEPA review
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 permit through DEP may be required for Great Ponds
- 404 permit through the Corps of Engineers
- 401 WQ permit through the DEP

All photos on this page provided by J. Walsh of BEC

- Solid Waste permit for sediment disposal through DEP
- Possible NPDES permitting through EPA/DEP

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality improvement); may also affect water quantity by uncapping springs and seepage areas.
- Protection of groundwater supply – Generally neutral (no significant interaction), although uncapping of springs and seepage areas may increase interaction. Possible adverse impacts below containment area if contaminants leach
- Flood control – Generally neutral (no significant interaction), although greater depth could be an asset if drawdown is later practiced for flood control.
- Storm damage prevention – Generally neutral (no significant interaction), although greater depth could be an asset if drawdown is later practiced for damage control.
- Prevention of pollution – Expected benefit (water quality enhancement), although short-term detriment is possible during hydraulic dredging with containment area problems
- Protection of land containing shellfish – Possible long-term benefit through water quality enhancement, but potential short-term detriment by direct removal
- Protection of fisheries - Possible long-term benefit through water quality and physical habitat enhancement, but potential short-term detriment by water quality impairment during dredging
- Protection of wildlife habitat – Expected long-term benefit (water quality enhancement, invasive plant control)

Impacts to interests of the Wetlands Protection Act from a specific dredging project are highly dependent upon site-specific features and project design.

Cost Considerations

Because the cost varies greatly with the volume of material removed, costs are usually expressed per cubic yard (cy) of material removed. Generally, the larger the project, the smaller is the cost per cubic yard. The proper way to estimate dredging costs is to consider each element of the project, which may vary dramatically among projects. The total cost can be divided by the total yardage to get a cost per cubic yard, but this may not be especially meaningful in estimating other dredging projects. With that caveat in mind, a typical range of costs for dry dredging projects in recent years is $7 to $20/cy, with $12/cy suggested as a rough estimator for considering the general magnitude of a project under initial consideration. It is important, however, to develop a more careful estimate during detailed project planning. Smaller dredging projects (<50,000 cy) applying hydraulic methods have incurred costs in excess of $30/cy.

For hydraulic dredging, cost factors of major importance include:

- Volume of material – Hydraulic dredging is often not economical at low volumes
- Distance to containment area – The need for booster pumps increases cost
- Size of containment area – The size of dredge and rate of pumping depend upon the available volume for containment and resultant detention time. Additionally, cost will escalate if dredging must cease periodically to allow containment area clean-out
- Obstructions and clogging agents – Efficient use of the cutterhead and pipeline will be impeded by rocks, stumps, structures and dense plant growths

Total cost can be reduced if the dredged material is clean enough to be sold as a soil amendment. Recovery of more than $1/cy is unusual, however. Income from resale should not be assumed, however, unless a firm agreement is in hand. Because hydraulic dredging is not suited to economic removal of coarse sand and gravel, no savings from access to such deposits is expected.

REVERSE LAYERING

How it Works
An alternative method to dredging that is believed to provide some of the same benefits is the reverse layering of sediments. While dredging involves the removal of sediment, reverse layering simply reorganizes sediment layers. It is still a largely experimental procedure that has been tested in small areas of Red Lily Pond in Barnstable, Massachusetts. It is believed to be especially applicable to the glacial "kettle hole" ponds that are common to Cape Cod and Southeastern Massachusetts because of a layer of glacial sand that lies beneath the accumulated muck layer. The purpose is to extract glacial sand that underlies the nutrient-rich, anaerobic, organic sediments of a eutrophic lake and place it on top of those less desirable sediments.

Reverse layering is accomplished by hydraulic jetting. Water is pumped down below the muck and/or peat layer to the layer of glacial sand. The glacial sand is forced up through pipes and spread over the bottom sediments. A cavity is created by the removal of glacial sand, which causes the bottom sediments to subside and fill the cavity. The purpose of this method is to retard or reverse the process of eutrophication, and to restore the lake bottom to the original sediment type that will promote a more diverse plant and animal community. This method does not require disposal of dredged materials, nor does it deepen the lake. It simply switches the location of existing sediment layers.

Reverse layering is not considered dredging by some groups, most notably the US Army Corps of Engineers, which therefore does not require a permit under Section 404 of the Clean Water Act as it normally does for dredging projects. It is certainly a very different technique than the other methods of actual sediment removal, but the underlying goal is the same with regard to nutrient and algae control; limit the availability of nutrients from accumulated muck sediments. The goal for plant control will not involve light limitation as with some dredging projects, but creation of a less hospitable substrate may be possible, thereby reducing rooted plant density or at least shifting community composition. In this regard, reverse layering is more like a benthic barrier treatment.

Benefits
- Control of rooted plants if a substrate limitation is imposed by the new sand layer
- Reduced algal mat formation by reduced nutrient supply and burial of resting cysts
- Reduced planktonic algal abundance if internal loading is an important nutrient source and enough organic sediment is covered
- Reduced sediment-water interactions, with potential improvement in water quality

Detriments
- Fine sediment mixed with sand may be dispersed during the jetting and layering operation, along with any associated contaminants
- The new surficial sediment layer may support plants with equal or greater nuisance potential

Information for Proper Application
- Data for surficial muck and deeper sand quality
- Evaluation of likely post-treatment plant growths and nutrient release
- Information on sensitive biological resources, which affect project goals and permitting
- Monitoring to assess overall project impacts

Factors Favoring the Use of this Technique
- There is a layer of coarse, clean sand under the surficial muck
- Studies have demonstrated the impact of internal loading on the lake
- Studies have demonstrated the presence of contaminants in surficial sediments that are impacting lake biota or uses

- Rooted plants and algal mats dependent on the soft sediments are impairing recreation and habitat value

Performance Guidelines

This technique is still too experimental to provide substantive guidance, but key aspects are likely to include:

- Determination of the physical nature and quality of sediment to be placed as a surficial layer
- Adequate burial of targeted sediments
- Adequate removal or burial of any target plants
- Avoidance of critical habitats and spawning areas unless expressly permitted
- Monitoring of turbidity and other relevant water quality during reverse layering

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

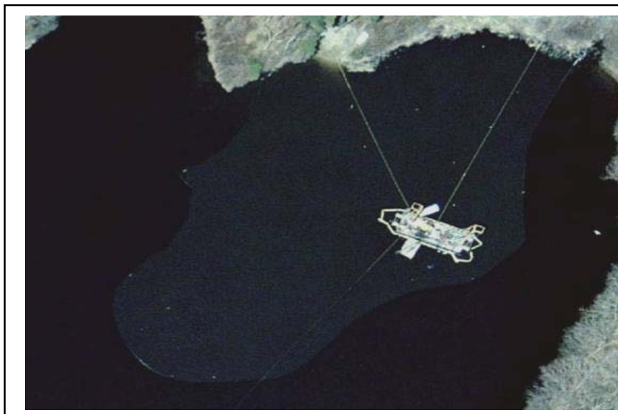
Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (water quality improvement)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Expected benefit (water quality enhancement), although short-term detriment is possible during layering process
- Protection of land containing shellfish – Possible long-term benefit through water quality enhancement, but potential short-term detriment by burial
- Protection of fisheries - Possible long-term benefit through water quality and physical habitat enhancement, but potential short-term detriment by habitat loss and/or turbidity
- Protection of wildlife habitat – Expected long-term benefit (water quality enhancement, invasive plant control), but possible short-term detriment by habitat loss

Cost Considerations

Costs for reverse layering of sediments were estimated at $10,000/acre in 1991. This technique has not been used enough to provide a reliable estimate of costs, however.

Reverse layering apparatus (provided by Rob Gatewood of Barnstable)



Reverse layering of Red Lily Pond – note lighter colored area of active layering (provided by Rob Gatewood of Barnstable)

HAND HARVESTING

How it Works

Hand pulling is exactly what it sounds like; a snorkeler or diver surveys an area and selectively pulls out unwanted plants on an individual basis. This is a highly selective technique, and a labor intensive one. It is well suited to vigilant efforts to keep out invasive species that have not yet become established in the lake or area of concern. Hand pulling can also effectively address non-dominant growths of undesirable species in mixed assemblages, or small patches of plants targeted for removal. This technique is not well suited to large-scale efforts, especially when the target species or assemblage occurs in dense or expansive beds.

Hand pulling can be augmented by various tools, including a wide assortment of rakes, cutting tools, water jetting devices, nets and other collection devices. McComas (1993) provides an extensive and enjoyable review of options. Suction dredging is also used to augment hand pulling, allowing a higher rate of pulling in a targeted area, as the diver/snorkeler does not have to carry pulled plants to a disposal point. Use of these tools transitions into more mechanized forms of harvesting.

Hand harvesting

Benefits

- Highly selective plant control
- Limited impact to non-target organisms
- Can prevent infestations before they become problems

Hand harvesting bags being ferried to shore

Detriments

- Incomplete harvesting may foster regrowth or dispersal of plants
- Turbidity generation may be substantial

Information for Proper Application

- Knowledge of plant assemblage – types, distribution, density
- Careful identification of target species
- Planning for collection and disposal of hand harvested plants
- Pre- and post-harvesting monitoring of plant assemblage to assess results

Factors Favoring the Use of this Technique

- Nuisance species are not yet established; target plant density is low (<500 stems/acre)
- Target species are in shallow water, or dive crew is readily available
- Target species are not strongly rooted or prone to fragmentation

Hand harvested Eurasian watermilfoil and curly leaf pondweed

Performance Guidelines

- Map the distribution of the target species and any protected non-target species in the lake
- Train all harvesting personnel to recognize the target species and any non-target species of concern
- Restrict hand harvesting to areas of sparse density of the target species (<500 stems/acre in most cases)
- Provide fragment barrier around areas to be harvested and bags in which harvested plants are to be placed
- Harvest entire plants; pull out root systems to the greatest extent possible

- Observe safety precautions in areas where boat traffic may be encountered or other risks exist; provide spotters on the surface for all divers
- Monitor turbidity in the harvest area before, during and after harvest
- Monitor pre- and post-harvest density of target plants
- Plan for follow-up inspection and harvesting within the same growing season and in the following growing season

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Note that some Conservation Commissions have issued a negative Determination of Applicability for hand pulling efforts under the WPA

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Generally neutral (no significant interaction)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if sediment disruption and resultant turbidity are high
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Generally neutral (no significant interaction), unless a very large effort is undertaken, in which case there may be benefits and detriments
- Protection of wildlife habitat – Generally neutral at expected scale of operation, but may have benefit and detriment to different species in same lake from same effort

Cost Considerations

Many hand harvesting efforts are volunteer programs, so costs are difficult to estimate. For programs where cost accounting is possible, the cost of hand harvesting when targeted plant density is sparse is estimated at $150-$300/acre, with most of these representing control of new and sparse milfoil growths. A range of $100 to $500/acre for sparse to moderate growths is suggested; the cost for hand harvesting dense stands would be much higher.

Costs for augmentation of hand pulling through suction harvesting are estimated at >$5,000/acre, with some estimates approaching $15,000/acre. This may be worthwhile for small areas, but will limit the utility of this technique on a lake-wide basis.

Fragment barrier used during hand harvesting to prevent the spread of target plants

MECHANICAL HARVESTING

How it Works

Mechanical harvesting is most often associated with large machines on pontoons that cut and collect vegetation, but encompasses a range of techniques from simply cutting the vegetation in place to cutting, collecting, and grinding the plants, to collection and disposal outside the lake. In its simplest form, cutting, a blade of some kind is applied to plants, severing the active apical meristem (location of growth) and possibly much more of the plant from the remaining rooted portion. Regrowth is expected, and in some species that regrowth is so rapid that it negates the benefits of the cutting in only a few weeks. If the plant can be cut close enough to the bottom, or repeatedly, it will sometimes die, but this is more the exception than the rule. Cutting is defined here as an operation that does not involve collecting the plants once they are cut, so impacts to dissolved oxygen and nutrient release are possible in large-scale cutting operations.

Hand held rake

Towed cutting bar

Advanced technology cutting techniques involve the use of mechanized barges normally associated with harvesting operations, in which plants are collected for out-of-lake disposal. In its use as a cutting technology, the “harvester” cuts the plants but does not collect them. A modification in this technique employs a grinding apparatus that ensures that viable plant fragments are minimized after processing. There is a distinct potential for dissolved oxygen impacts and nutrient release as the plant biomass decays, much like what would be expected from many herbicide treatments.

Mechanized harvester (provided by J. Dauffenbach, Aquarius Systems)

Harvesting may involve collection in nets or small boats towed by the person cutting the weeds, or can employ smaller boat-mounted cutting tools that haul the cut biomass into the boat for eventual disposal on land. It can also be accomplished with larger, commercial machines with numerous blades, a conveyor system, and a substantial storage area for cut plants. Offloading accessories are available, allowing easy transfer of weeds from the harvester to trucks that haul the weeds to a composting area. Choice of equipment is really a question of scale, with larger harvesting operations usually employing commercially manufactured machines built to specifications suited to the job. Some lake associations choose to purchase and operate harvesters, while others prefer to contract harvesting services to a firm that specializes in lake management efforts.

Mechanized harvester with offloading conveyor (provided by J. Dauffenbach, Aquarius Systems)

Cutting rates for commercial harvesters tend to range from about 0.2 to 0.6 acres per hour, depending on machine size and operator ability, but the range of possible rates is larger and is often dependent upon distance to the offloading location when out-of-lake disposal is planned. Even at the highest conceivable rate, harvesting is a slow process that may leave some lake users dissatisfied with progress in controlling aquatic plants. Weed disposal is not usually a problem, in part because lakeshore residents and farmers often will use the weeds as mulch and fertilizer. Also, since aquatic plants are more than 90 percent water, their dry bulk is comparatively small. Key issues in choosing a harvester include depth of operation, volume and weight of plants that can be stored, reliability and ease of maintenance, along with a host of details regarding the hydraulic system and other mechanical design features.

Benefits

- Clears target area of plant biomass to selected depth (usually up to 7 ft)
- Does not kill most plants through single cutting
- Repeated harvest may reduce abundance of seed-producing species
- Harvesting at the sediment level may disrupt plants and provide greater longevity of results or shift to more desirable species

Detriments

- Minimally selective; only depth of harvest is controlled, Although this may be adequate to favor desirable low-growing plants, it may also open areas for colonization by invasive species
- Will rarely control species that propagate vegetatively, and may help expand their populations
- Regrowth may overrun ability of harvester to keep target area clear of plants in larger operations
- Harvesting with collection tends to collect many small fish and other aquatic life forms
- Cutting without collection may affect water quality through plant decay

Mechanical harvesting of species prone to viable fragmentation has been demonstrated to promote the spread of those species and is not desirable when such species are present at low densities or in only a localized portion of the waterbody. However, if such species are already abundant, harvesting may be a useful maintenance strategy.

Information for Proper Application

- General plant mapping and knowledge of any sensitive areas, especially where protected species are involved
- For large or repeated efforts, more detailed mapping with estimates of cover or biomass that aid planning
- Fragment control plan, where species that expand by this process are not yet dominant or where downstream movement must be prevented
- Harvesting plan to include areas to be harvested, timing and pattern of harvest, and means to dispose of the plant material
- Information on underwater obstructions, shallow areas, and other possible interference factors
- Monitoring plan for assessing results, including impact on plant types and abundance, regrowth rates, achieved cutting rate, and any impacts to non-target organisms of concern

Harvesting repeatedly at the sediment-water interface may be sufficiently disruptive to lower plant biomass for a prolonged period of time. In most cases, however, regrowth to pre-harvest densities is expected within two growing seasons.

Factors Favoring the Use of this Technique

- The lake is dominated by undesirable annual species that propagate by seeds
- Overall density of macrophytes is excessive throughout the littoral zone
- Surficial and underwater obstructions in targeted areas are minimal
- Suspended sediments resettle quickly and leave minimal residual turbidity
- Convenient access for equipment and trucks and a nearby location for plant disposal are available

Harvesting before seed-producing species such as pondweeds and water chestnut can generate and disperse seeds can reduce the abundance of those species once the existing seed bed has been depleted.

Performance Guidelines

- Map the distribution of the target species and any protected non-target species in the lake

- Develop a harvesting plan that divides the lake into zones and addresses which zones will be harvested in what order, designated offloading sites, and any protected (no harvest) areas
- Select equipment consistent with goals; cutting depth and hopper capacity are important features, and auxiliary barges and offloading equipment may improve efficiency
- Inspect and clean all equipment before entering or leaving a lake
- Avoid areas of known sensitive habitat during active use
- Avoid harvesting of plants that spread by vegetative fragmentation when present at low densities unless the collection system is very effective
- When cutting dense and extensive assemblages of plants that spread by vegetative fragmentation, collect the cut plants or kill them by grinding or other methods; fragment control may be needed
- When harvesting annual (seed-producing) plants, harvest before seeds are formed and dispersed for greatest longevity of results
- Harvest as close to the bottom as equipment allows for maximum effect; actually disturbing the root systems in soft sediment may prolong control, but may also produce excessive turbidity
- Monitor pre- and post-harvest density of target plants and the plant community in general
- Monitor collection of non-target fauna (e.g., fish, turtles) and avoid excessive collection
- Develop a harvester maintenance plan; routine repairs are essential to keeping a harvesting program on schedule

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral (no significant interaction), although reduced plant density may benefit taste and odor control and minimize clogging of intakes
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if sediment disruption and resultant turbidity are high, or if cut vegetation is left in the lake to decay
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Detriment from mechanical harvesting (direct fish removal), but with potential benefit by habitat improvement (may have benefit and detriment to different species in same lake from same effort)
- Protection of wildlife habitat - Potential benefit by habitat improvement, but may have benefit and detriment to different species in same lake from same effort

Cost Considerations

Commercial harvesting costs vary depending on the target plant(s), the density of growth, travel distance for disposal of harvested plants and the number of obstructions present. The harvesting cost per acre usually ranges from $350 to $550, including trucking and disposal. An exception to this range is very dense growths, such as water chestnut (*Trapa natans*), where costs have ranged from $1,000 to $1,500/acre. Lower costs are possible where cut vegetation is left in the lake. Where a lake association owns its own harvesting equipment and has substantial experience with operation and maintenance, cost may also be lower. The cost per acre of harvesting is inversely proportional to the size of the area harvested; there is an efficiency of scale for larger projects. A cost range of $200 to $600 per acre for mechanical harvesting at typical densities and $1,000 to $2,000 per acre for very high densities of plants is suggested.

HYDRORAKING

How it Works

Hydroraking involves the equivalent of a floating backhoe, usually outfitted with a york rake that looks like a farm implement for tilling or moving silage. The tines of the rake attachment are moved through the sediment, ripping out thick root masses and associated sediment and debris. A hydrorake can be a very effective tool for removing submerged stumps, water lily root masses, or floating islands. Use of a hydrorake is not a delicate operation, however, and will create substantial turbidity and plant fragments. Hydroraking in combination with a harvester can remove most forms of vegetation encountered in lakes.

Hydroraking is effective in the short-term in that it removes plants immediately. It is not an especially thorough or selective technique, and is therefore not well suited to submergent species that can re-root from fragments (e.g., milfoil) or mixed assemblages with desirable species present at substantial densities. It is particularly effective for water lilies (white or yellow) and other species with dense root masses. Hydroraking is also often used to remove subsurface obstructions such as stumps or logs.

Hydroraking can kill and remove some benthic invertebrates during operation, and non-target plants will also be impacted in treated areas. High turbidity is usually generated by hydroraking operations, as there is extensive sediment disturbance. This technique is applied on a very limited areal scale in the vast majority of cases, however, and is not expected to have a lakewide effect on non-target organisms or water quality.

Benefits

- Removes vegetation difficult to harvest by other means
- Allows removal of stumps or other obstructions

Detriments

- Very disruptive in areas applied; may generate high turbidity and drastically alter habitat
- May spread plants that reproduce by fragmentation

Information for Proper Application

- Mapping of targeted plant masses or obstructions and knowledge of any sensitive areas, especially where protected species are involved
- Fragment control plan, where species that expand by this process are not yet dominant or where downstream movement must be prevented
- Turbidity control plan, where sensitive receptors are present or a large part of the lake is to be hydroraked
- Monitoring plan for assessing results, including changes in physical features and plant assemblages and any impacts to non-target organisms of concern

Factors Favoring the Use of this Technique

- The target species has dense root masses but occupies only a small part of the lake
- Underwater obstructions are targeted for removal
- Suspended sediments resettle quickly and leave minimal residual turbidity.
- Convenient access for equipment and trucks and a nearby location for plant disposal are available.

Performance Guidelines

- Map the distribution of the target species or obstructions to be removed; note the distribution of any protected non-target species in the lake
- Provide turbidity control (sequestering curtains) if extensive bottom area is to be disturbed

- Provide fragment control if working among plants that reproduce by vegetative fragmentation if those plants are not already widespread in the lake
- Inspect and clean all equipment before entering or leaving a lake
- Avoid areas of known sensitive habitat during active use
- Monitor turbidity around the hydroraking area before, during and after hydroraking
- Monitor nutrients and oxygen in the lake overall before and after hydroraking
- Monitor pre- and post-harvest density of target plants

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral (no significant interaction)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Possible detriment if sediment disruption and resultant turbidity are high over a large enough area
- Protection of land containing shellfish – Possible detriment if applied to areas containing shellfish
- Protection of fisheries – Alteration of habitat may have benefits and detriments, but on a small scale is generally neutral
- Protection of wildlife habitat - Potential benefit by habitat improvement, but may have benefit and detriment to different species in same lake from same effort

Cost Considerations

Costs for hydroraking range from about $1,500 to $4,000 per acre for typical submergent operations and $6,000 to $10,000 per acre for emergent growths, large floating mats and dense root masses. This cost may be worthwhile for small areas where other techniques are ineffective, but will limit lakewide feasibility.

Hydrorake (provided by G. Smith of ACT)

Hydrorake (provided by G. Smith of ACT)

ROTOVATION

How it Works
Rotovation is basically the application of an underwater rototiller to an area of sediment, typically one with dense growths of an unwanted rooted aquatic plant. A rotovator is a hydraulically operated tillage device mounted on a barge. The tiller can be lowered to depths of 10 to 12 feet for the purpose of tearing up roots. On a much simpler scale, cultivation equipment or even old bed springs pulled behind tractors can accomplish much root disturbance. Rototilling and the use of cultivation equipment are highly disruptive procedures normally applied on a small scale. Rotovation has a limited track record, mostly in British Columbia. Use of a variety of cultivation equipment has been practiced in New England for many years, but is rarely documented. Potential impacts to non-target organisms and water quality are substantial, but where severe weed infestations exist, this technique could be appropriate.

Benefits
- Disrupts the entire plant, especially the roots

Detriments
- Very disruptive in areas applied; may generate high turbidity and drastically alter habitat
- May spread plants that reproduce by fragmentation
- Decay of damaged plants may affect water quality

Information for Proper Application
- Mapping of targeted plant masses or obstructions and knowledge of any sensitive areas, especially where protected species are involved
- Fragment control plan, where species that expand by this process are not yet dominant or where downstream movement must be prevented
- Turbidity control plan, where sensitive receptors are present or a large part of the lake is to be rotovated
- Monitoring plan for assessing results, including changes in plant assemblages and any impacts to non-target organisms of concern

Factors Favoring the Use of this Technique
- The target species depends on root masses for expansion or overwintering but occupies only a small part of the lake
- Underwater obstructions are minimal
- Suspended sediments resettle quickly and leave minimal residual turbidity

Performance Guidelines
- Map the distribution of the target species and any protected non-target species in the lake
- Provide turbidity control (sequestering curtains) or control outflow from the lake if a large portion of the lake bottom is to be disturbed
- Provide fragment control if working among plants that reproduce by vegetative fragmentation if those plants are not already widespread in the lake
- Inspect and clean all equipment before entering or leaving a lake
- Avoid areas of known sensitive habitat during active use
- Monitor turbidity around the rotovating area before, during and after rotovation
- Monitor nutrients and oxygen in the lake overall before and after rotovation
- Monitor pre- and post-harvest density of target plants and any sensitive non-target organisms (e.g., benthic invertebrates)

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral (no significant interaction)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Possible detriment if sediment disruption and resultant turbidity are high over a large enough area
- Protection of land containing shellfish – Possible detriment if applied to areas containing shellfish
- Protection of fisheries – Alteration of habitat may have benefits and detriments, but on a small scale is generally neutral
- Protection of wildlife habitat - Potential benefit by habitat improvement, but may have benefit and detriment to different species in same lake from same effort

Cost Considerations

Rotovating has not been practiced in Massachusetts or nearby states, but costs from other areas have been on the order of $500 to $2,000/acre. Use of cultivation equipment has not been documented, but may be very inexpensive if readily available materials are used and access for pulling equipment is available.

Rotovator (provided by Washington State Dept. of Ecology)

Rotovator (provided by Washington State Dept. of Ecology)

BENTHIC BARRIERS

How it Works

The use of benthic barriers, or bottom covers, is predicated upon the principles that rooted plants require light and cannot grow through physical barriers. Applications of clay, silt, sand, and gravel have been used for many years, although plants often root in these covers eventually, and current environmental regulations make it difficult to gain approval for such deposition of fill. Artificial sediment covering materials, including polyethylene, polypropylene, fiberglass, and nylon, have been developed over the last three decades. A variety of solid and porous forms have been used. Manufactured benthic barriers are negatively buoyant materials, usually in sheet form, which can be applied on top of plants to limit light, physically disrupt growth, and allow unfavorable chemical reactions to interfere with further development of plants. Various plastics and burlap have also been used, but are not nearly as durable or effective in most cases.

In theory, benthic barriers should be a highly effective plant control technique, at least on a localized, area-selective scale. In practice, however, there have been difficulties with the deployment and maintenance of benthic barriers, limiting their utility over the broad range of field conditions. Benthic barriers can be effectively used in small areas such as dock spaces and swimming beaches to completely terminate plant growth. The creation of access lanes and structural habitat diversity is also practical. Large areas are not often treated, however, because the cost of materials, application and maintenance is high.

Benthic barrier problems of prime concern include long-term integrity of the barrier, billowing caused by trapped gases, accumulation of sediment on top of barriers, and growth of plants on porous barriers. Successful use is related to selection of materials and the quality of the installation. As a result of field experience with benthic barriers, several guidelines can be offered:

- Porous barriers will be subject to less billowing, but will allow settling plant fragments to root and grow; annual maintenance is therefore essential
- Solid barriers will generally prevent rooting in the absence of sediment accumulations, but will billow after enough gases accumulate; venting and strong anchoring are essential in most cases
- Plants under the barrier will usually die completely after one to two months, with solid barriers more effective than porous ones in killing the whole plant; barriers of sufficient tensile strength can then be moved to a new location, although continued presence of solid barriers restricts recolonization

Proper application requires that the screens be placed on the sediment surface and staked or securely anchored. This may be difficult to accomplish over dense plant growth, and a winter drawdown can provide an ideal opportunity for application in exposed areas. Late spring application has also been effective, despite the presence of plant growths at that time, and barriers applied in early May have been removed in mid-June with no substantial plant growth through the summer. Scuba divers normally apply the covers in deeper water, which greatly increases labor costs. Bottom barriers will accumulate sediment deposits in most cases, which allow plant fragments to root. Barriers must then be cleaned, necessitating either removal or laborious in-place maintenance. Despite application and maintenance issues, a benthic barrier can be a very effective tool. Benthic barriers are capable of providing control of rooted plants on at least a localized basis, and have such desirable side benefits as creating more edge habitat within dense plant assemblages and minimizing turbidity generation from fine bottom sediments.

Considerations for the installation of benthic barriers include the size of the area to be treated, bottom features and possible obstructions, the cost of the product, application and maintenance costs, and possible impacts to non-target organisms in the installation area. Sheeting materials come in a variety of dimensions, from about 20 ft by 50 ft to 7 ft by 100 ft, although custom sizes of a wider range are possible. Deployment is therefore a function of manpower and cleverness by the installer. Careful consideration of site conditions is essential to maximizing effectiveness, as barriers must remain in place for at least a month and possibly two months to kill the target plants.

There are many ways to install barriers, ranging from spreading them out with the lake drawn down to underwater positioning by divers. In water less than about 10 ft. deep, snorkeling may be sufficient to get the barrier properly positioned. One aid to application involves rolling the barrier onto PVC pipe with a slightly longer wooden or metal pole inside the PVC pipe, allowing the barrier to be rolled out like paper towels. Anchoring systems vary with barrier type, but most forms do require staking or weighting. Sleeves can be sewn into sheet materials to allow rebar to be inserted, pieces of chain can be attached to edges, or patio blocks can be dropped onto the barrier to hold it in place. Burial under sandy sediments has been tried, but may allow more rapid plant recolonization. Where removal at a later date is desired, the weighting system should be simple and reversible (patio block weights are very convenient in this regard).

One way to extend the benefits of benthic barrier involves flipping the barrier over into the adjacent area after one to two months. Plants are killed over that time period, and the barrier can be re-deployed to the adjacent plot as part of normal maintenance. In this manner, two or three times the area of the benthic barrier can be treated in a single growing season. If plant elimination is not necessary, and simply reducing plant biomass is acceptable, it may be possible to move the barrier on a biweekly schedule. This could allow a linear band of nuisance vegetation to be managed over the first few months of the growing season, creating acceptable conditions over a larger area with a smaller barrier. Manpower is the primary limiting factor in this approach, although not all barriers can be moved once installed.

Benefits

- Complete elimination of plants in target area with proper application and maintenance
- Some barrier materials are re-useable, allowing coverage of multiple areas over time with the same material
- Creates edge effect and habitat enhancement when portions of dense assemblages are covered
- May foster improved assemblage after removal, by seeds or selective planting

Porous weave benthic barrier

Detriments

- Non-selective technique; all plants under barrier will be killed
- Effectiveness declines without labor-intensive maintenance

Information for Proper Application

- Mapping of area to be covered by barrier, with information on plant types and density
- Knowledge of sediment features, along with any obstructions or other interference factors
- Inventory of biological features of the target area, especially the presence of any protected species
- Plan for installation and maintenance

Preparing benthic barrier for easier installation

Factors Favoring the Use of this Technique

- The target area has dense plant growths of undesirable species
- The target area is small (<1 acre) and relatively free of obstructions (stumps, logs, boulders, pilings and moorings)
- The target area represents only a small portion of the whole lake (<10%)

- Long-term control is sought over a small area with recognition of necessary maintenance needs
- Inexpensive labor is available
- No significant shellfish resources are present in the target area
- A favorable plant assemblage is expected to develop (or can be encouraged by planting) after barrier removal

Performance Guidelines

- Map the vegetation and other resources in the target area; avoid barrier use on protected species
- Select a benthic barrier with properties consistent with project goals and site features
- Avoid installation over >10% of lake littoral zone
- Lay out and anchor barrier in a manner that maximizes stability in response to wave action or other influences
- Post the area to inform potential users of barrier presence
- Leave barrier in place for at least one month
- Develop a maintenance program that monitors and maximizes barrier effectiveness; avoid discontinuous coverage, sediment accumulation, and rooting of plants through porous barriers
- Monitor the plant community before and after barrier application
- Monitor water quality near the barrier and in the lake in general if the installation is large (>1 acre)

Installed benthic barrier in a swimming area

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral (no significant interaction), although reduced plant density may benefit taste and odor control
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control – Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Neutral (no significant interaction), but could be a detriment if nutrient cycling promotes algal blooms
- Protection of land containing shellfish – Generally neutral (no significant interaction), but covering of significant shellfish resources must be avoided
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover), but over a relatively small area no lakewide effects are expected
- Protection of wildlife habitat - Potential benefit by habitat improvement, but may have benefit and detriment to different species in the same relatively small area

Cost Considerations

The most commonly used materials for benthic barriers and the cost (material only) include Texel at $0.25/sq.ft, Palco at $0.40/sq.ft, and Aquatic Weed Net at $0.60/sq.ft. Less expensive substitutes can be found, but usually lack the properties that make these barriers as effective as they are. Such substitution will save initial material costs, but may require more material over the long-term and may increase labor costs to achieve the same effectiveness. Cost per acre is estimated at $20,000 to $50,000 for benthic barrier installation, including design, permitting, materials and labor for a year. The initial capital cost is substantial, but the annual cost diminishes greatly after original installation, as material costs are minimal after initial purchase.

***HERBICIDES AND ALGAECIDES**: An Overview*

Chemical treatment is one of the oldest methods used to manage nuisance aquatic weeds, and is still the most frequently applied approach. Other than perhaps drawdown, few alternatives to herbicides were widely practiced until relatively recently. There are few aspects of plant control that breed more controversy than chemical control through the use of herbicides, which are a subset of all chemicals known as pesticides. Part of the problem stems from pesticides that have come on the market, enjoyed widespread use, been linked to environmental or human health problems, and been banned from further use. Some left long-term environmental contamination and toxicity problems behind.

As chemicals are an integral part of life and the environment, it is logical to seek chemical solutions to such problems as infestations of non-native species that grow to nuisance proportions, just as we seek physical and biological solutions. Current pesticide registration procedures are far more rigorous than in the past. A premise of federal and state pesticide regulation is that use will not result in unreasonable human health or environmental effects when the chemical is used according to label restrictions. Those considering chemical use should become aware of all possible benefits, known limitations and constraints, and possible negative impacts, and should carefully evaluate the applicability and efficacy for the target lake.

Herbicides and algaecides contain active ingredients that are toxic to target plants (The reader should consult Appendix III of the GEIR for a full technical discussion of the herbicides and algaecides described here.). For convenience, we will refer to this collective group of chemicals as herbicides here, with inclusion of algaecides inferred. 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 perhaps several 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 is usually substantial. If annual species are the target of control, additional treatment will be required, normally a year after initial treatment and for as long as the seed bank facilitates new growths.

Another way to classify herbicides is by whether the active ingredients are selective or broad spectrum. Selective herbicides are more effective on certain plant species than others, with control of that selectivity normally dependent on dose and exposure duration. Plant factors that influence selectivity include plant morphology, physiology and the stage of growth. Even a selective herbicide can kill most plants if applied at high rates. Likewise, contact herbicides may show some selectivity based on dose and plant features, but tend to induce impacts on a broad spectrum of plant species.

There are only six active ingredients currently approved for use in aquatic herbicides in Massachusetts (five in Table 8 plus copper), with one additional ingredient recently federally approved and being given consideration for use in Massachusetts now. Herbicides often come in terrestrial and aquatic formulations, creating some confusion over which trade name is applicable to which medium among laypersons. Additional compounds, mostly peroxides and other membrane-active substances, are in use in some states and can be acquired by mail order, so they may be present in some Massachusetts lakes. These compounds basically rupture algal cell membranes and are marketed as algaecides with low toxicity to other plants and animals. Experience with these compounds in Massachusetts is limited, but a new peroxide-based algaecide is being tested.

Herbicides may also contain adjuvants. An adjuvant is any chemical added to the herbicide to increase the effectiveness of the application. There are different classes of adjuvants, which generally function to increase the uptake of the herbicide by the plant, spread the herbicide through the water column, or help the herbicide adhere to the plant. Adjuvants are not expected to be toxic to the target species, but increase the toxicity of the herbicide or otherwise aid herbicide effectiveness.

Aquatic herbicides must be registered by the EPA and the Massachusetts Department of Agricultural Resources for legal use in Massachusetts. The criteria addressed in the registration process include data on forms of toxicity, impacts to non-target organisms, environmental persistence, breakdown products and fate of the herbicide constituents in the aquatic environment. Herbicide toxicology reports generally report toxicity in terms of LC50 or LD50. The LC50 is usually defined as the concentration (in ppm or mg/L of active ingredient) in water that will result in 50 percent mortality of the test species within the time period (usually 48 hours) and conditions of the test. The LD50 is defined as the amount of pesticide administered per kg of body weight of the test organism that will result in 50 percent mortality of the test species within the time period (usually 48 or 96 hours) and conditions of the test. The LC50 tests are usually conducted for aquatic species such as fish and zooplankton, for which uptake is generally via gills or other direct absorption. The LD50 tests are usually conducted for birds and/or mammals such as rats or mice, and the tests usually refer to oral doses of the herbicide.

Toxicology data are usually given in parts per million (ppm), which is roughly equivalent to mg/L. In some toxicology reports, only the mass (weight) of the active cation or the equivalent mass of the acid form of the active anion is considered when reporting units of concentration. The nature and variability in toxicity reporting can lend themselves to confusion and ambiguity in herbicide evaluations. Risk is a function of toxicity and exposure, and expressions of risk should address both of these key elements.

While it is generally considered prudent to avoid contact with water immediately after treatment, and some states have their own use restrictions, there are no swimming restrictions on the federal label for any herbicide currently in use in Massachusetts. Irrigation restrictions of several days or more are common, and only copper and fluridone products are used in human drinking water supplies.

The choice of herbicide to manage an undesirable plant population depends on the properties of the herbicide, the relative sensitivity of the target and non-target plants and other organisms that will be exposed, water use restrictions after herbicide use, and cost. Effectiveness in controlling the target plant species is normally the primary consideration. Other factors determine possible choice between two or more potentially effective herbicides, dose, and whether a treatment is actually feasible.

Aquatic plants controlled by commonly used herbicides are listed in Table 9. The list is not all-inclusive and effective control depends on the rate of application and other factors. Copper and peroxides, which are primarily algaecides, and triclopyr (not yet approved for use in Massachusetts) are not included in Table 9. Herbicide effectiveness may be influenced by such factors as timing, rate and method of application, species present and weather conditions. Additionally, dose determination should consider detention time, morphometry and water hardness to maximize effectiveness

Herbicide treatment can be an effective short-term (and sometimes, longer) management procedure to produce a rapid reduction in algae or vascular plants for periods of weeks to months. Although long-term effectiveness of herbicide treatments is possible, in most cases herbicide use is considered a short-term control technique. Herbicides are generally applied seasonally to every four years to achieve effective control. Systemic herbicides, which kill the entire plant including the roots, generally provide results with greater longevity than contact herbicides, which can leave roots alive to regrow. In many cases, use of herbicides will reduce the amount of regrowth the following season. In some cases involving fluridone or 2,4-D, as many as five years of control can be gained. In other cases, however, several applications per year may be necessary to achieve control goals.

Table 8. Aquatic Plants Controlled in Massachusetts by Herbicide Active Ingredients

C = consistent control (with correct dose, proper formulation and suitable conditions), P = partial control (control sometimes achieved, but may require a higher dose or be affected by conditions that are difficult to control). Re-growth or re-infestation may occur at some time after treatment, but usually not within the same year. The ability to control a plant with an herbicide does not necessarily indicate that the plant requires control in Massachusetts. NE indicates that there is no experience with the management of this species in Massachusetts, while NNM signifies that the species is not normally managed in Massachusetts.

	Diquat	Endothall	2,4-D	Glyphosate	Fluridone
Emergent Species					
Butomus umbellatus (flowering rush) NE				P	
Alternanthera philoxeroides (alligatorweed) NE					P
Dianthera americana (water willow) NE			P		
Eleocharis spp. (spikerush)	P				P
Glyceria borealis (mannagrass) NE	C				
Juncus spp. (rush) NNM				P	
Lythrum salicaria (purple loosestrife)				C	
Phragmites spp. (reed grass)				C	
Pontederia cordata (pickerelweed)	P			C	
Sagittaria spp. (arrowhead – emergent forms)				C	
Scirpus spp. (bulrush)				C	
Typha spp. (cattail)	P			C	P
Floating/Floating leaf Species					
Brasenia schreberi (watershield)			P	C	P
Eichhornia crassipes (water hyacinth) NE	C		C		
Hydrocotyle spp. (water pennywort) NE			P		P
Lemna spp. (duckweed)	P				C
Marsilea quadrifolia (pepperwort) NE	P			P	
Nelumbo lutea (American lotus) NNM			P	C	P
Nuphar spp. (yellow water lily)			P	C	P
Nymphaea spp. (white water lily)			P	C	P
Pistia stratiotes (water lettuce) NE	C		C		
Polygonum amphibium (water smartweed)			P	C	P
Salvinia spp. (Salvinia) NE					P
Spirodela polyrhiza (big duckweed) NE					C
Trapa natans (water chestnut)			C		P
Wolffia spp. (watermeal)	P				C
Submergent Species					
Cabomba caroliniana (fanwort)					C
Ceratophyllum demersum (coontail)	C	C	P		C
Chara spp. (stonewort)	P	P			
Coleogeton pectinatus (sago pondweed, also known by the genera *Potamogeton* and *Stuckenia*)	C	C			C
Egeria densa (Brazilian elodea)	C				C
Elodea canadensis (waterweed)	C				C
Elodea nuttallii (slender waterweed)	C				C
Hydrilla verticllata (hydrilla)	C	C			C
Megalodonta beckii (water marigold) NNM	P	P	C		C

Table 8 (continued). Aquatic Plants Controlled in Massachusetts by Herbicide Active Ingredients

	Diquat	Endothall	2,4-D	Glyphosate	Fluridone
Submergent Species (continued)					
Myriophyllum aquaticum (parrotfeather) NE	C	C	C		P
Myriophyllum heterophyllum (variable watermilfoil)	C	P	C		P
Myriophyllum humile (low watermilfoil)	C	P	C		P
Myriophyllum spicatum (Eurasian watermilfoil)	C	C	C		C
Najas flexilis (bushy naiad)	C	C	P		C
Najas guadalupensis (southern naiad)	C	C	P		C
Najas minor(spiny naiad)	C	C	P		C
Nitella spp. (nitella) NNM	P	P			
Nymphoides cordata (little floating heart)	C		P		P
Nymphoides peltata (yellow floating heart) NE	C		P		
Polygonum spp. (water smartweed)			P	C	P
Potamogeton amplifolius (largeleaf pondweed)	P	C	P		P
Potamogeton crispus (curlyleaf pondweed)	C	C	P		C
Potamogeton diversifolius (waterthread)	C	C	P		P
Potamogeton epihydrus (pondweed)	C	C	P		P
Potamogeton foliosus (pondweed)	C	C	P		P
Potamogeton gramineus (variable pondweed)	C	C	P		P
Potamogeton illinoensis (Illinois pondweed)	P	C	P		P
Potamogeton natans (floating leaf pondweed)	P	C	P		P
Potamogeton praelongus (boatleaf pondweed)	P	C	P		P
Potamogeton pulcher (heartleaf pondweed)	P	C	P		P
Potamogeton pusillus (pondweed)	C	C	P		P
Potamogeton richardsonii (Richardson's pondweed)	P	C	P		P
Potamogeton robbinsii (Robbins' pondweed)	P	C	P		P
Potamogeton zosteriformis (pondweed)	P	C	P		P
Ranunculus spp. (buttercup)	C				P
Sagittaria spp. (submergent arrowhead) NNM	P	P			
Utricularia spp. (bladderwort)	C				C
Vallisneria americana (water celery)	P	P			P

Note: *Chara* spp. (stonewort or muskgrass) and *Nitella* spp. can be controlled with copper, which also enhances the performance of Diquat on *Eichhornia crassipes* (water hyacinth) and some other species. Copper is the most common active ingredient in algaecides.

The use of herbicides to get a major plant nuisance under control is a valid element of long-term management when other means of keeping plant growths under control are then applied. However, failure to apply alternative techniques on a smaller scale once the nuisance has been abated places further herbicide treatments in the cosmetic maintenance category; such techniques tend to have poor cost-benefit ratios over the long-term.

Important questions to be answered before adopting a management program involving herbicides include:

- ♦ What is the acreage and volume of the area(s) to be treated? Proper dosage is based upon this information.
- ♦ What plant species are to be controlled? This will determine the herbicide and dose to be used.
- ♦ How is this water body used? Many herbicides have restrictions of a day or up to two weeks on water use following application, and most cannot be used in drinking water supplies.
- ♦ Is the applicator trained, experienced, licensed and insured, and has a permit been obtained from the appropriate regulatory agency? All are necessary prior to treatment.
- ♦ What will the long-term costs of this decision be? Most herbicides must be reapplied annually, with a range of two or three times per growing season to once per five years possible.

The answers to these questions will have bearing on the effectiveness of treatment.

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 formulation, 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. Some level of temporary impact to non-target flora is almost unavoidable with herbicide use, but recovery of plant communities is often rapid. Where light and nutrients are sufficient, plants will grow. This applies to planktonic algae or floating vascular plants in the water column and rooted vascular plants and algal mats associated with benthic habitat. This will limit the longevity of benefits and the duration of impacts derived from herbicide use. Where protected plant species are threatened or even temporary loss of cover is viewed as an unacceptable impact, herbicide use may not be permitted, but usually the benefits of plant control by herbicides are perceived to outweigh limited temporary impacts to non-target flora.

A concern with respect to herbicides is the potential for direct toxic effects on non-target fauna. To eliminate direct impacts to non-target organisms, the application rate must be below the rate that will impact the most sensitive non-target organism. While long-term chronic toxicity studies may be suitable to evaluate the impacts of repeated application of herbicides, most short-term effects are usually evaluated by means of the common LC50 lethality tests on fish, invertebrates and sometimes other aquatic organisms. Note that the fish used in the tests may be more or less sensitive than those found in the lake to be treated. In most cases aquatic herbicides have relatively short aquatic half-lives and thus the standard 96-hour (or sometimes 24-hour) LC50 is commonly used. It is difficult to judge sublethal effects or estimate the No Observable Effects Level or the Maximum Acceptable Toxicant Concentration based on LC50 data alone. Commonly, the Maximum Acceptable Toxicant Concentration is set at 10 percent or less than the LC50 for any given herbicide to provide a margin of safety.

Other mitigating factors such as the herbicide form (granular or liquid), application timing, water temperature, water hardness and other environmental conditions are taken into account in testing and dose planning. The comparison of the initial environmental herbicide concentrations to the LC50 levels assumes there is no reduction in herbicide concentration due to adsorption to sediments or degradation during the 24- or 96-hour period after introduction. Larval or juvenile fish and invertebrates are often used in testing to maximize the effect, as older organisms tend to have higher resistance to impacts. A number of other conservative assumptions are typically made and are intended to result in allowable doses being lower than those that would actually cause observable effects on fauna in the aquatic environment. Field experience is taken into consideration during the re-registration process that herbicides must periodically undergo.

In general, the likelihood of undesirable impacts decreases as the applied concentration decreases relative to the LC50 for a given exposure. Each herbicide is evaluated individually based on the formulation, and the expected concentration as a function of the percent active ingredient, application rate and depth of water. It is important to note that the concentrations allowed as application rates are much higher than those to which the public would be exposed under normal circumstances. The product may be applied at lower rates, and often is. The granular products may only slowly dissolve in the water over time and dissipate. Many of the compounds are rapidly removed from the water. Use in accordance with label instructions and restrictions is therefore not expected to result in toxicity to non-target fauna, including humans, other mammals, waterfowl, fish and invertebrates. There have been toxic reactions in rare cases, and the chronic effects of frequent exposure are not truly known in many cases.

Yet the chemical improvements of the last 30 years have greatly reduced non-target faunal toxicity, and testing advancements have allowed much more detailed evaluation of possible impacts. Fish kills are very rarely observed with use of herbicides today, and the few fish kills that have occurred in the USA in recent years have almost always been traced to improper use or unforeseen circumstances. Human error cannot be eliminated, and we can never be sure that chronic impacts will not occur, but herbicide use today has been advanced considerably over related techniques in the 1950s and 1960s.

Information for individual herbicidal active ingredients in use today is further discussed in association with each active ingredient in subsequent parts of review.

Before herbicide (fluridone) application at Wares Cove, Charles River; dense cover by fanwort, lilies and filamentous algae (provided by G. Smith of ACT)

After herbicide (fluridone) application at Wares Cove, Charles River: control of nuisance species lasted over three years (provided by G. Smith of ACT)

TREATMENT WITH COPPER

How it Works

Copper is a contact herbicide that is generally considered non-selective, although some selectivity may be possible when copper is used at a continuous low dose. The active ingredient in copper sulfate and copper complexes is the copper ion. The mode of action of copper is to inhibit photosynthesis and may affect nitrogen metabolism. Copper is by far the most used active ingredient in algaecides. Copper has been the only algaecide approved for use in potable water supplies in Massachusetts for some time, but a new peroxide-based algaecide is likely to gain approval soon.

While copper is generally used for the control of algae, in some cases it is also used for macrophyte control (usually in chelated form). Copper is sometimes part of a broad spectrum formulation intended to reduce the biomass of an entire plant assemblage, especially if it includes a substantial algal component. Also, certain copper formulations are also used on particular vascular plants when the water use restrictions of other herbicides prevent their use. Copper concentrations should not exceed 1 mg/L in the treated waters, and doses >0.3 mg/L are rarely applied in Massachusetts.

While copper sulfate is used at concentrations up to 1 ppm, it appears that control of some algae can be achieved at very low levels of copper (0.10 mg/L or less). Many blue-green algae appear to be more sensitive to copper than other forms of algae. Effectiveness of low doses depends on monitoring algal densities and adding low doses (potentially less than 0.10 mg/L) prior to the formation of an algal bloom. Once a bloom has formed, higher doses may be required and may still be ineffective if adequate contact with algal cells cannot be achieved. In general, bright sunlight appears to enhance the effectiveness of the treatment.

Most species of blue-greens are sensitive to copper and are controlled by 0.06 to 0.125 ppm copper. Some species of *Calothrix* and *Nostoc* are more resistant, however, and resistant strains of the more troublesome *Aphanizomenon* and *Anabaena* have been encountered with increasing frequency. While many green algae are sensitive to copper, algae of the group Chlorococcales such as *Scenedesmus* are resistant. The mat-forming, filamentous green algae *Cladophora, Rhizoclonium* and *Pithophora* are notoriously resistant to copper, mainly as a function of limited copper mobility in the thick tangle of filaments that often forms. Most diatoms and golden algae are very susceptible to control with copper, as are nearly all species of dinoflagellates, cryptomonads and euglenoids.

Beyond the susceptibility of the algal species present, the effectiveness of copper-containing aquatic herbicides is dependent in particular on the alkalinity, dissolved solids content, suspended matter and water temperature. Low doses of copper sulfate (less than 0.10 mg/L) may be effective in acidic waters. In cases where the alkalinity is high, however, carbonate and bicarbonate ions and water react with copper and form a precipitate that prevents the uptake of copper by algal cells. In such cases chelated copper compounds are used instead of copper sulfate. Suspended solids provide additional substrates on which copper sorption can occur, removing it from the water column. These conditions that reduce the toxicity of copper as an algaecide/herbicide also reduce the toxicity to non-target organisms. Additionally, algae do not respond as well to copper treatments in water less than 10^{o}C (50^{o}F), although some success has been achieved.

Copper sulfate can be applied by towing burlap or nylon bags filled with granules (that dissolve) behind a boat. Other formulations can be applied as broadcast granules or sprayed liquids. A copper slurry can be delivered to an intended depth by a weighted hose. The method of delivery is not as important as the duration of effectiveness, however. In alkaline waters (150 mg calcium carbonate per liter, or more) or in waters high in hardness or organic matter, copper can be quickly lost from solution and thus rendered ineffective. In these cases, a liquid chelated form is often used. This formulation allows the copper to remain dissolved in the water long enough to kill algae. Dilution is another important factor, as copper is often applied to only the upper 10 ft of water to provide a deeper refuge for zooplankton and sensitive fish species. Vertical or horizontal mixing can rapidly decrease doses below an effective level.

Depending on individual circumstances, it may be recommended that the lake or pond be treated in sections to minimize oxygen depletion from the decomposition of dead algae, allowing 1 to 2 weeks between treatments so that oxygen levels can recover. Algaecide should be distributed as evenly as possible over the treated area. Once applied there is little mitigative potential. Careful planning and implementation are needed to avoid undesirable impacts.

Given the many potentially negative aspects of algaecide applications, especially those involving copper, such treatments should only be used as the last line of defense. Frequent need for algaecides should be taken as an indication that a more comprehensive watershed management plan is needed. Where algaecides are used, effectiveness is enhanced through improved timing of application. Algaecides should be applied early in the exponential growth phase, when algal sensitivity is greatest and the impacts of lysing cells on the aquatic environment are minimized. Proper timing of application requires daily to weekly tracking of algal populations, potentially at greater annual expense than the actual annual treatment cost.

Blue-green algal scum

Benefits

- Rapid kill of susceptible algae
- Rapidly eliminated from water column, minimizing prolonged adverse impacts

Detriments

- Toxic to many non-target organisms
- Releases contents of most killed algal cells back into the water column; this may include nutrients, taste and odor compounds, and toxins
- Ineffective on some algae; repeated treatments may favor those resistant algae, some of which are major nuisance species
- Accumulates in sediments, although long-term impacts may not be severe

Planktonic algal bloom

Information for Proper Application

- Algal monitoring to determine proper timing of treatment
- Water quality data to evaluate dose needs and likely effectiveness
- Inventory of non-target biota for potential impact assessment
- Monitoring program to assess impacts and effectiveness

Factors Favoring the Use of this Technique

- Algal monitoring allows early response before bloom formation
- Periodic algal blooms impair recreation of water supply use, but are not a frequent occurrence
- A susceptible invasive plant species has been detected at non-dominant levels but is not amenable to physical control techniques

Performance Guidelines

- Monitor algae at a frequency appropriate to detection of bloom formation before blooms become dense; know which types of algae are dominant
- Choose a copper product appropriate for the quality of water to be treated; pH, alkalinity, hardness and organic content are key variables
- Copper should be applied by licensed applicators with few exceptions

- Apply copper while algal growth is in its exponential phase; do not wait for a dense bloom to form
- Apply copper product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- Apply copper product evenly throughout target area to minimize adverse impacts
- For applications over a large area, consider dividing the lake into zones and treating with time gaps in between treatments to provide refuges for non-target aquatic species
- Monitor water quality before and after treatment, with emphasis on oxygen and nutrient levels
- Where blue-greens or other algae with potential for toxicity are treated, monitor for toxin level in the water before and after treatment
- If repeated treatment is necessary in a single growing season, pursue nutrient controls on algal growth
- Where copper is used as an aid to other herbicides, use as directed for auxiliary purpose

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Benefit (used to control algae)
- Protection of groundwater supply – Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction).
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if algae/plant die-off causes low oxygen at the bottom of the lake or causes release of taste and odor compounds or toxins
- Protection of land containing shellfish – Generally neutral (no significant interaction), but reduced algae might reduce food resources for shellfish, and direct toxicity is possible under unusual circumstances.
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, direct toxicity).
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, toxicity).

Cost Considerations

Copper treatments are inexpensive, typically $50 to $100 per acre, although repetitive application, chelated forms, and appropriate monitoring will increase the cost on an annual basis.

Proper Use of Algaecides:

- Applied to prevent a bloom, not remove a bloom
- Must know when algal growth is accelerating
- Must know enough about water chemistry to determine most appropriate form of algaecide
- May involve surface or shallow treatment where nutrients are fueling expansion of small population
- May require deep treatment where major migration from sediment is occurring
- May require repeated application, but at an appropriate frequency; if that frequency becomes too high, recognize that the technique requires adjustment or will not be adequate for long-term control

TREATMENT WITH DIQUAT

How it Works

Diquat is a fast acting contact herbicide, producing results within 2 weeks of application through disruption of photosynthesis. It is a broad-spectrum herbicide with potential risks to aquatic fauna, but laboratory indications of invertebrate toxicity have not been clearly documented in the field. A domestic water use restriction of 3 days is normally applied. Irrigation restrictions of 2 to 5 days are applied, depending on dose and crop to be irrigated. Regrowth of some species has been rapid (often within the same year) after treatment with diquat, but two years of control have been achieved in some instances. Concentrations in treated water should not exceed 2 mg/L, and are usually no more than half that dose in Massachusetts.

Diquat is used as a general purpose aquatic herbicide, both as a primary control agent for a broad range of macrophytes and as a follow-up treatment chemical for control of plants (especially milfoil) missed by other herbicides or physical control techniques. Treatment with diquat is recommended early in the season to impact early growth stages, but can be applied any time. Usage in Massachusetts has shown that the effects of diquat are generally visible after 2-3 days and plants are controlled within 7-10 days. Diquat is less effective in turbid, muddy water due to adsorbance onto sediments and other particles.

Since diquat is a broad spectrum herbicide, it can be expected to impact non-target plants when they are present. Loss of vegetative cover may have some impact on aquatic animals, but short-term effects are not expected. The acute toxicity of diquat for fish is highly variable depending on species, age, and hardness of water. Young fish are more sensitive than older fish. Toxicity is decreased as water hardness increases. Toxicity is rare at doses applied in Massachusetts.

Field concentrations of diquat are hard to maintain because diquat rapidly sorbs to the sediments. Maximum concentrations based on the Reward brand label are currently 0.72 ppm as the cation, based on the maximum rate of 2 gallons per acre in areas deeper than 2 feet. For water less than or equal to 2 feet in average depth, a maximum of 1 gallon of Reward per acre is allowed. Normally Reward is used at a rate of 1 gallon per surface area in Massachusetts waters with an average depth of 4 feet. This typically renders a concentration of 0.1 ppm of active ingredient. Treatment doses are therefore not expected to exceed thresholds for potential toxicity. Other formulations of diquat may have different dose restrictions, but concentrations tend to be low relative to maximum allowable rates.

As a contact herbicide, diquat is relatively non-selective and will leave root systems that may generate regrowth. It is often used for spot treatment of limited areas as a follow-up to more selective lakewide treatment with another herbicide, but is also used where other herbicides are less effective.

Benefits

- Effective against a wide variety of species
- Relatively rapid kill of targeted vegetation
- Can be used for spot treatments; limited drift or impact outside target area

Detriments

- Not very selective; kills most species contacted
- Does not damage portions of plants with which it does not contact; regrowth from roots is common
- Potential for toxicity to fauna, but uncommon in practice

Information for Proper Application

- Knowledge of lake and downstream water uses
- Inventory of aquatic biota with emphasis on sensitive species
- Mapping of aquatic vegetation with accurate identification of all species and general appraisal of relative abundance and overall cover/biomass

- Water quality data that facilitate dose planning and evaluation of effectiveness and impacts; suspended solids/water clarity, hardness, dissolved oxygen and temperature should be included at a minimum
- Treatment plan to include dose, areas treated, expected alteration of plant community, and follow-up activities
- Knowledge of use restrictions after treatment
- Monitoring program for assessing effectiveness and impacts

Factors Favoring the Use of this Technique

- An invasive plant species has been detected as patches of dense growth but is not amenable to physical control techniques
- Overall vegetative density is excessive over a large portion of the lake, negatively affects habitat and water uses, and is not amenable to alternative control methods
- Localized control of plants is needed either to support localized use (e.g., swimming area) or as follow-up to alternative controls

Performance Guidelines

- Map plant community and note density and distribution of target and non-target species; presence of protected species may prevent treatment
- Application must be performed by licensed applicators
- Apply diquat product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- Where a large portion of the lake is treated, apply diquat in strips or zones to provide faunal refuges
- Monitor water quality before and after treatment, with emphasis on oxygen and nutrient levels, if more than 10% of lake is treated
- Monitor plant community features before and after treatment

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Neutral
- Protection of groundwater supply – Neutral no interaction as diquat is adsorbed to soil particles
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if plant die-off causes low oxygen at the lake bottom
- Protection of land containing shellfish – Generally neutral (no significant interaction), but reduced algae might reduce food resources for shellfish, and direct toxicity is possible under unusual circumstances
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)

Cost Considerations

Diquat treatments typically cost $200 to $500 per acre.

TREATMENT WITH ENDOTHALL

How it Works

Endothall is a contact herbicide, attacking a wide range of plants. The method of action of endothall is suspected to inhibit the use of oxygen for respiration. Only portions of the plant with which the herbicide can come into contact are killed. There are two forms of the active ingredient; the inorganic potassium salt that is found in the products Aquathol® Granular and Aquathol® K and the alkylamine salt formulations of Hydrothol® 191 Granular and Hydrothol® 191. Effective control can range from weeks to months. Most endothall compounds break down readily and are not persistent in the aquatic environment, disappearing from the water column in under 10 days and from the sediments in under 3 weeks.

Endothall acts quickly on susceptible plants, but does not kill roots with which it cannot come into contact, and recovery of many plants occurs. Rapid death of susceptible plants can cause oxygen depletion if decomposition exceeds re-aeration in the treated area, but this can be mitigated by conducting successive partial treatments. Toxicity to invertebrates, fish or humans is possible but not expected at typical doses, but endothall is not used in drinking water supplies.

Endothall is primarily a broad spectrum vascular plant control chemical. The Massachusetts experience is that endothall has not been very effective against milfoil, but works well on most species of pondweeds, coontail and naiads. It is used less than most other herbicides in Massachusetts, mainly due to dose limits that are observed to avoid impacts to non-target fauna.

Hydrothol 191 is an alkylamine salt formulation of endothall. This formulation is effective against algae as well as macrophytes, but is much more toxic to fish than Aquathol K. The environmental hazards listed on the Hydrothol 191 (Dimethylalkylamine endothall granular and liquid) labels warn that fish may be killed by dosages in excess of 0.3 ppm. Hydrothol 191 is less toxic to fish in cool water (<65^{o}F). However, Hydrothol 191 granular is rarely used in Massachusetts because of potential dust problems and possible toxicity to the applicator. Aquathol K is much less toxic and is used more frequently in Massachusetts than Hydrothol 191. Aquathol K application rates vary with water depth. Although usually applied at lower rates, the maximum rate of 269 lbs per 2 acre feet or 6.4 gallons per 2 acre-feet for spot treatment would result in a maximum concentration of 5 ppm according to the product labels. Average concentrations in Massachusetts are <1 mg/L from the Aquathol K form.

As a contact herbicide, endothall is relatively non-selective, although dose and timing may limit impacts to non-target vegetation in some cases. Endothall is used much like diquat, for spot treatment of limited areas. It is preferred where diquat is expected to be less effective, but is used less than diquat in Massachusetts.

Benefits

- Effective against a wide variety of species
- Relatively rapid kill of targeted vegetation
- Areally selective; limited drift or impact outside target area

Detriments

- Not very selective; kills most species contacted
- Does not damage portions of plants with which it does not contact; regrowth from roots is common
- Potential for toxicity to fauna, but uncommon in practice

Information for Proper Application

- Knowledge of lake and downstream water uses; endothall cannot be used in all cases
- Mapping of aquatic vegetation with accurate identification of all species and general appraisal of relative abundance and overall cover/biomass
- Inventory of aquatic biota with emphasis on sensitive species

- Water quality data that facilitates dose planning and evaluation of effectiveness and impacts; suspended solids/water clarity, hardness, dissolved oxygen and temperature should be included at a minimum
- Treatment plan to include dose, areas treated, expected alteration of plant community, and follow-up activities
- Knowledge of use restrictions after treatment
- Monitoring program for assessing effectiveness and impacts

Factors Favoring the Use of this Technique
- An invasive plant species has been detected as patches of dense growth but is not amenable to physical control techniques
- Plant density is excessive over a large portion of the lake, negatively affects habitat and water uses, and is not amenable to alternative control methods
- Localized control of plants is needed either to support localized use (e.g., swimming area) or as follow-up to alternative controls

Performance Guidelines
- Map plant community and note density and distribution of target and non-target species; presence of protected species may prevent treatment
- Application must be performed by licensed applicators
- Apply endothall product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- Where a large portion of the lake is treated, apply endothall in strips or zones to provide faunal refuges
- Monitor water quality before and after treatment, with emphasis on oxygen and nutrient levels, if more than 10% of lake is treated
- Monitor plant community features before and after treatment

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

The Aquathol formulation is less toxic than the Hydrothol form and is therefore used more often.

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Neutral
- Protection of groundwater supply–Neutral (no interaction as endothall is adsorbed to soil particles)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if plant die-off causes low oxygen at the lake bottom
- Protection of land containing shellfish – Generally neutral (no significant interaction), but reduced algae might reduce food resources for shellfish, and direct toxicity is possible under unusual circumstances
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)

Cost Considerations
Endothall treatments typically cost $400 to $700 per acre

TREATMENT WITH GLYPHOSATE

How it Works

Glyphosate is a systemic, broad spectrum herbicide. Its mode of action is to disrupt the plant's shikimic acid metabolic pathway. Shikimic acid is a precursor in the biosynthesis of aromatic amino acids. The disruption in the pathway prevents the synthesis of aromatic amino acids and the metabolism of phenolic compounds. The net effect is that the plant is unable to synthesize protein and produce new plant tissue. Glyphosate penetrates the cuticle of the plant and moves to the phloem where it is translocated throughout the plant, including the roots. Its aquatic formulation is effective against most emergent or floating-leaved plant species, but not against most submergent species. Rainfall shortly after treatment can negate its effectiveness, and it readily adsorbs to particulates in the water column or to sediments and is inactivated. It is relatively non-toxic to aquatic fauna at recommended doses, and degrades readily into non-toxic components in the aquatic environment. The maximum concentration for treated water is typically about 0.7 mg/L, but a dose of no more than 0.2 mg/L is usually recommended.

The most common aquatic use of glyphosate is for control of emergent and floating leaf species, in particular water lilies (*Nuphar* spp*., Nymphaea* spp*.*), reed grass (*Phragmites* spp.), purple loosestrife (*Lythrum salicaria*) and cattail (*Typha* spp.). Glyphosate is not effective for control of submerged macrophytes because it is water soluble and the concentration after dilution would be insufficient to damage a submergent plant. It is, however, recommended for control of many wetland and floodplain species that include trees, shrubs and herbs. Glyphosate effectiveness is greater in soft water. Additives such as ammonium phosphate are recommended for hard water glyphosate applications, and non-ionic surfactants are often recommended to increase overall effectiveness.

Because it is a broad spectrum herbicide, glyphosate should be expected to impact non-target emergent or floating leaf plants if the spray contacts them. Control of the spray can therefore greatly limit impacts to non-target vegetation. The LC50 levels for fish species vary widely, perhaps due to variations in formulations tested (i.e., with or without surfactant). Most applications would result in aquatic concentrations far lower than any toxic threshold.

Glyphosate is used to control emergent vegetation and to create open areas for waterfowl or human use. Invertebrates do not appear to be harmed directly by the herbicide, but may be impacted by the alteration of vegetation Glyphosate has a low order of toxicity in the case of acute exposure in mammals. Rat LD50s are >5,000 mg/kg. LC50 values for various types of fish are also high.

Glyphosate is a common terrestrial herbicide that is also used on emergent and floating leaved aquatic plants but not submergent forms. This herbicide is translocated throughout susceptible species and can kill the whole plant. Uptake is dependent on features of the exposed plant surface and exposure time. It is washed off by rain, but requires only a few hours of contact time.

Benefits

- Effective on emergent vegetation
- Kills entire plant for susceptible species
- Selective by area and vegetation type (emergent/floating vs. submergent)

Detriments

- Ineffective against submergent species
- Precipitation (rain) interferes with uptake

Information for Proper Application

- Mapping of aquatic vegetation with accurate identification of all species and general appraisal of relative abundance and overall cover/biomass
- Inventory of aquatic biota using the targeted vegetation

- Weather forecast; application shortly before storms is not advised, as rain will wash the herbicide off target vegetation
- Treatment plan to include dose, areas treated, expected alteration of plant community, and follow-up activities
- Knowledge of use restrictions after treatment
- Monitoring program for assessing effectiveness and impacts

Factors Favoring the Use of this Technique
- Overall floating or emergent vegetative density is excessive over a large portion of the lake, negatively affects habitat and water uses, and is not amenable to alternative control methods
- Localized control of floating or emergent plants is needed either to support localized use (e.g., swimming area) or as follow-up to alternative controls

Performance Guidelines
- Map the floating leaved and emergent plant community and note density and distribution of target and non-target species
- Application must be performed by licensed applicators
- Apply glyphosate product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- Apply directly to target plants or areas to maximize selectivity
- Do not apply if rain or strong wind is expected within several hours
- Monitor water quality before and after treatment, with emphasis on oxygen and nutrient levels, if more than 10% of lake is treated
- Monitor plant community features before and after treatment

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Detriment (prohibition within one quarter mile of surface drinking water supplies due to toxicity), but generally neutral where allowed
- Protection of groundwater supply - Neutral (no interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if plant die-off causes low oxygen at the bottom of the lake
- Protection of land containing shellfish – Neutral (no significant interaction)
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)

Cost Considerations

Glyphosate treatments typically cost $500 to $1000 per acre

TREATMENT WITH 2,4-D

How it Works

2,4-D, the active ingredient in a variety of commercial herbicide products, has been in use for over 30 years. This is a systemic herbicide; it is absorbed by roots, leaves and shoots and disrupts cell division throughout the plant. Vegetative propagules such as winter buds, if not connected to the circulatory system of the plant at the time of treatment, are generally unaffected and can grow into new plants. Seeds are also not affected. It is therefore important to treat plants early in the season, after growth has become active but before such propagules form.

2,4-D is sold in liquid or granular forms as sodium and potassium salts, as ammonia or amine salts, and as an ester. Doses of 50 to 150 pounds per acre are usually applied for the control of submersed weeds, most often of the dimethylamine salt (DMA) or the butoxyethanolester (BEE) in granular formulation. Lower doses are more selective but require more contact time; a range of one to three days of contact time is typically needed at the range of doses normally applied. 2,4-D has a short persistence in water but can be detected in the mud for months.

Experience with granular 2,4-D in the control of nuisance macrophytes has generally been positive, with careful dosage management providing control of such non-native nuisance species as Eurasian watermilfoil with only sublethal damage to many native species. 2,4-D has variable toxicity to fish, depending upon formulation, dose and fish species. The 2,4-D label does not permit use of this herbicide in water used for drinking or other domestic purposes, or for irrigation until the concentration is less than 0.1 ppm, typically about 3 weeks. Controversy continues over the potential impact of 2,4-D treatments on well water.

By far the most common 2,4-D product used in Massachusetts waters is the BEE form. This granular formula is easy to apply for spot treatments and the active ingredient is slowly released near the root zone. The BEE form is typically more toxic to both plants and fish than the DMA salt, but toxicity is rarely observed at normal application rates of any formulation. The maximum application rate for 2,4-D is 200 lb/acre with a maximum concentration of 3.4 ppm, assuming 4-foot water depth. The average effective application rate in Massachusetts is about 67 pounds per acre with an estimated concentration of 1.14 ppm active ingredient.

2,4-D is a systemic herbicide; it is translocated throughout the plant and kills all parts except seeds and certain winter buds. 2,4-D is very effective against submergent species not otherwise easily controlled.

The LC50 level for sensitive fish species is 1.1 ppm from the BEE formulation in static 96-hour tests, but field toxicity is rarely observed. Tests conducted in flow through systems may overestimate toxicity in the field. Invertebrate impacts are rarely reported, but may occur. Rat LD50s are between 720 and 1090 mg/kg for the various formulations of 2,4-D, well above of any plausible aquatic exposure.

Benefits

- Complete kill of susceptible vegetation, typically provieds multiple years of control for target species
- Acts relatively quickly in the aquatic environment; plant death may be delayed, but sufficient uptake occurs within 3 days
- Can be used selectively on certain major invasive species at low doses, and for partial (especially shoreline) lake treatments

Detriments

- Potential for toxicity to fauna, but a rare occurrence in practice
- Use restrictions in or near drinking water supplies (surface or wells) limits application

2,4-D was developed at a time when non-target impacts of herbicides were given less consideration than today. Consequently, issues with toxicity and selectivity restrict application, particularly where drinking water supplies are involved.

Information for Proper Application (see DEP 2004)
- Knowledge of lake and downstream water uses; 2,4-D use is restricted
- Mapping of aquatic vegetation with accurate identification of all species and general appraisal of relative abundance and overall cover/biomass
- Inventory of aquatic biota with emphasis on sensitive species
- Treatment plan to include dose, areas treated, expected alteration of plant community, follow-up activities, and notification of lake users about use restrictions after treatment
- Monitoring program for assessing effectiveness and impacts

Factors Favoring the Use of this Technique
- Complete kill of targeted submergent vegetation is desired
- An invasive plant species has been detected at non-dominant levels or on a localized basis but is not amenable to physical control techniques
- Overall plant density is excessive over a large portion of the lake, impacts habitat and water uses, and is not amenable to alternative control methods
- Localized control of plants is needed either to support localized use (e.g., swimming area) or as follow-up to alternative controls

Performance Guidelines
- Map plant community and note density and distribution of target and non-target species; presence of protected species may prevent treatment
- Application must be performed by licensed applicators
- Apply 2,4-D product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- If a large portion of the lake is treated, apply 2,4-D in strips or zones to provide faunal refuges
- Monitor water quality before and after treatment, with emphasis on oxygen and nutrient levels, if more than 10% of lake is treated
- Monitor plant community features before and after treatment

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Detriment (prohibition from drinking water supplies due to toxicity)
- Protection of groundwater supply – Possible detriment (prohibition from zone II well recharge areas due to toxicity, but likelihood of 2,4-D reaching wells is uncertain and controversial)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction), but could be a detriment if plant die-off causes low oxygen at the lake bottom
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)

Cost Considerations
2,4-D treatments typically cost $300 to $800 per acre

TREATMENT WITH FLURIDONE

How it Works

Fluridone is a systemic herbicide that comes in two general formulations, an aqueous suspension and a slow release pellet, although several forms of pellets are now on the market. This chemical inhibits carotene synthesis, which in turn exposes the chlorophyll to photodegradation. Most plants can be damaged by sunlight in the absence of protective carotenes, resulting in chlorosis of tissue and death of the entire plant with prolonged exposure to a sufficient concentration of fluridone. When carotene is absent the plant is unable to produce the carbohydrates necessary to sustain life. Some plants, including Eurasian watermilfoil, are more sensitive to fluridone than others, allowing selective control at low doses.

For susceptible plants, lethal effects are expressed slowly in response to treatment with fluridone. Existing carotenes must degrade and chlorosis must set in before plants die off; this takes several weeks to several months, with 30-90 days given as the observed range of time for die off to occur after treatment. The slow rate of plant die-off minimizes the risk of oxygen depletion. Fluridone concentrations should be maintained in the lethal range for the target species for at least 6 weeks, preferably 9 weeks, and ideally 13 weeks. This presents some difficulty for treatment in areas of substantial water exchange.

If the recommended contact time can be achieved, the use of the liquid formulation of fluridone in a single treatment has been very effective. Where dilution is potentially significant, the slow release pellet form of fluridone has been applied, but in highly organic, loose sediments a phenomenon termed "plugging" has been observed, resulting in a failure of the active ingredient to be released from the pellet in a predictable manner. New pellet formulations are intended to avoid this problem. Multiple sequential treatments with the liquid formulation can be used in areas with extremely soft sediments and significant flushing. It may also be possible to sequester a target area with limno-curtains to reduce dilution effects in the target area.

The selectivity of fluridone for the target species depends on the timing and the rate of application. Early treatment (April/early May) with fluridone effectively controls overwintering perennials before some of the beneficial species of pondweed and naiad begin to grow. Variability in response has also been observed as a function of dose, with lower doses causing less impact on non-target species. However, lesser impact on target plants has also been noted in some cases, so dose selection involves balancing risk of failure to control target plants with risk of impact to non-target species.

Maximum label application rates are 8 lb per acre-foot and 0.4 quarts per acre-foot for the Sonar SRP and Sonar AS formulations, respectively. The maximum concentrations of fluridone expected would be 0.15 ppm, but since the mid-1990s it has been extremely rare to have a target concentration greater than 0.02 ppm. With target levels as low as 0.006 ppm, control of the target species is not always achieved, and only the most sensitive non-target vegetation is impacted. At application rates more certain to kill milfoil, damage to many non-target plants has been observed, but recovery of native plants within 1-3 years is typical.

Fluridone is a systemic herbicide; it is translocated throughout the plant and kills all parts except seeds and certain winter buds. It is used at relatively low doses (now routinely <20 ppb) and can be used selectively through adjustment of dose, application timing, and duration of exposure.

Fluridone is considered to have low toxicity to invertebrates, fish, other aquatic wildlife, and mammals, including humans. The USEPA has set a tolerance limit of 0.15 ppm for fluridone or its degradation products in potable water supplies, although some state restrictions are lower. Substantial bioaccumulation has been noted in certain plant species, but not in animals. The LC50 for sensitive fish species is 7.6 ppm, which is 50 times higher than the expected maximum concentration and about 500 times higher than typical doses used today. Fluridone was not found to impact non-target organisms at concentrations of 0.1 to 1.0 ppm. Rat LD50s are >10,000 mg/kg.

Benefits
- Complete kill of susceptible vegetation
- Can be used selectively on certain major invasive species at low doses
- Slow death of plants minimizes oxygen demand and nutrient release
- Minimal risk of any direct impacts on fauna

Detriments
- Acts slowly in the aquatic environment; exposure time of up to 90 days needed
- Highly diffusive; dilution will limit effectiveness in areas of high flushing activity

Information for Proper Application
- Knowledge of water intake locations if dose is to be >20 ppb
- Knowledge of system hydrology and detention time; need to provide adequate contact time
- Mapping of aquatic vegetation with accurate identification of all species and general appraisal of relative abundance and overall cover/biomass
- Inventory of aquatic biota with emphasis on sensitive species
- Treatment plan to include dose, areas treated, expected alteration of plant community, and follow-up activities
- Tracking of concentration over intended exposure period
- Monitoring program for assessing effectiveness and impacts

Fluridone is very diffusive and requires extended contact time (40-90 days, depending on dose and species). If flushing cannot be controlled, slow release pellet forms may provide the desired combination of dose and exposure time.

Factors Favoring the Use of this Technique
- Complete kill of targeted submergent vegetation is desired
- High selectivity for susceptible species is desired
- Long exposure time can be maintained
- Essential to eliminate potential direct impacts on fauna
- Treatment is within a drinking water supply

Fluridone has not been found to be toxic to animals at any field concentrations.

Performance Guidelines
- Map plant community and note density and distribution of target and non-target species; presence of protected species may limit treatment
- Application must be performed by licensed applicators
- Apply fluridone product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- Control flushing in the lake or target areas to maximize exposure time
- Track fluridone levels and add more herbicide as necessary to achieve the needed combination of dose and exposure
- Monitor plant community features before and after treatment

An enzyme limited immuno-sorbent assay (ELISA) has been developed that allows tracing of the concentration of fluridone. Biochemical tests for potential and actual impact have also been developed, allowing much more sophisticated use of this herbicide.

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

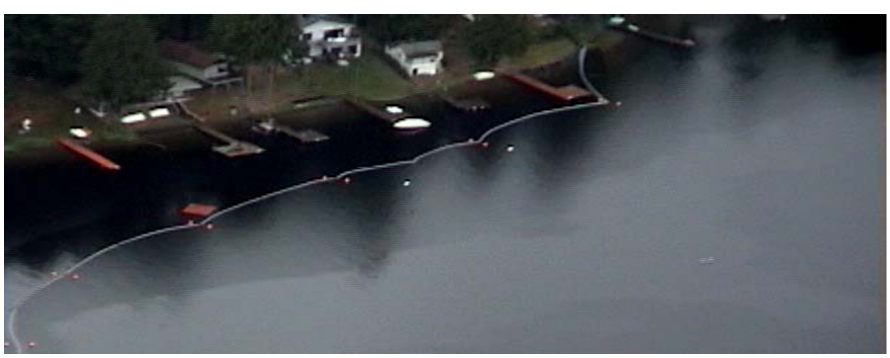
Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral, but may have detriment at high doses (prohibition within one quarter mile of drinking water intakes at dose >20 ppb)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction)
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)

Cost Considerations

Fluridone treatments typically cost $500 to $1000 per acre for single treatments with the liquid form. Costs rise to $1000 to $2000 per acre for sequential treatments. For partial lake treatments in which a portion of the lake is sequestered, an additional cost of about $10 to $20 per linear foot of sequestering curtain is to be expected. The cost of application with the pelletized form is usually $800 to $1200 per acre.

Sequestered treatment of parts of Shoecraft Lake in Washington with fluridone. An average dose of 20 ppb for about 55 days resulted in virtual elimination of Eurasian watermilfoil with no discernible impact on the remainder of the lake. (Photos provided by Remetrix)



TREATMENT WITH TRICLOPYR

How it Works

Triclopyr is a systemic herbicide. Its mode of action is to stimulate growth (auxin mimic) while preventing synthesis of essential plant enzymes, resulting in disruption of growth processes. Uptake of the herbicide generally occurs within 6 to 12 hours of exposure, with effects becoming observable in about a day. Plants sink from the lake surface in 3 to 5 days and death of the plant is complete in 1 to 3 weeks. The active herbicidal ingredient triclopyr received federal registration for aquatic habitats at the end of 2002. *It was not registered for aquatic use in Massachusetts as of this writing, but registration may occur in the near future*. Triclopyr has previously been registered by the USEPA for terrestrial use as Garlon 3A and Garlon 4. These herbicides are used for vegetation control in rights-of-way in some states, and the aquatic formulation is more similar to Garlon 3A. Trade names for the aquatic formulation include Renovate and Restorate, liquids with 3 lbs of active ingredient per gallon, or 44.4% triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid, triethylamine salt).

Federal product labels call for concentrations of 0.75 to 2.5 ppm (as active ingredient) for control of submergent plants, with target concentration rising with water exchange rate. Triclopyr can be applied to waters used as potable water supply, but with a setback distance from any functioning intake that is determined by dose and size of the area treated. There are no federal label restrictions for recreational use of treated waters or for use in livestock watering. Crop irrigation use is prohibited for 120 days or until the triclopyr concentration is undetectable by immunoassay testing. There is no restriction on use for irrigating established grass (i.e., lawns).

Various studies have shown triclopyr to be an effective herbicide for control of certain macrophytes. It is highly selective and effective against Eurasian watermilfoil and other dicotyledonous plants. The recommended dose appears to be about 1.5 mg/L for most applications, with variation relating to exposure time as a function of water exchange. Effectiveness increases as both concentration and exposure time increase. Experimental treatments revealed little or no effect on most monocotyledonous naiads and pondweeds, which are mostly valued native species. This herbicide is most effective when applied during the active growth phase of young plants. The list of potential target species known to cause nuisances in Massachusetts and on which this herbicide should be effective includes all forms of milfoil, American lotus, white and yellow water lilies, purple loosestrife and pickerelweed. Triclopyr is also considered effective for control of alligator weed and water hyacinth, species found at nuisance levels further south.

The half-life for triclopyr can range from 12 hours to 29 days, with degradation into non-toxic forms. Lethal effects on the most sensitive tested animal populations have occurred at concentrations 5 to 40 times the maximum recommended dosage rate. Carcinogenic, mutagenic and teratogenic potentials are low, as is bioaccumulation potential. Chronic effects have not been observed within the recommended dosage range. It should be noted that one of the terrestrial formulations, Garlon 4, has much higher toxic potential, but that aquatic formulations are derived from the chemical family of the less toxic Garlon 3A (triethylamines).

Benefits

- Complete kill of susceptible vegetation
- Can be used selectively on certain major invasive species
- Lower necessary exposure time allows for treatment in areas of greater water exchange
- Low risk of any direct impacts on fauna

Detriments

- Lowered oxygen levels are possible as a function of vegetation decay after treatment.
- No experience yet with application approaches and control success in Massachusetts

Information for Proper Application
- Knowledge of water intake locations to determine required setback distances for treatment
- Knowledge of system hydrology and detention time; need to provide adequate contact time
- Mapping of aquatic vegetation with accurate identification of all species and general appraisal of relative abundance and overall cover/biomass
- Inventory of aquatic biota with emphasis on sensitive species
- Treatment plan to include dose, areas treated, expected alteration of plant community, and follow-up activities
- Tracking of concentration over intended exposure period
- Monitoring program for assessing effectiveness and impacts

The greatest value of triclopyr appears to be for spot treatment of invasive milfoil species after lake-wide treatment with other herbicides such as fluridone.

Factors Favoring the Use of this Technique
- Complete kill of targeted vegetation is desired
- High selectivity for susceptible species is desired
- Long exposure time cannot be maintained
- Essential to minimize potential direct impacts on fauna
- Treatment is within a drinking water supply

Performance Guidelines
- Map plant community and note density and distribution of target and non-target species; presence of protected species may limit treatment
- Application must be performed by licensed applicators
- Apply triclopyr product in accordance with label instructions and restrictions; justify dose, location and timing of treatment
- Track triclopyr levels to ensure that needed combination of dose and exposure is achieved
- Monitor plant community features before and after treatment

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Generally neutral, but may have detriment at high doses (setback of treatment required, with distance based on dose and area treated)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction)
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – Possible benefit (habitat enhancement) and possible detriment (food source alteration, loss of cover)

Cost Considerations
Triclopyr treatments are expected to cost $600 to $800 per acre for single treatments with the liquid form, but there is little experience upon which to base cost estimates. The cost may be somewhat lower for emergent vegetation control and somewhat higher if complications arise in the permitting and monitoring of this relatively new herbicide.

DYES AND COVERS

How it Works

The use of dyes as algal or vascular plant control agents is often grouped with herbicides in lake management evaluations, but this can be very misleading with regard to how dyes work. Dyes are used to limit light penetration and therefore restrict the depth at which rooted plants can grow or the total amount of light available for algal growth. They are only selective in the sense that they favor species tolerant of low light or with sufficient food reserves to support an extended growth period (during which a stem could reach the lighted zone). Dyes are generally non-toxic to all aquatic species, including the target species of plants. In lakes with high transparency but only moderate depth and ample soft sediment accumulations, dyes may provide open water where little would otherwise exist. Repeated treatment will be necessary, as the dye eventually flushes out of the system. Dyes are typically permitted under the same process as herbicides, despite their radically different mode of action. Dyes have been used very rarely in Massachusetts.

Surface shading has received little attention as a rooted plant control technique, probably as a function of potential interference with recreational pursuits, the enhancement of which is a goal of most rooted plant control programs. This procedure should be a useful and inexpensive alternative to traditional methods of weed control in small areas such as docks and beaches, and could be timed to yield results acceptable to summer human users with minimal negative impacts to system ecology. The shading effect of bottom barriers is well known, and would be at work with surface covers. Likewise, the tendency of docks, floats, and other surface structures to shade out plants underneath is recognized by most lake users. However, the compression effect of benthic barriers would not be applicable to surface covers, so eliminating existing growths would be expected to be a slow process.

Although dyes can be an effective method of algae and plant control in small ornamental and golf course ponds, dyes have not provided consistently acceptable control in larger systems and are not generally applied as a control method for either rooted aquatic plants or algae in larger lakes. The dye should be applied early in the growing season for greatest effectiveness. Dyes can usually only be used in lakes and ponds without a flowing outlet, making it a logical choice for small, contained ornamental ponds. There is insufficient information available to evaluate field applications of dyes other than AQUASHADE®, but the light attenuating mechanism is the same for other commercially available dyes.

Surface covers have not been widely used in recreational lakes, presumably because they restrict access for recreation. However, applied on a localized basis early in the growing season, surface covers have the potential to retard rooted plant growths. Removal of the cover once the swimming or boating season commences may provide the desired level of control.

Polyethylene sheets, floated on the lake surface, have been used to shade weeds. Two to three weeks of cover were sufficient to eliminate all species of pondweeds for the summer if the sheets were applied in spring before plants grew to maturity. Coontail was also controlled, but the generally desirable macroalga *Chara* was not. Surface covers are used in many distribution storage reservoirs for drinking water. While the purpose is mainly to minimize inputs from birds and other wildlife that would find the water surface attractive but may add contaminants to this treated water, growth of algae and rooted plants is also minimized. As most such water has been treated with chlorine, the effect may not be entirely a function of the covers, but the impact of restricted light on plant growth is well known. No cases of surface cover use specifically for control of vascular plants and algae are known for Massachusetts lakes.

Surface covers represent a physical impediment to lake use by people and waterfowl, but may provide cover for many fish and invertebrates. As surface cover materials should be inert, no toxicity or other adverse impacts other than light restriction are expected. The light restriction might interfere with visually feeding fish and invertebrates, but unless a large portion of the lake was covered, no significant impact would be expected.

Plants that live in shallow water (2 feet or less) and floating plants may not be impacted, but those that live in deeper water may be replaced over time by species more tolerant to low light. Growths may be stunted in some cases. Organisms that depend on sight for predation may also be restricted to shallower water due to lower light levels, and loss of plants will change the physical habitat in ways that may affect fish and invertebrate populations. Where a part of a lake is treated with surface covers, no long-term lake-wide impact to non-target organisms is expected. Where dyes are used, the change in light regime and the plant community may be substantial enough to cause shifts in faunal communities.

Dye application

Benefits

- Can cause shifts in plant community without physical disruption or toxic reactions
- Surface covers could be used for localized control on a temporary basis
- Dyes can mask discoloration due to algae and create the illusion of greater depth; aesthetic appearance is often enhanced

Dye dispersal with a fountain aerator

Detriments

- Dyes may be ineffective at controlling plants in shallow water
- Altered color may not appear natural to many viewers
- Increased heat absorption may cause stratification of shallow lakes and possible loss of oxygen in the bottom waters
- Surface covers will interfere with many forms of recreation
- Wind and waves may compromise cover effectiveness
- Cannot be used in water bodies with active outflows

Information for Proper Application

- Evaluation of plant assemblage and tolerance to lower light regime
- Assessment of the physical and biological features of the target area
- Knowledge of pond bathymetry and hydrology, to facilitate calculation of the amount of dye needed

Factors Favoring the Use of this Technique

- The target area has dense plant growths of undesirable species that require a high light regime
- There is normally no surface outflow from the lake or pond if dyes are being considered
- Increased surface temperature and possible stratification of shallow areas pose no obvious ecological threat where dyes are being considered
- The target area is shielded from high winds or waves and has convenient means to anchor surface covers
- Access for humans or waterfowl is not an issue during the time surface covers will be in place

Performance Guidelines

- Collect needed data for hydrologic, algae and plant community features to determine applicability of dyes or surface covers
- Dyes are treated like herbicides in the permit process; label instructions and restrictions must be followed
- Dyes are not normally applied to lakes with active outflow
- Combining dye with a circulation system can maximize effectiveness and aesthetic appeal

- Monitor temperature and oxygen after dye addition, as thermal regime may be affected
- Monitor water clarity as a function of dye concentration; retreat if concentration declines below an acceptable level
- Surface covers are rarely used in recreational lakes, but application between April and June to localized areas (dockside, swimming areas) can retard plant growths and yield desirable conditions
- Anchor covers firmly
- Monitor the plant community in the target area before and after the cover period

As dyes are chemicals placed in water, they are permitted under the same process as herbicides. However, the mode of action is completely different and toxicity is not a substantial concern. Typically applied to ornamental ponds and some swimming lakes, dyes limit light penetration and availability to algae and rooted plants. Dyes also mask coloration by algae and suspended sediment.

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- License to Apply Chemicals from DEP (dyes unless pond is private and has no flowing outlet)
- Chapter 91 Permit through DEP may be required for Great Ponds (surface covers only)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral (no significant interaction) for surface covers, detrimental (not allowed) for dyes, although reduced plant density may benefit taste and odor control
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control – Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Neutral (no significant interaction), but could be a detriment if dyes cause stratification that then causes low oxygen at the bottom of the lake
- Protection of land containing shellfish – Generally neutral (no significant interaction), but reduced algae might reduce food resources for shellfish
- Protection of fisheries – Possible benefit (habitat enhancement) and possible detriment (food source alteration, reduced visual predation success, loss of cover). For surface covers applied over a relatively small area, no lake-wide effects are expected
- Protection of wildlife habitat – Dyes may reduce predation success by predatory birds and mammals that feed by sight. Surface covers applied to small areas are not expected to have lake-wide effects on wildlife habitat

Cost Considerations

The cost of dye is about $70 per gallon or $250 for a 4 x 1 gallon case. One gallon treats about 4 acre-feet. A cost of $100 to $500 per acre, including planning, permitting, materials and labor, might be expected. Costs have not been reported for any surface cover installations, but assuming the use of bottom barrier materials, the cost would be at least $20,000/acre for materials. Assuming the use of simple black plastic sheeting, material costs would be largely a function of frame and anchoring materials. It seems likely that a cost of $2,000 to $5,000 per acre could be achieved.

FOOD WEB BIOMANIPULATION

How it Works

Any introduction of organisms may have impacts on the aquatic community structure and food web, however imperceptible. Greater impact occurs when the introduced species becomes abundant or affects another species that is or was abundant. Understanding the nature of these interactions can allow manipulation of system biology to produce a desired effect. However, the biggest pitfall of biomanipulation is that we seldom fully understand all of the relevant interactions.

Interest has grown in biological control methods over the last two to three decades. Most methods are still experimental and have a limited degree of achieved effectiveness. Most methods have the potential to inflict negative impacts on the environment. Biological methods differ from other plant control methods in that there are more variables to consider and usually a longer time span needed to evaluate effectiveness. These methods are unusual in that the treatments consist of either altering conditions to favor certain organisms or introducing live organisms that may be difficult or impossible to control or recall once introduced. For this reason non-native introductions are restricted in most cases. Biological control has the advantage that it is perceived as a more "natural" or "organic" plant control option, but it still represents human interference within an ecological system. The potential for long-term effectiveness with limited maintenance is attractive, but has been largely illusive with biological controls.

Zooplankton: grazers of algae

Biomanipulation can refer to any induced alteration of the biota of a lake, but is used here to refer to algal control options usually involving fish community structure. It is used in lakes where an abundance of algae is believed to be caused by a lack of zooplankton that graze on the algae. The lack of zooplankton in turn is thought to be a result of an overabundance of small fish that prey on zooplankton. By introducing or augmenting fish such as largemouth bass that eat the small fish, those planktivorous fish are reduced in numbers and the populations of large-bodied zooplankton can increase and graze on the algae, thus clearing the water. However, simply adding bass to a pond will not solve the algae problem as many ponds already are at carrying capacity for these predators.

In theory, better fishing and clearer water result. Although some algae are resistant to grazing, continual strong grazing pressure will tend to depress overall algal abundance and increase transparency. Excessive nutrients may allow growth by resistant algae to overcome this grazing effect, but for any given level of fertility, the presence of large-bodied grazers will maintain the lowest possible algal biomass and highest possible clarity. Where non-algal turbidity is substantial, such grazing may have no observable effect, but where algae are the primary determinants of clarity, a variety of benefits are possible. Figure 13 depicts relevant food web interactions, which are subject to considerable spatial and temporal variability. This form of biomanipulation is known as "top down" control.

In order to increase the density of large-bodied zooplankton, the density of zooplankton-eating fish must be reduced. Where piscivore (fish-eating fish) stocking is performed, some control of piscivorous fish removal by anglers may be necessary to maintain stocked piscivorous fish density. Harvesting planktivorous fish is another way to reduce predation on zooplankton without stocking piscivores, and has been successful in smaller lakes and ponds. Netting and electroshocking are the preferred harvest methods. It is difficult to collect enough planktivores in a single season to make a difference in larger lakes. Fishing derbies can be an enjoyable way to reduce small fish abundance, but a major reduction has almost never been achieved in this manner. Most fishery professionals tend to view the problems associated with overabundance of panfish as a consequence of inadequate piscivore populations. Common management goals of clear water and desirable fishing are usually better served by focusing on enhancing piscivorous fish populations.

Another method to reduce the numbers of small planktivorous fish is to treat the lake with rotenone, a poison that can kill all fish, large and small. This is a highly disruptive technique used only to reclaim the entire lake when the fish community has become very unsatisfactory. It was popular in Massachusetts in the 1960s and is still used in some other northeastern states, but rotenone currently is not registered for use in Massachusetts, so this option is not available within the Commonwealth.

Other conditions that might affect the population of zooplankton grazing on algae include an anoxic metalimnion or hypolimnion, common in eutrophic lakes, that eliminates these zones as daytime refuges for zooplankton from visually feeding fish and thus enhances zooplankton mortality. An appropriate aeration program can eliminate this problem. Another cause of zooplankton mortality is the toxic effect of pesticides that enter the lake with agricultural or urban runoff. The use of copper sulfate for temporary algal control can also produce significant zooplankton mortality at doses below those needed for algae control.

In lakes with blue-green blooms, it may be possible to favor the growth of diatoms and other desirable species of algae by adding silica and/or nitrate. Alteration of nutrient ratios has been demonstrated to cause shifts in algal assemblage composition in accordance with algal group preferences. Low ratios of N to P (<12 to 24 on a molecular basis, < 5 to 11 on a weight basis) tend to favor nitrogen-fixing blue-greens, while high ratios (>50 to 70 by molecule or >22 to 30 by weight) favor the green algae. Addition of nutrients to lakes is perceived as very risky, and it is generally preferable to raise the N:P ratio by lowering phosphorus. This approach to controlling algal assemblages is often called "bottom up" control.

Unbalanced fish community

Benefits

- Harnesses natural processes to develop desirable conditions
- May be self-sustaining or require only limited maintenance
- May produce both clearer water and better fishing

Detriments

- High variability of results; not especially reliable

Information for Proper Application

- Knowledge of the food web and relative abundance of key components
- Water quality data to provide baseline and suitability assessment relating to any introductions
- Monitoring program of sufficient scale to track progress and allow informed adjustment

Balanced fish community

Factors Favoring the Use of this Technique

- Manipulation represents a shift in existing populations and community structure; no new species introductions are needed
- Relationships between any introduced species and the lake are understood from studies at other lakes
- Small scale field tests can be run to examine likely effectiveness and non-target impacts before moving to full scale introduction
- A gradual transition to more desirable conditions is acceptable
- A higher degree of uncertainty and variability of results is tolerable

Performance Guidelines

- Conduct physical, chemical and biological surveys to determine potential for method and stocking or removal needs
- Develop and follow a scientifically based plan to achieve target densities of predators and/or grazers
- Use native and indigenous species to the maximum extent possible
- Be prepared to pursue biological programs for at least 5 years before achieving all goals
- Monitor target populations and water quality features

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally beneficial (reduced algal density may benefit solids and taste and odor control)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Generally beneficial (lowered algal densities minimize water quality fluctuation)
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Generally beneficial (enhanced food source and community structure)
- Protection of wildlife habitat – May have benefit and detriment to different species in same lake from same effort

Cost Considerations

Costs vary substantially among and within treatments classified as biological control. Choice of introduced organism, magnitude of application, necessary mitigative measures, and monitoring can each have a major impact on cost, even when standardized to an areal unit (i.e., $/acre). Food web biomanipulation costs will depend on the labor cost for removing planktivores or the stocking cost of added piscivores. Costs of $1 to $20/fish are common for stocked piscivores. A cost of $500 to $1,500/acre for piscivore stocking and a cost of $1,000 to $5,000/acre for planktivore removal might be expected, but the duration of effects is uncertain, so this is not necessarily an annual cost.

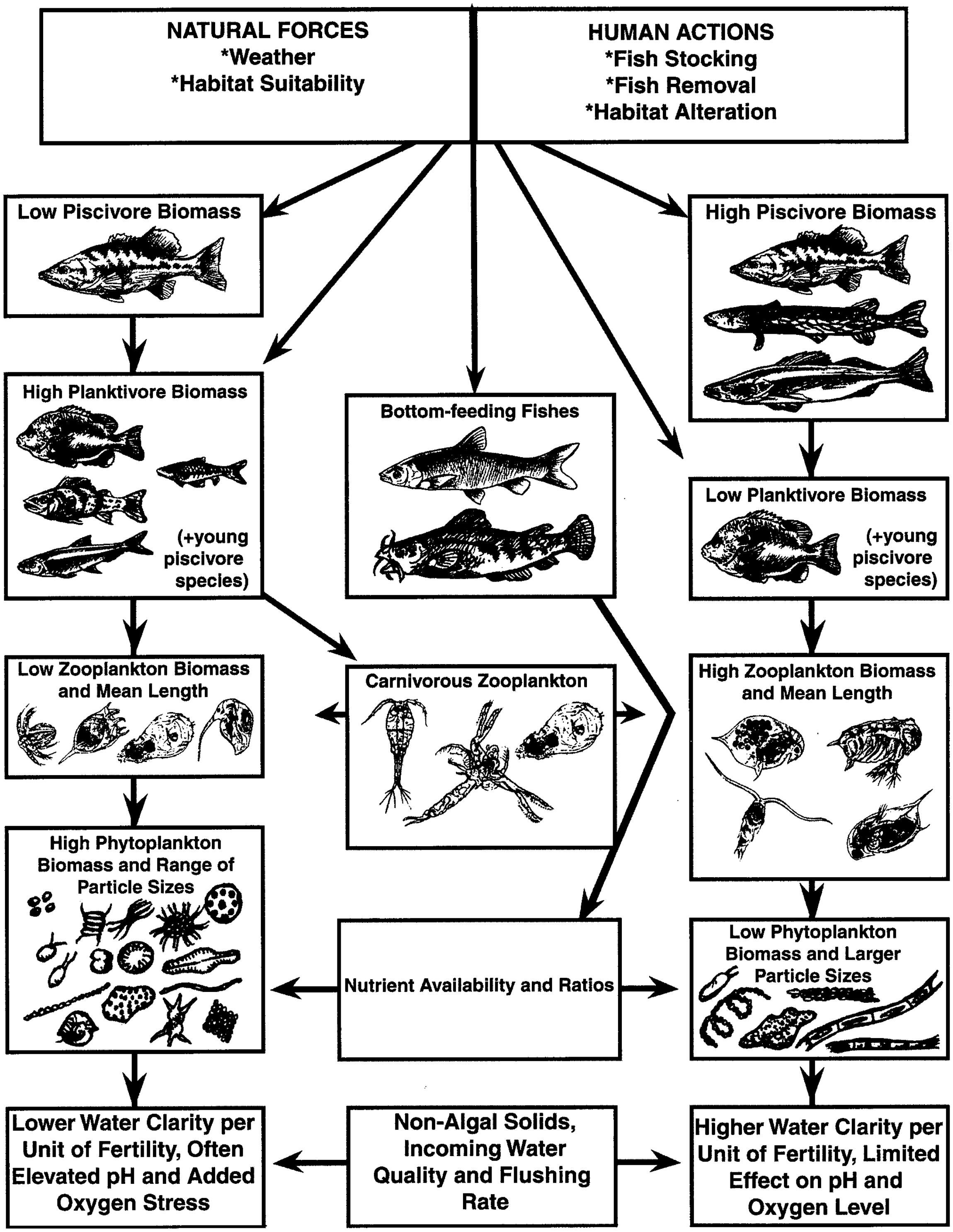


Figure 13. The Role of Fish Community Structure in Determining Plankton Features and Water Clarity (from Wagner, 2001).

HERBIVOROUS FISH

How it Works

Herbivorous fish can be divided into two groups: those that consume plankton and those that consume macrophytes. The use of planktivores to remove plankton (specifically, algae) directly has not been very successful. Gizzard shad (*Dorosoma cepedianum*) have been used in the southern United States to reduce large algae. Gizzard shad also eat zooplankton, however, and as a result the algal component of the plankton tends to increase rather than decrease. Other planktivores include silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*H. nobilis*), both exotic fish from China that eat zooplankton, phytoplankton and detritus. The effectiveness of these species is limited and some evidence suggests that algae might increase as zooplankton are consumed by silver and bighead carp.

There are several species of fish that consume macrophytes, including the African cichlids (*Tilapia* spp.). *Tilapia* species can only survive in water temperatures greater than 10^{o}C and are therefore unlikely candidates for macrophyte control in Massachusetts. The introduction of herbivorous fish therefore generally centers on grass carp (*Ctenopharyngodon idella*). Grass carp are not approved for introduction in Massachusetts, however, so this option is not available within the Commonwealth. The use of grass carp comes up repeatedly in discussions of plant control options, however, so the following information is provided in the interest of complete coverage of techniques.

The grass carp (*Ctenopharyngodon idella*), also known as the white amur, is a species of fish that is used to control aquatic macrophytes. The native range of grass carp includes the Pacific slope of Asia from the Amur River of China and Siberia, south to the West River in southern China and Thailand. They are typically found in low gradient reaches of large river systems. Grass carp can grow to 4 feet long and attain weights of over 100 pounds, making them the largest member of the cyprinid family. They have a very high growth rate, with a maximum at about 6 pounds per year. They typically grow to a size of 15-20 pounds in North American waters and have adapted quite well to life in reservoirs where they are stocked for aquatic vegetation control.

As with other carp species, they are tolerant of wide fluctuations in water quality including water temperatures from 0 to 35^{o}C, salinities up to 10 ppt, and oxygen concentrations approaching 0 mg/L. Grass carp do not feed when water temperatures drop below 11^{o}C (52^{o}F) and feed heavily when water temperatures are between 20^{o}C and 30^{o}C (68^{o}F and 86^{o}F).

Dietary preference is an important aspect of grass carp, as pertains to their use as a plant control mechanism. Grass carp have exhibited a wide variety of food choices from study to study. In some cases grass carp have been reported to have a low feeding preference for *Myriophyllum spicatum*, one of the common invasive aquatic plants in Massachusetts, Yet in a recently completed Connecticut study, grass carp did consume milfoil more readily than other submergent species. Grass carp readily eat other non-native plants such as *Cabomba caroliniana* and *Egeria densa* as well as various native species. In some cases grass carp will also eat and control filamentous algae (e.g., *Pithophora*). Generally, grass carp avoid cattails and water lilies, but the high level of variability in grass carp diet among lakes should be kept in mind.

Grass carp are believed to have been introduced to the United States in 1963 by the Bureau of Sport Fisheries and Wildlife at the Fish Farming Experimental Station in Stuttgart, Arkansas and Auburn University, Alabama, for research purposes. Expansion of their range since that time has largely been a result of stocking for macrophyte control. In response to the threat of diploid reproduction, a sterile triploid grass carp was first developed for commercial use in 1984. The majority of grass carp currently stocked in North America are triploids.

Fish are usually stocked in the size range of 200 mm to 300 mm (8 to 12 inch). The most common stocking rates are at 80 to 100 fish per acre for plant eradication and 25 to 80 fish per acre for plant control with higher rates recommended for cool waters. New York State officials have found that lower stocking rates are sufficient for macrophyte reduction, and stocking rates in New York average 12.7 fish per acre. In Connecticut, the stocking rate of triploid fish is based on an equation that includes climatic zone, percentage of pond area covered with macrophytes and percentage of pond area less than 10 feet deep. Effective grass carp stocking rates are a function of grass carp mortality, water temperature, plant species composition, plant biomass and desired level of control.

The major difficulty in using grass carp to control aquatic plants is determining what rate will be effective and yet not so high as to eradicate the plants completely. The fish usually live ten or more years but the typical plant control period is reported to be 3 to 4 years with some restocking often required. They are difficult to capture and remove unless the lake is treated with rotenone that will kill other fish species as well and is illegal in Massachusetts.

Grass carp may decrease the density or even eliminate vascular plants, although in a Connecticut study, the carp preferred milfoil to other plants. Algal blooms resulting from nutrients being converted from plant biomass by the grass carp have been common, even without elimination of vascular plants. In light of the uncertainty associated with this technique and the generally poor track record of non-native species introductions, Massachusetts remains closed to the import of grass carp.

Benefits

- Potential control of aquatic plants from a single introduction of an appropriate density of fish for perhaps 5 years

Detriments

The introduction and use (including experimental use) of grass carp in Massachusetts have been reviewed by the MDFG, its Non-game Advisory Committee, and the Fisheries and Wildlife Board. This review concluded that introduced grass carp would pose a significant environmental risk to native wildlife and their habitats in Massachusetts. As a result, the Massachusetts Fisheries and Wildlife Board has not issued any permits to introduce grass carp. The following reasons are given:

- Grass carp can decimate native plant communities, resulting in severe impacts to waterfowl, invertebrate, and fish habitats
- Grass carp stocking can result in major impacts to water quality, including algae blooms, increased turbidity, and fluctuating dissolved oxygen and pH
- Grass carp exhibit variable feeding preference for some nuisance non-native plants and have the potential to decimate native flora
- By reducing some species of macrophytes, grass carp reduce interspecific competition and lead to increased growth of other species
- Grass carp are long-lived and nearly impossible to remove from a system once introduced
- Grass carp are highly migratory and can easily escape over spillways or through bar grates to impact waters other than those intended
- Grass carp are known disease carriers that can transmit diseases to other fish species
- Grass carp do not remove nutrients from the system, but instead recycle them from one form to another
- The impacts and effectiveness of grass carp are highly variable and unpredictable

Information for Proper Application

This technique is not permitted in Massachusetts.

Factors Favoring the Use of this Technique

This technique is not permitted in Massachusetts.

Performance Guidelines
As the introduction of grass carp into waters of Massachusetts is not permitted, no performance guidelines are offered.

Possible Permits
The importation of grass carp is currently illegal in Massachusetts. No permits are granted for the introduction of this fish.

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Generally neutral (no significant interaction), although reduced plant density may benefit taste and odor control
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Could be a detriment if nutrient cycling promotes algal blooms
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Probable detriment (food source alteration, loss of cover)
- Protection of wildlife habitat – May have benefit and detriment to different species in same lake from same effort

Cost Considerations
Costs for 8-10 inch grass carp vary widely between $4 and $13 depending on the source. At stocking rates of 7 to 15 fish per acre this would amount to a cost of $28 - $195 per acre, and the treatment effects typically last about five years. A cost range of $50 to $300/acre for grass carp stocking might be expected, including planning and monitoring, but this is not a legal approach in Massachusetts.

Grass carp, *Ctenopharyngodon idella* (provided by C. Gilbert of Allied Biological)

HERBIVOROUS INVERTEBRATES

How it Works

Significant improvement in our future ability to achieve lasting control of nuisance aquatic vegetation may come from plant-eating biocontrol organisms, or from a combination of current procedures such as harvesting, drawdown, and herbicides with these organisms. Biological control has the objective of achieving control of plants without introducing toxic chemicals or using machinery. Yet it suffers from an ecological drawback; in predator-prey (or parasite-host) relationships, it is rare for the predator to completely eliminate the prey. Consequently, population cycles or oscillations are typically induced for both predator and prey. It is not certain that the magnitude of the upside oscillations in plant populations will be acceptable to human users, and it seems likely that a combination of other techniques with biocontrols may be necessary to achieve lasting, predictable results.

Biological control using invertebrates (mainly insects) from the same region as the introduced target plant species include the root boring weevil (*Hylobius transversovittatus*) and two leaf beetles (*Galerucella calmariensis* and *G. pusilla*) for the control of purple loosestrife (*Lythrum salicaria*). Such efforts also include the tuber feeding weevil (*Bagous affinis*) and the leaf-mining fly (*Hydrellia pakistanae*), both for the control of *Hydrilla verticillata* in Florida. However, as introduced non-native species have sometimes caused bigger problems than they solved, native species are preferred.

The native crayfish (*Orconectes immunis*) was used experimentally in Conesus Lake, New York, but did not prove effective. Augmentation of a native insect population has been studied with the milfoil midge (*Cricotopus myriophylli*), a moth (*Acentria ephemerella*) and the milfoil weevil (*Euhrychiopsis lecontei*). Releases in Massachusetts of the native weevil (*Euhrychiopsis lecontei*) for the control of Eurasian milfoil have occurred since 1995, and there are signs of success in two of the original test lakes. This review focuses on the milfoil weevil as an example of invertebrate herbivore use.

The milfoil midge, *Cricotopus myriophylli, above and the milfoil moth, Acentria ephemerella, below* (provided by R. Johnson of Cornell University)

Euhrychiopsis lecontei is a native North American insect species believed to have been associated with northern watermilfoil (*Myriophyllum sibericum*), a species largely replaced by non-native, Eurasian watermilfoil (*M. spicatum*) since the 1940's. It does not utilize non-milfoil species. In controlled trials, the weevil clearly has the ability to impact milfoil plants through structural damage to apical meristems (growth points) and basal stems (plant support). Adults and larvae feed on milfoil, eggs are laid on it, and pupation occurs in burrows in the stem. Field observations linked the weevil to natural milfoil declines in nine Vermont lakes and additional lakes in other states.

Lakewide crashes of milfoil populations have generally not been observed in cases where the weevil has been introduced into only part of the lake, although localized damage has been substantial. Widespread control may require more time than current research and monitoring has allowed. As with experience with introduced insect species in the south, the population growth rate of the weevil is usually slower than that of its host plant, necessitating supplemental stocking of weevils for more immediate results. Just what allows the weevil to overtake the milfoil population in the cases where natural control has been observed is still unknown.

Densities of 1-3 weevils per stem appear to collapse milfoil plants, and raising the necessary weevils is a major operation. The State of Vermont devoted considerable resources to rearing weevils for introduction over a two-year period, using them all for just a few targeted sites. Weevils are now marketed commercially as a milfoil control, with a recommended stocking rate of 3000 adults per acre. Release is often from cages or onto individual stems; early research involved attaching a stem fragment with a weevil from the lab onto a milfoil plant in the target lake, a highly labor-intensive endeavor.

Although weevils may be amenable to use within an integrated milfoil management approach, interference from competing control techniques has been suggested as a cause for sub-optimal control by weevils. Harvesting may directly remove weevils and reduce their density during the growing season. Also, adults are believed to overwinter in debris along the edge of the lake, and techniques such as drawdown, bottom barriers, or sediment removal could negatively impact the weevil population. Extension of lawns to the edge of the water and application of insecticides also represent threats to these milfoil control agents.

The milfoil weevil, *Euhrychiopsis lecontei* (provided by R. Johnson of Cornell University)

Other insects used for plant control are mainly southern species used to controls invasive species not typically found in Massachusetts. The primary exception is the loosestrife beetle (*Galerucella* spp.), used to control purple loosestrife (*Lythrum salicaria*). The Association of Massachusetts Wetland Scientists has developed a beetle-rearing program that allows interested groups to raise these biocontrol agents for placement in targeted growths of purple loosestrife. Success has been reported in New York with this approach and could be expected in Massachusetts as this program expands.

Benefits

- Potential control with native (or carefully researched and approved non-native) species that may be self-perpetuating
- Harnesses natural processes to control nuisance or invasive species

Detriments

- High variability in results; not especially reliable
- Generally slow in achieving desired results

Healthy (bottom) and weevil-damaged (top) stems of milfoil (provided by R. Johnson of Cornell University)

Information for Proper Application

- Knowledge of the interactions between the target species and introduced or augmented herbivore
- Appropriate stocking density
- Water quality data to provide baseline and suitability assessment relating to introductions or augmentations
- Monitoring program of sufficient scale to track progress and allow informed adjustment

Factors Favoring the Use of this Technique

- The biocontrol agent is a native species that is highly host-specific for the target species.
- Relationships between the introduced species and the lake are understood from studies at other lakes.
- The biocontrol agent can be removed from the lake if necessary, or has limited powers of reproduction, migration, or longevity.
- Small-scale field tests can be run to examine likely effectiveness and non-target impacts before moving to full-scale introduction.

- Rearing procedures allow cost effective propagation of the biocontrol agent, or natural increases in abundance can be stimulated.
- Other techniques are available to augment biocontrol as needed.
- A gradual transition to more desirable conditions is acceptable.
- A higher degree of uncertainty and variability of results is tolerable.

Performance Guidelines

- Match the herbivore to the target plant; high specificity is desirable
- Develop and follow a scientifically based plan to achieve target densities of invertebrate herbivores
- Use native and indigenous species to the maximum extent possible
- Be prepared to pursue biological programs for at least 5 years before achieving all goals
- Monitor target populations (plant and herbivore)

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally neutral, but reduced plant density may benefit taste and odor control
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Generally neutral, but reduced plant density may benefit taste and odor control
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Possible benefit (habitat enhancement, reduction of invasive species density)
- Protection of wildlife habitat – Possible benefit (habitat enhancement, reduction of invasive species density)

Loosestrife beetle (*Galerucella* sp.) (provided by R. Johnson of Cornell University)

Cost Considerations

Milfoil weevils are sold for $1 each, with a recommended stocking density of 3,000 per acre. Loosestrife beetles are available for a similar price, but the Association of Massachusetts Wetland Scientists recommends that interested groups raise the beetles themselves at a reduced cost. Insect introduction costs of $300 to $3,000 per acre are suggested as typical.

PLANT COMPETITION

How it Works

Although invasive nuisance plant species are just what the name implies, there is evidence that the presence of a healthy, desirable plant community can minimize or slow infestation rates. Most invasive species are favored by disturbance, so a stable plant community should provide a significant defense. Unfortunately, natural disturbances abound, and almost all common plant control techniques constitute disturbances. Therefore, if native and desirable species are to regain dominance after disturbance, it may be necessary to supplement their natural dissemination and growth with seeding and planting. The use of seeding or planting of vegetation is still a highly experimental procedure, but if native species are employed, it should yield minimal controversy.

Experiments indicate that the addition of dried seeds to an exposed area of sediment will result in rapid germination of virtually all viable seeds and rapid cover of the previously exposed area. However, if this is not done early enough in the growing season to allow annual plants to mature and produce seeds of their own, the population will not sustain itself into the second growing season. Transplanting mature growths into exposed areas has generally been found to be a more successful means of establishing a seed producing population. The use of cuttings gathered by a harvester has not been successful in establishing native species, so it appears that whole, viable plants must be added.

More research is needed, but establishment of desired vegetation is entirely consistent with the primary plant management axiom: if light and substrate are adequate, plants will grow. Rooted plant control should extend beyond the limitation of undesirable species to the encouragement of desirable plants.

Plantings for reduced light penetration might also control algae, but there could be many negative side effects of such an effort. Surface-covering growths of duckweed, water hyacinth, or water chestnut could provide such a light barrier, but at great expense to habitat and water quality.

Areas of dense, healthy, indigenous plants tend to resist colonization by invasive species. Resistance may not be complete or lasting, but invasions have been greatly slowed where bare sediment is minimized. The basic premise of plant competition as a management technique is therefore to maximize spatial resource use by desirable species to keep out undesirable plants.

Benefits

- Harnesses natural processes to develop desired conditions
- May be self-perpetuating
- Augments other techniques for plant control

Using a harvester to transplant *Chara* to a site cleared of milfoil

Detriments

- May not prevent invasions over a long time period
- Requires ongoing effort to keep up with natural disturbances
- Indigenous species may become nuisances in some cases
- Likely to require application of a major control technique prior to planting

Information for Proper Application

- Detailed assessment of existing plant assemblage
- Knowledge of ecology of species targeted for removal/control and for planting/expansion
- Water quality baseline for assessing suitability for any species introductions or expansions
- Sediment baseline data for assessing suitability for any species introductions or expansions

- Familiarity with planting techniques or willingness to experiment
- A monitoring program to track results and support informed adjustment

Factors Favoring the Use of this Technique
- Portions of the lake support healthy growths of desirable species
- Other sources of desirable species are available
- Control methods for undesirable species are applicable and supported

Performance Guidelines
- Conduct physical, chemical and biological surveys to determine potential for plant replacement
- Choose replacement plants for competitive and ecological value, then provide them with an advantage over nuisance or invasive species
- Develop and follow a scientifically based plan to remove unwanted plants and achieve target densities of desired plants
- Use native species only and indigenous species to the extent possible
- Be prepared to pursue biological programs for at least 5 years before achieving all goals
- Monitor target populations

A mixed assemblage ↑ is better than a nuisance monoculture ↓

Possible Permits
- Possible WPA permit through local Conservation Commission/DEP
- Possible review by NHESP (further action if protected species are present)

This is a new area of management that has not been fully evaluated in the regulatory arena. Efforts to date have largely been supported as experiments by state agencies, or have been conducted informally without regulatory consultation. Individuals or groups interested in applying this approach should consult with their local Conservation Commission and their regional DEP office.

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Generally neutral (no significant interaction)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Generally neutral (no significant interaction)
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Possible benefit (habitat enhancement, reduction of invasive species density)
- Protection of wildlife habitat – Possible benefit (habitat enhancement, reduction of invasive species density)

Cost Considerations
Costs are largely unknown and unpredictable, but will be determined by the need for removal of unwanted vegetation, the source of desired vegetation, planting method, and monitoring approach. Most costs will be associated with labor.

BARLEY STRAW

How it Works

The use of rotting barley straw (*Hordeum vulgare*) to control algae blooms has received considerable attention over the last decade, and appears to be at least partly an allelopathic technique. The use of barley as a treatment to improve water clarity in ponds has been tested, but is not well understood. Barley straw can control algal densities in some cases. Preferably added to shallow, moving water or from pond-side digesters, decaying barley straw gives off substances that inhibit algal growth and seem to be particularly effective against blue-green algae.

Re-packing barley straw in mesh bags (provided by S. McComas of Bluewater Science)

Although this is not a thoroughly understood or widespread technique at this time, research conducted mainly in England has demonstrated that the decomposition of the barley straw produces allelopathic compounds that act as algaecides. Also, competition for nutrients between heterotrophic decomposers and autotrophic algae appears to favor the heterotrophs after barley straw addition. Stagnant water reduces production of the essential compounds and uptake of nutrients as low oxygen levels in the straw slow decomposition, and highly turbid water also reduces effectiveness.

Doses of barley straw under well-oxygenated conditions are typically around 2.5 g/m^2 of pond surface, with doses of 50 g/m^2 or more necessary where initial algal densities are high or flow is limited. Doses of 100 g/m^2 may cause oxygen stress in the pond as decomposition proceeds, but this can be avoided by the use of a land-based digester into which straw is deposited and through which water is pumped as the straw decays.

Positioning mesh bags of barely straw (provided by S. McComas of Bluewater Science)

Application of the straw as whole bales or completely loose has been less successful that installation in loose but contained portions. A Christmas tree bailer was used in one case to repackage barley straw in a manageable mass that was coherent enough to generate the microbiological activity that appears essential yet loose enough to allow water movement to carry the natural algaecide into the water column. Digesters, in which pond water circulates through incubated barley straw in a chamber before discharge to the pond, is another seemingly more successful approach to application. Many factors may be involved in success of such treatments, and the technique is not understood well enough to be reliable at this time.

Benefits

- Possible control of selected algae (notably blue-greens) at low cost

Detriments

- Possible oxygen depression and related biotic impacts
- Highly variable results; not especially reliable

Information for Proper Application

- Algal assemblage composition and relative abundance
- Water quality data, especially oxygen levels
- Flow and mixing information for the pond
- Source of barley straw (a very specific product, and not just any straw or hay)

Using a tree baler to re-pack barley straw (provided by S. McComas of Bluewater Science)

Factors Favoring the Use of this Technique

- Dominance by blue-green algae
- Small pond size for ease of application
- Sufficient through flow or aeration to ensure mixing and limited oxygen depression
- Willingness to tolerate variable results

Performance Guidelines

Based on experience in other states, guidance could include:

- Evaluate the algal community for applicability of this technique; it appears to be most effective on blue-greens
- Target an appropriate concentration of barley straw
- Bundle straw in loose aggregations held together with mesh or other porous support; alternatively, digest the straw in a separate container and inject the slurry into the lake
- Monitor algae and oxygen levels

Securing loosely baled barley straw (provided by S. McComas of Bluewater Science)

Possible Permits

- Possible WPA permit through local Conservation Commission/DEP
- Possible Review by NHESP (further action if protected species are present)

This is a problematic technique with regard to permitting. Given its apparent algaecidal properties, barley straw is currently regarded as an unregistered herbicide by the USEPA. As such it cannot be covered under a License to Apply Chemicals from DEP, and licensed herbicide applicators cannot apply it to lakes. There is no clear guidance on whether a Conservation Commission can issue an Order of Conditions for use of barley straw, but actual placement of such straw in lakes might be considered to impact resource areas governed by the WPA. Individuals or groups wishing to apply this technique should consult with their local Conservation Commission and their regional DEP office.

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Generally beneficial (reduced algal density may benefit solids and taste and odor control)
- Protection of groundwater supply – Generally neutral (no significant interaction)
- Flood control – Generally neutral (no significant interaction)
- Storm damage prevention – Generally neutral (no significant interaction)
- Prevention of pollution – Generally beneficial (lowered algal densities minimize water quality fluctuation), but possible detriment if oxygen is lowered
- Protection of land containing shellfish – Generally neutral (no significant interaction)
- Protection of fisheries – Possibly beneficial (lowered blue-green abundance) or detrimental (lowered oxygen)
- Protection of wildlife habitat – May have benefit and detriment to different species in same lake from same effort

Cost Considerations

Costs are largely unknown. Cost of barley straw and labor to apply it are the primary factors.

BACTERIAL ADDITIVES

How it Works

The use of bacterial additives in lakes and ponds has received some attention in recent years, but little detailed scientific study. The theory is simple: add natural or engineered bacteria to the aquatic environment that will out-compete algae for nutrients, binding up the supply of N or P and reducing available concentrations in the lake. In practice, most bacterial additives focus on nitrogen, which would seem to favor undesirable blue-green algae that can fix gaseous nitrogen. Also, it is not clear that a bacterial community capable of precluding algal blooms would not itself constitute an impairment of aquatic conditions. Nevertheless, some practitioners report favorable results, albeit anecdotally with limited supporting data. Further evaluation is needed.

Benefits

- Reduced algal abundance through competition with bacteria

Detriments

- Possible bacterial biomass build-up
- Favorable conditions for blue-green algae

Information for Proper Application

Considerable information about the expected mode of action by such additives would be helpful, but most manufacturers consider key aspects of bacterial additives to be proprietary. Not enough research has been done to know how to best apply this approach.

Factors Favoring the Use of this Technique

- Simple and inexpensive option, although it has no scientific track record

Performance Guidelines

There is not enough information on this technique to provide clear guidance.

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Possibly beneficial (reduced algal density) or detrimental (blue-green algal production may be favored)
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control – Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Possibly beneficial (lowered algal densities), but possible detriment (if blue-green algae are favored)
- Protection of land containing shellfish – Neutral (no significant interaction)
- Protection of fisheries – Possibly beneficial (lowered algal abundance) or detrimental (increased blue-green abundance)
- Protection of wildlife habitat – Possibly beneficial (lowered algal abundance) or detrimental (increased blue-green abundance)

Cost Considerations

Costs are not well known, but bacterial additives are not expensive, especially on the small scale at which they have been applied

REMOVAL OF BOTTOM FEEDING FISH

How it Works

Biomanipulation to reduce nutrient availability and improve lake transparency includes elimination of fish such as the common carp or bullheads that are bottom browsers. Browsing has been shown to release significant amounts of nutrients to the water column as these fish feed and digest food. Turbidity is also generated by their foraging activities. Harvesting these fish has resulted in increased clarity in some cases, and it has been suggested that alternative stable states exist for lakes, based on biological structure. Removing such fish, however desirable, can be very difficult since they tolerate very low levels of dissolved oxygen and high doses of fish poisons. Labor intensive programs appear necessary to achieve substantial reductions in bottom-feeding fish populations, unless the entire fish population can be sacrificed through complete drawdown, complete freezing, or high doses of rotenone or other fish poisons. This technique has not been practiced in many years in Massachusetts, except as a side effect of dry dredging or complete drawdown for structural dam repairs.

Benefits

- Reduces populations of fish that add turbidity and nutrients to the water
- May improve water clarity and algal community features
- May improve plant community features

Detriments

- Difficult to accomplish at significant level, especially in absence of approved fish poison in Massachusetts
- May not be effective if nutrient loading from other sources is high

Information for Proper Application

- Detailed fish population data
- Water quality data and nutrient budgets that indicate importance of bottom feeders in nutrient recycling or direct turbidity generation
- Monitoring program to track removal success and resultant changes in nutrient status and water clarity

Factors Favoring the Use of this Technique

- High densities of bottom feeders
- Documented link between fish and water clarity based on bottom disturbance
- Physical layout conducive to large scale collection effort (small size, minimal obstructions for netting, shallow depth for electroshocking)

Performance Guidelines

- Collect fish community data to facilitate evaluation of level of control needed
- Arrange for fish disposal
- Select collection/eradication method appropriate to lake
- Monitor fish removal
- Monitor water quality before and after fish removal

Possible Permits

- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Permit from MDFW for collection of fish

Impacts Specific to the Wetlands Protection Act

- Protection of public and private water supply – Possibly beneficial (reduced algal density and turbidity)
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control – Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Possibly beneficial (lowered algal densities and turbidity)
- Protection of land containing shellfish – Probably neutral (no significant interaction)
- Protection of fisheries – Possibly beneficial unless target fish are an important component of food web for desirable species
- Protection of wildlife habitat – Possibly beneficial to some species and detrimental to others

Cost Considerations

Costs are largely unknown, but the effort involved in anything but a small pond would be very large. Labor expense is likely to be the primary cost factor.

Common carp, *Cyprinus carpio*, a large bottom feeder (provided by the American Fisheries Society)

Brown bullhead, *Ameiurus nebulosus*, a bottom feeder (provided by the American Fisheries Society)

SONICATION

How it Works
Sonication is used to break up algae in samples for better analysis, but is a new technique on an application scale for lake management. A floating sonicator is now available commercially, and product literature claims that it will break up algae and cause them to sink to the lake bottom over target areas that range from 150 to 15,500 square meters, depending upon the model installed. Power consumption is a maximum of 45 watts, and the sonic waves reportedly have no effect on zooplankton or fish. The product literature warns that some algae may float after sonication, but that they will eventually sink. No scientific tests of this apparatus have been reported in the lake management literature, and this product is likely to provide only short-term relief, but it may be a viable option for smaller lakes and ponds. Impacts on non-target organisms bear further investigation.

Benefits
- Rapid reduction in algal biomass without chemical addition

Detriments
- Will result in algal cell contents being released into the water column; possible taste and odor and toxicity issues, recycling of nutrients likely
- Safety issue associated with power cables in ponds

Information for Proper Application
This technique has just been introduced in the USA and in Massachusetts. It does not appear to require special information about algal populations, but achieving maximum effectiveness may require substantial additional research and field trials.

Factors Favoring the Use of this Technique
- Localized problem; units handle only small areas
- Accessible shoreline power source

Schematic of the sonic apparatus (provided by D. Taylor of Sonic Solutions)

Performance Guidelines
This technique is too new to provide clear guidance. Likely issues would include:
- Assessment of potential for taste, odor and toxicity from ruptured algal cells
- Power supply safety
- Portion of lake to be treated and associated sonicator needs
- Monitoring for impacts to non-target organisms

Possible Permits
- WPA permit through local Conservation Commission/DEP
- Review by NHESP (further action if protected species are present)
- Chapter 91 Permit through DEP may be required for Great Ponds, due to navigational hazard

Impacts Specific to the Wetlands Protection Act
- Protection of public and private water supply – Possibly beneficial (reduced algal density), but possibly detrimental (release of taste and odor compounds or toxins)
- Protection of groundwater supply – Neutral (no significant interaction)
- Flood control – Neutral (no significant interaction)
- Storm damage prevention – Neutral (no significant interaction)
- Prevention of pollution – Possibly beneficial (lowered algal densities and turbidity)
- Protection of land containing shellfish – Probably neutral (no significant interaction)

- Protection of fisheries – Possible benefit (reduced algae), but impacts of sound waves on fish require more research
- Protection of wildlife habitat – Possible benefit (reduced algae), but impacts of sound waves on wildlife require more research

Cost Considerations

Units have list prices of about $1000 to $3000 and influence no more than a few acres per unit. Installation costs, with power supply, will increase the capital cost. Operational costs are unknown. If power is available at the site, this may be an economical option for smaller ponds.

Pond prior to sonication treatment (provided by D. Taylor of Sonic Solutions)

Pond after sonication treatment (provided by D. Taylor of Sonic Solutions)

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