Hydrilla Management Options for Chesdin Reservoir, Virginia

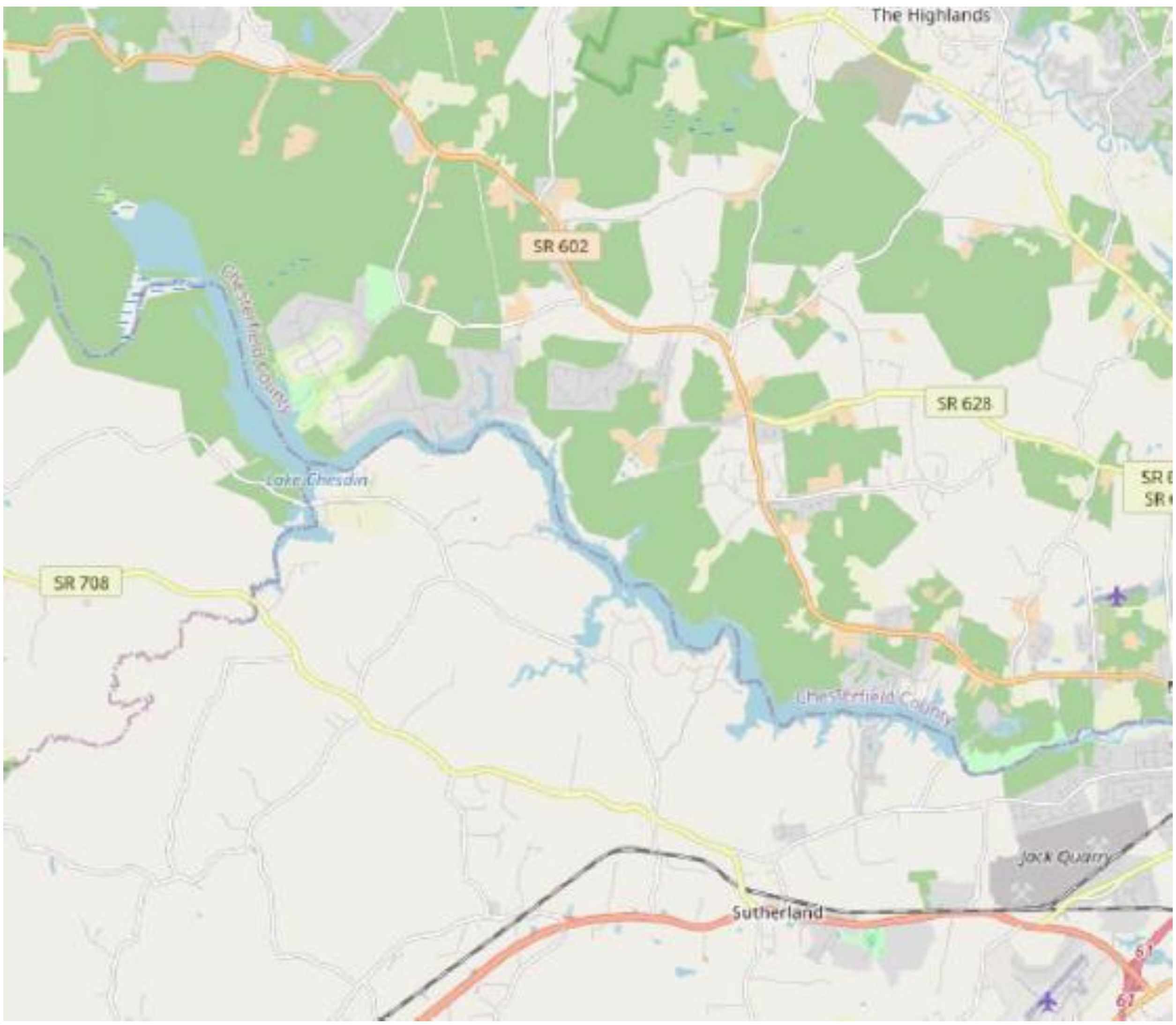
Prepared by:
Water Resource Services

APRIL 2024

Introduction

Chesdin Reservoir is an impoundment of the Appomattox River west of Petersburg, Virginia (Figure 1) and is a potable water source managed by the Appomattox River Water Authority (ARWA). The reservoir covers about 3100 acres with a deep (15+ feet) central channel and many shallow side channels and coves, often where small tributaries enter. Travel time from the western end of the reservoir to the dam at the eastern end is less than a week. There are multiple residential developments along the roughly 13-mile length of the reservoir. Private property along the shore does not extend lower than an elevation of 164 feet above sea level, while the top of the dam is at 158 feet above sea level, so the bottom of the reservoir and a variable buffer zone along its banks is not in private ownership. Chesdin Reservoir is also a popular recreational waterbody, especially for fishing, with both public and private boat launches and multiple access points, including a fishing pier.

. Figure 1. Overview of Chesdin Reservoir area



Hydrilla was found in Chesdin Reservoir in 2018 but was undoubtedly present in its upper reaches for some years prior. The distribution of hydrilla was mapped in 2019 by Golder, with coverage extending to about 560 acres (Figure 2, Table 1). Most of that coverage was very dense but also located in the farthest upstream third of the reservoir. Infested areas further downstream tend to have lower densities of hydrilla and are all coves or inlet areas, including Cattle Creek, Stoney Creek, Miry Run, an unnamed tributary cove between Whipponock Creek and Miry Run on the south side, and another unnamed tributary cove between Cattle and Stoney Creeks on the north side, as reported by Golder. Hydrilla has not been found in the rocky nearshore area of the downstream two thirds of the reservoir, with only a few coves exhibiting growths. Hydrilla has so far been absent over the downstream third of the reservoir, but downstream colonization is possible where substrate is hospitable and light penetrates to the bottom of the reservoir.

Figure 2. Distribution of hydrilla in Chesdin Reservoir, August 2019.

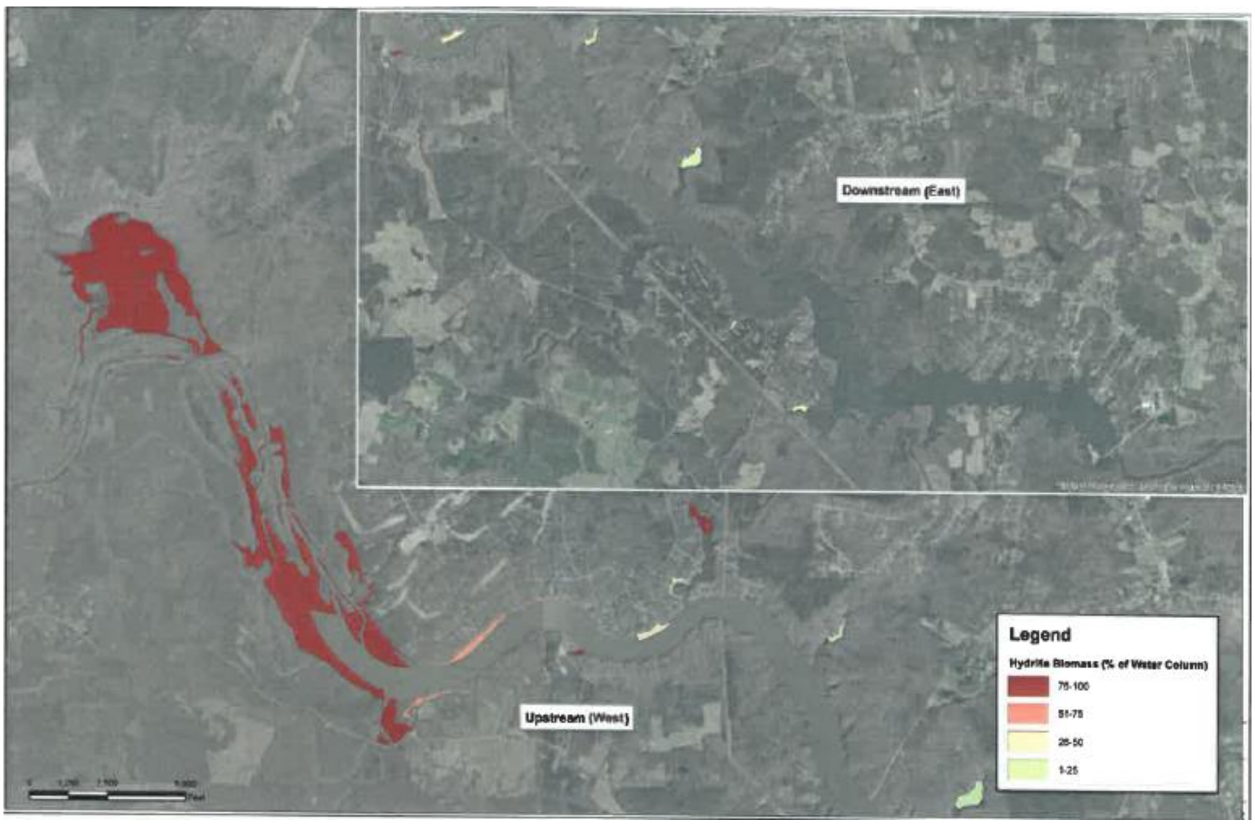


Table 1. Density and coverage of Chesdin Reservoir by hydrilla.

Total Area Impacted 560 Acres		
% Biomass	Acres	%Area
1-25	22	4
26-50	5	1
51-75	21	4
76-100	518	91

Hydrilla verticillata (hydrilla) is a submerged aquatic perennial plant. The roots of hydrilla are long and thin, typically whitish to light brown in color. Roots are usually buried in the hydrosoil but may form adventitiously at nodes. Stems are ascending and heavily branched near the water surface but horizontal and creeping under the soil. Stems of hydrilla can reach a length of 8.5 meters (m) but most growths tend to occur in shallower water. Turions are formed infrequently in the axils of the leaves on the upper part of the stem, while tubers are formed on subsoil stolons. Leaves are narrow, 1-2 cm (0.4-0.8 inches) long, and whorled around the stem in groups of 4-8. On the lower stem, leaves may be opposite in arrangement. The leaf margins are serrated, visibly to the naked eye. Flowers are unisexual, less than 6 mm in diameter, and translucent to white in color. Two biotypes of hydrilla plants occur, dioecious and monecious. Flowers of only one sex are produced on dioecious plants, while monecious plants produce both male and female flowers. Male flowers grow on a short stalk and are free floating at maturity. Female flowers are composed of six colorless segments and are 1.2 to 3.0 mm (0.05 to 0.12 inches) long. Fruits of hydrilla are cylindrical in shape and 5 to 10 mm (0.2-0.4 inches) long. The hydrilla in Chesdin Reservoir is reportedly monoecious hydrilla.

Hydrilla grows under a wide range of environmental conditions. It usually grows in shallow waters but can grow at depths up to about 10 m (33 feet). Hydrilla grows in both acidic and alkaline environments and at trophic levels ranging from oligotrophic to eutrophic. Although hydrilla can grow on almost any type of substrate, it grows best on sediments with high organic content. Hydrilla is adapted to grow under very low light conditions and can quickly dominate native vegetation. Hydrilla can also tolerate a wide range of temperatures and is reportedly winter-hardy, although hydrilla in Virginia tends to die back over the winter and regrow from roots, turions, or tubers.

Hydrilla is well adapted to rapid spread and growth due to multiple modes of reproduction. Pollination occurs above the surface of the water and its seeds develop into hypocotyles up to 6 mm (0.25 inches) in length. The hypocotyle produces a short stem at the node along with 3 leaves and a few roots. Hydrilla can also reproduce from roots, turions, tubers, and vegetative nodes. Entire colonies can be formed from one single node which can produce adventitious roots and start new growths. A single germinated tuber can produce a plant that yields more than 6,000 new tubers per square meter (10.8 square feet).

The invasion of Chesdin Reservoir represents a change in habitat that most lake users will find objectionable. Swimming and boating uses may be substantially impaired, and while hydrilla growths may be preferable to no plants at all for fish and wildlife, the reduced diversity of plants and extremely high density achievable by hydrilla represent undesirable shifts for many species of fish and wildlife. Hydrilla may increase the organic content of water upon winter die off, and water intake clogging can occur if dense growths reach an intake area. However, hydrilla in the farther reaches of any reservoir tends not to represent a threat to raw water quality for supply purposes and may actually act as a filter for sediment and many contaminants entering the reservoir from its watershed. The tendency of hydrilla to colonize soft sediment in inlet coves stabilizes that sediment and may actually improve the quality of runoff entering from the watershed, especially from developed or agricultural areas.

Therefore, from the perspective of the ARWA, hydrilla is not nearly the threat to its operation as it would appear to be to other lake users. The ARWA recognizes the impairments to other uses besides water supply and is willing to support reasonable control efforts, but those efforts cannot risk impairment of the water supply. Further action therefore must consider all implications of any chosen hydrilla control technique.

Alternatives for Hydrilla Management

There are many possible approaches to plant control in general, but only a portion of these apply to hydrilla, and actual applicability is dependent on specific conditions in the target waterbody. Table 2 provides a listing of plant management techniques, with mode of action, major advantages and drawbacks, and a brief assessment of applicability to the hydrilla situation in Chesdin Reservoir. Inapplicability results from:

1. The method is not effective for hydrilla, although it may be effective against other species.
2. The method is not allowed or advisable in a potable water supply as a consequence of impact on drinking water quality.
3. The technique has impacts on other uses of the reservoir that make it unattractive.

All techniques have benefits and disadvantages, but many are simply not applicable or not appropriate, as outlined in Table 2. Cost is not used as a criterion here but will certainly affect the choice of potentially applicable control methods. Methods that have distinct technical potential for managing hydrilla in Chesdin Reservoir include:

1. Benthic barriers on a localized scale, to facilitate access by boats to deeper water, create boating lanes in shallow areas infested with dense hydrilla growths, or prevent growths in shallow areas intended for swimming.
2. Dredging, either peripherally under dry conditions created by a drawdown or wherever desired hydraulically with the reservoir at full level, to remove hydrilla and all reproductive parts from a target area.
3. Application of fluridone (Sonar), an herbicide that is effective against hydrilla and is approved for use in drinking water supplies with limited restrictions.
4. Application of diquat, an herbicide that is effective against hydrilla and can be used in potable water supplies where travel time to an intake is more than 3 days.
5. Application of florpyrauxifen benzyl (ProcellaCOR), an herbicide that can control hydrilla at the higher end of allowable concentration and is approved for use in drinking water supplies, although there may be irrigation restrictions.
6. Stocking of grass carp, a fish that eats plants including hydrilla, and could consume enough over several years to limit hydrilla densities to an acceptable level.

While hydrilla control may be possible with these applicable methods of hydrilla control, each has limitations that create issues for use in Chesdin Reservoir. Benthic barriers have no expected impact on the water supply but would only be applicable on a localized basis; widespread control of hydrilla would be cost prohibitive and logistically difficult. Dredging is very costly and will cause major (but temporary) disruption where applied. Unless dredging to a hard substrate is very thorough, regrowth of hydrilla can be expected, although probably at lower density. All of the herbicides would likely require sequestering target sites to avoid impact to water supply,

Table 2. Options for control of macrophytes with applicability to hydrilla in Chesdin Reservoir

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
Physical Controls				
1) Benthic barriers	♦ Mat of variable composition laid on bottom of target area, preventing growth ♦ Can cover area for as little as a month or permanently ♦ Maintenance improves effectiveness	♦ Highly flexible plant control ♦ Reduces turbidity from soft bottoms ♦ Can cover undesirable substrate ♦ Can improve fish habitat by creating edge effect	♦ 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	♦ Highly applicable on a localized basis; could allow for boat access through dense vegetation with limited maintenance, but rarely used on a large scale, due to cost and logistic considerations.
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 build up underneath ♦ Panels may be flipped in place or removed for relatively easy cleaning or repositioning	♦ Allows some growth through pores ♦ Gas may still build up underneath in some cases, lifting barrier from bottom	♦ Appropriate, but will allow some growth through pores; plant fragments may land on screen and root down through it.
1.b) Non-porous or sheet synthetic materials	♦ Laid on bottom and anchored by many stakes, anchors or weights, or by layer of sand ♦ Some types can be removed, but also 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 can make removal difficult and can hinder maintenance	♦ Appropriate, but may need slits to vent trapped gases; probably more suitable to boating access or swim areas in this situation.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
1.c) Sediments of a desirable 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 and propagules can be buried ♦ Sediment can be made less hospitable ♦ Nutrient release from sediments may be reduced ♦ Surface sediment can be made more appealing to humans ♦ Reverse layering requires no addition or removal of sediment	♦ Lake depth may decline ♦ Sediments may mix with underlayment ♦ Permitting for added sediment difficult ♦ Addition of sediment may cause initial turbidity ♦ New sediment may contain nutrients or other contaminants ♦ Generally too expensive for large scale application	♦ Would reduce reservoir volume and hydrilla is likely to regrow unless gravel or rock is used. Not likely to be permitted and generally impractical at needed scale.
2) Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area ♦ 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	♦ 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 uses during dredging ♦ Usually very expensive	♦ Highly applicable; removes plants and related propagules, deepens reservoir, removes accumulated contaminants; primary impediment will be cost.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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	♦ Working under “dry” conditions with a drawdown would be challenging in impoundment, but could use barriers to sequester area, drain, and dredge.
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 ♦ Sediment deposition in surrounding area ♦ Normally requires containment area to dry sediments prior to hauling ♦ Severe disruption of ecological function ♦ Lake uses impaired during dredging	♦ Generation of turbidity and spread of hydrilla likely unless area sequestered. Generally not a desirable approach in an active supply reservoir.
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	♦ Applicable where water level control is inadequate to allow work under dry conditions. Flexible application over space and time. Primary consideration is need for dewatering area and quality of return water.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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	♦ Would impede recreation and alter aesthetics; possible negative consequences for water supply, either perceived (dyes) or actual (boating interference or oxygen issues under covers).
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	♦ Where problem plants occupy maximum area possible, this is akin to mowing the lawn and can be effective for maintaining uses. Where hydrilla distribution is limited, mechanical harvesting will encourage spread.
4.a) Hand pulling	♦ Plants uprooted by hand ("weeding") and preferably removed	♦ Highly selective technique	♦ Labor intensive ♦ Difficult to perform in dense stands	♦ Not well suited to hydrilla removal, density too high in most areas to be effective.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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 re-growth ♦ Leaves cut vegetation to decay or to re-root ♦ Not selective within applied area	♦ Ability of hydrilla fragments to re-root negates effectiveness of this option; will spread plant.
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 ♦ Not selective within applied area ♦ More expensive than cutting	♦ Appropriate on a maintenance basis, but not completely efficient at collection. Applied where target plants are already occupying most of possible area. Threat of spread is high.
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	♦ Creates high turbidity, unlikely to control hydrilla growths for more than a year.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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	♦ Largely inapplicable. Less effective than harvesting with collection, similar impacts to cutting without collecting, but with high turbidity generation.
5) Water level control	♦ Lowering or raising the water level to lower suitability for aquatic plants ♦ Disrupts plant life cycle by drying/ freezing, or light limitation	♦ Requires only outlet control to affect large area ♦ Provides widespread control in increments of water depth ♦ Complements dredging and flushing	♦ Potential issues with water supply ♦ Potential issues with flooding ♦ Potential impacts to non-target flora and fauna	♦ Drawdown could kill plants but not tubers. Rise in water level not likely effective. Current fluctuations not having known impact
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	♦ 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 emergent wetlands ♦ Possible effects on overwintering reptiles and amphibians ♦ Reduction in potential supply ♦ Alteration of downstream flows ♦ Possible overwinter water level variation ♦ May result in greater nutrient availability for algae	♦ Long term alteration of sediment features through drawdown may limit plant growths but could take several decades. Direct impacts on plants possible, but germination of new plants from tubers expected. Inexpensive option, with limited potential and possible impact on water supply

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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	♦ Issues with peripheral private property limit water level rise; would not eliminate problems with peripheral growths in shallow water, which are the primary problem in this case.
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	♦ 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	♦ Issues with real or perceived impacts on water quality in a drinking water supply limit applicability. Only a few herbicides approved for use in potable supplies, but applicable to gain control. Likely to need to sequester target areas and monitor downstream concentrations

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
6.a) Forms of copper	♦ Contact herbicide ♦ Cellular toxicant, suspected membrane transport disruption ♦ Applied as wide variety of liquid or granular formulations	♦ Moderately effective control of some submersed plant species ♦ More often an algal control agent	♦ Toxic to aquatic fauna as a function of concentration, formulation, and water chemistry ♦ Ineffective at colder temperatures ♦ Copper ion persistent; accumulates in sediments	♦ Some impact on hydrilla, but used more often to kill associated algae and make plants more susceptible to other herbicides.
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 recommended dosages ♦ Rapid action	♦ Non-selective in treated area ♦ Toxic to aquatic fauna (varying degrees by formulation) ♦ Time delays on use for water supply, agriculture and recreation ♦ Safety hazards for applicators	♦ Inappropriate for use in potable supply.
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 ♦ Rapid action	♦ Non-selective in treated area ♦ Toxic to zooplankton at recommended dosage ♦ Inactivated by suspended particles; ineffective in muddy waters ♦ Time delays on use for water supply, agriculture and recreation	♦ Can be used in potable supplies with limits, but usually kills only the contacted portion of plants; regrowth will occur within a year in most cases; likely to need to use repeatedly

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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 emersed 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 water intakes ♦ Highly corrosive; storage precautions necessary	♦ Not effective against hydrilla.
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 emersed, floating and submersed plants ♦ Can achieve some selectivity through application timing and concentration ♦ Fairly fast action	♦ Variable 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 water supplies	♦ Inappropriate for use in potable supply.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
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 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	♦ Most effective herbicide for hydrilla, used at <10 ppb, approved for use in drinking water supplies at least ¼ mile from intakes. Will not kill tubers, so repeated treatments necessary
6.g Amine salt of triclopyr (3,5,6-trichloro-2-pyridinyloxyacetic acid)	♦ Systemic herbicide ♦ 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 ♦ Selectively effective against dicot plant species, including many nuisance species ♦ Effective against several difficult-to-control species ♦ Low toxicity to fauna ♦ Fast action	♦ Impacts on non-target plant species possible at higher doses ♦ Current time delay of 30 days on consumption of fish from treated areas ♦ Necessary restrictions on use of treated water for supply or recreation not yet certain	♦ Not effective against hydrilla
6.h Forms of florpyrauxifen-benzyl (2-pyridinecarboxylic acid, 4-amino-3chloro-6-(4-chloro-2-fluoro-3-methoxy-phenyl)-5-fluoro-, phenyl methyl ester)	♦ Systemic herbicide ♦ Synthetic auxin, alters cell wall elasticity and gene expression, disrupts tissue formation, causes slow death ♦ Liquid sprayed on emergent/floating plants or injected into water column	♦ Effectively controls several invasive species ♦ Can be used selectively, more effective against dicotyledon plant species ♦ Low toxicity to aquatic fauna ♦ Limited exposure time needed	♦ Limited target species, higher doses limited by solubility ♦ Time delays on use of treated water for irrigation ♦ Mixed results on hydrilla, especially monoecious form	♦ Not as effective against hydrilla as fluridone, but allows treatment over shorter time period

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
6.i) Forms of flumioxazin (N-(7-fluoro-3,4-dihydro-3-oxo-4-prop-2-ynyl-2H-1,4benzoxazin-6-yl)-cyclohex-1-ene-1,2-dicarboxamide)	♦ Contact herbicide with limited translocation potential ♦ Blocks biosynthesis in several metabolic pathways, toxic porphyrins build up ♦ Damages cell membranes, physical structures	♦ Moderately to highly effective control of a variety of submersed and floating leaved species ♦ More effective on algae mats than many herbicides ♦ Fairly fast action	♦ Potential toxicity to aquatic fauna, depending upon formulation and ambient water chemistry ♦ Limited selectivity ♦ Time delays for use of treated water for agriculture and turf management	♦ Not typically used against hydrilla or in potable water supplies, multiple use restrictions (irrigation, fishing, livestock watering), not a good candidate for this case
6.j) Forms of imazapyr (2-(4-isopropyl-4-methyl-5-oxo-2-imidazolin-2-yl)-nicotinic acid)	♦ Systemic herbicide ♦ Inhibits acetolactate synthase (ALS), inhibits synthesis of amino acids ♦ Applied as liquid spray to emergent or floating leaved vegetation ♦ Causes slow death by structural deficiency	♦ Moderately to highly effective control of emergent and floating plant species ♦ Can be used selectively, based on application to individual plants ♦ Low toxicity to animals, which do not have ALS	♦ Non-selective in treated area ♦ Not for use within 0.5 miles of potable surface water intakes ♦ Potentially long delay for agricultural use after treatment	♦ Not effective on submerged hydrilla
6.k) Forms of imazamox ((±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1Himidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid)	♦ Systemic herbicide ♦ Inhibits acetolactate synthase (ALS), an enzyme involved in the synthesis of amino acids ♦ Applied as liquid to emergent, floating leaved, or submerged plants, ♦ Causes slow death by structural deficiency	♦ Moderately effective control of aquatic vegetation ♦ Extends control to submergent plants unlike the similar imazapyr ♦ Limited exposure time needed ♦ Low toxicity to animals, which do not have ALS	♦ Low selectivity in treated area ♦ Not for use within 1/4 mile of potable surface water intakes ♦ Potentially long delay for agricultural use after treatment	♦ Can be used against hydrilla, but with concentration limits within ¼ mile of any intake and substantial restrictions on use for irrigation; less applicable than other effective herbicides.

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES	APPLICABILITY
Biological Controls				
7) Biological introductions	♦ Fish, insects or pathogens which feed on or parasitize plants are added to system to affect control ♦ Grass carp most commonly used, but the larvae of several insects have been used 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	♦ Exercise caution; unintended consequences are very common with introductions of species new to aquatic systems. Potential control at acceptable level is possible for hydrilla, however.
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	♦ 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	♦ Grass carp used in other Virginia reservoirs, mixed results over about 20 years of application in the USA, will convert plant biomass into fish and algae, but could lower hydrilla density.
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	♦ Incomplete control likely; oscillating cycle of control and re-growth expected ♦ Predation by fish may complicate control ♦ Other lake management actions may interfere	♦ None known to be effective against hydrilla.

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	♦ None known to be effective against hydrilla.
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 ♦ May not prevent nuisance species from returning ♦ Introduced species may become nuisances	♦ A healthy native assemblage is more resistant to hydrilla invasion, but hydrilla is a superior competitor for space and light in most cases.

adding cost and interfering with access by boats for a week to several months. Keeping grass carp in a reservoir and getting them to consume hydrilla in target areas is challenging and stocking these fish may not be permitted by state environmental agencies as a consequence of impacts on non-target species within and possibly outside the reservoir.

Two overriding considerations apply to hydrilla control in Chesdin Reservoir:

1) There is no impetus for attempting to eradicate hydrilla. About 500 acres of upstream area is infested, control would be very difficult and costly, and no significant adverse impacts on the water supply have been documented. Areas that may be targeted for control are mostly side coves and there will be an ongoing threat of infestation in the downstream portion of the reservoir. Ongoing management need is therefore to be expected.
2) The quality of water entering the potable supply intake cannot be compromised by any hydrilla control action. The closer the target area to the intake, the higher the probability of impacts to water supply quality from hydrilla management efforts. Any action with the potential to alter water quality in any way deleterious to raw water quality will require controls and monitoring to ensure that the water supply is protected. If the risk is perceived as too high, such control actions may be prohibited.

Possible Application of Feasible Hydrilla Controls

Benthic barriers

The placement of sheeting materials on the reservoir bottom around docks and as access lanes to deeper water is a workable local solution for shoreline homeowners who want access for boats through hydrilla infested waters. Benthic barrier could also be used to create swimming areas where contact recreation is allowed. It is not a reservoir-wide control strategy, however, on the basis of cost, maintenance needs, and ecological impact, but can provide localized relief. Benthic barrier could be placed at nearly any time and will provide immediate relief, whereas most other options will require more time to implement. It is not practical to reclaim the large weed-choked upstream area of more than 500 acres with benthic barrier, and even the roughly 50-acre area in the middle third of the reservoir represents more area than benthic barrier is normally used to cover within a waterbody. Yet control in select areas where property owners abut the reservoir or public use is compromised by hydrilla growths could be achieved, allowing recreational access.

Considerations for the use of benthic barrier are covered in Appendix A. A cost of approximately $1 per square foot of area covered should be assumed. Various materials are available, but a non-porous barrier such as Lake Bottom Blanket would probably work best in Chesdin Reservoir. Such a barrier comes in a 10-foot width at variable length, with a 100 ft length being about the maximum that can be easily placed and retrieved for cleaning. Such non-porous barriers can usually remain in place for two years before cleaning is needed. Cleaning does not have to include removal and re-installation, but that approach offers the best results.

Use of benthic barrier presents no significant risk to the water supply. Low oxygen can develop under the barrier but any effects would be dissipated over very short distances from the barrier. No chemicals are leached from barriers and minimal water volume is displaced. As long as the barrier remains in place and is periodically cleaned to avoid sediment build-up, it should prevent hydrilla (and other plant) growth. Barriers have lasted for more than a decade, so the long-term cost is favorable despite an initially high capital investment.

Dredging

Removal of sediment holds the greatest promise of restoring desirable conditions in the reservoir. Plants, root systems, tubers, turions, and seeds are all removed, and the uncovered sediment may be less hospitable to future growths. Depth is added, possibly limiting growths through reduced light penetration to the bottom. While ecologically disruptive, dredging can set a target area back in time and biological recovery can result in more desirable features. There are a number of possible impediments to dredging, however, and the cost is usually very high. Appendix B contains substantial supplemental information about dredging for anyone considering a possible dredging project.

The main impediments to dredging are cost and possible environmental impacts. Sediment quality must be evaluated before dredging can be implemented in any aquatic system and will affect disposal options and therefore cost. Sediment should not be allowed to leave the area in suspension, moving downstream toward the supply intake, so it may be necessary to place turbidity curtains around any work area. As most target areas of hydrilla infestation are coves with inlet streams, control of inflow may be necessary during actual dredging, typically by diverting flows around the work area. Cost is a large deterrent to dredging; a low-end cost of $30 per cubic yard, or $50,000 per acre-foot, is to be expected. Cost will escalate quickly where the work site requires more advanced sequestration (like portodams) or the sediment is contaminated and requires special disposal, typically on the order of $100/cy.

While thorough dredging should eliminate hydrilla from an area and create a substrate limitation that may reduce the density of any subsequent plant growths, re-infestation by hydrilla will remain possible by virtue of upstream growths which are not targeted for control. If soft sediment accumulates to just a small extent in a dredged area, most likely from watershed inputs through associated small tributaries, hydrilla density could resurge. The high cost of dredging with the threat of re-infestation makes dredging less attractive as a hydrilla control method.

Fluridone application

Maintaining a concentration of the herbicidal compound fluridone of 6-10 ppb for at least 60 days would kill any exposed hydrilla. Getting 100% kill is very difficult to do under any circumstances, but the maximum damage is done when a lethal concentration of fluridone (>6 ppb) is maintained for the first half of the growing season. Maintaining the desired concentration is a function of initial and any subsequent inputs of fluridone versus losses due to flushing, photodegradation, and uptake. Monthly booster treatments are typically necessary, as the half-life is normally around 40 days even without flushing, and the maximum concentration that would be applied in a potable water supply is 20 ppb. Additional information is supplied in Appendix C.

For isolated areas of hydrilla, it may be preferable to use a granular formulation that will gradually release fluridone near the target plants and limiting the volume of water treated. Booster treatments are still likely to be necessary, and the frequency will increase where there is a tributary that contributes dilution water unless the tributary can be routed beyond the treatment area. As fluridone is very diffusive, sequestering a target area with a curtain that extends from the water surface to the sediment is advisable to maintain the desired concentration for as long as possible. With a downstream potable supply intake, it may become even more important to sequester the target area, unless dilution is documented to be adequate to reduce fluridone to non-detectable levels over the distance between the treatment area and the intake. Fluridone concentration can be monitored fairly easily and monitoring within the target area and downstream towards the water supply intake would be necessary to proper use of this herbicide in Chesdin Reservoir.

Even with proper exposure to fluridone in any one treatment, random germination of tubers or turions over most of the year can necessitate repeat treatments over multiple years to gain the desired level of control. Eradication is very rare, and the use of herbicides in drinking water supplies creates negative public perceptions of water quality, despite regulatory approval when granted. Fluridone provides a potentially effective means to get initial control over hydrilla, but that control is unlikely to last without follow-up, and repeat use of fluridone (or any herbicide) will require a strong public relations campaign. In the case of Chesdin Reservoir, a large, uncontrolled, upstream population of hydrilla will present the threat of re-infestation, so use of fluridone (or any herbicide) is not likely to be a one-time event even where control within a target area is complete.

Diquat application

Diquat is known as a contact herbicide, killing parts of a plant into which it comes into contact, mainly leaves and stems. Where that is the case, regrowth from roots as well as from seeds or other reproductive structures is to be expected. Regrowth from roots often occurs with a month or two. This has made diquat and other contact herbicides less desirable for plant control, but more recently there have been studies indicating that diquat exhibits some systemic properties, killing root systems as well as vegetative parts in the water column at lower doses. It appears that the differentiation between systemic and contact herbicides is a gradient, not a hard line, and lower dose treatments with diquat can provide greater control of some species than previously expected. Hydrilla falls into this category, with some recent diquat treatments demonstrating more complete control.

Diquat is less expensive than herbicides considered to have greater systemic activity, including fluridone and ProcellaCOR, and requires a lower contact time than at least fluridone. Diquat would provide the most rapid and least expensive control of hydrilla. Additional information is supplied in Appendix C.

Diquat will still not affect fully developed tubers or turions, so where hydrilla has become established, repeated treatments over a period of years is to be expected. This creates some risk to water supply quality and will foster a negative impression of water quality that would need to be tempered by public education and monitoring to demonstrate a lack of impact on water quality.

Water treated with diquat will have use restrictions that vary by applied concentration. Irrigation use is not allowed for 1-5 days, while potable consumption is not allowed for 1-3 days. Treatment of currently infested areas of Chesdin Reservoir is most likely to involve an applied concentration near the lower range for diquat applications and would likely be more than a day of travel time from the water supply intake, but to ensure no impact it would be appropriate to sequester treatment areas for up to one week. Testing of how much diquat leaves the treatment area and how far it travels how fast should be conducted and may allow lesser control of dose and sequestration if results are favorable.

ProcellaCOR application

Florpyrauxifen-benzyl, known as ProcellaCOR, its sold tradename to date, is a relatively new herbicide that can control a range of invasive species and does not require the extended contact time necessary for desirable results with fluridone. Hydrilla is listed as a species that can be controlled, but only at the high end of the applied concentration range for this herbicide. Experience to date has been mixed with some indication that ProcellaCOR is less effective on monoecious hydrilla than the dioecious form. Appendix C contains additional information about this herbicide.

As a systemic herbicide, ProcellaCOR should kill entire plants but will not affect fully formed turions or tubers, so where hydrilla has become established, it is likely that multiple treatments over a period of years will be needed even if individual treatments are effective. As with any herbicide, this creates a negative impression of reservoir water quality that must be managed through education. Actual impacts on water quality may be minimal, but greater monitoring to document water supply safety will be needed.

Sequestering target areas may not be necessary to achieve some level of hydrilla control, but such sequestration with curtains may be needed for maximum control and may be necessary to ensure a lack of impact on water supply quality. As ProcellaCOR requires a lower necessary contact time, sequestration could be terminated after less time than necessary for fluridone treatment, but some monitoring would be needed to document achievement of low levels that would not represent any threat to water supply quality. It is not clear that the reduced need for sequestration offsets the apparent lesser effectiveness of ProcellaCOR than fluridone for hydrilla control.

Grass carp addition

Stocking herbivorous fish has the potential to reduce hydrilla densities markedly and to keep them low with relatively little maintenance over at least five years. With biological controls, however, variability in results can be substantial, and oscillations of target populations are often observed. Getting the right density of grass carp is difficult; too few fish will not achieve control, while too many fish can eliminate all plants (temporarily) and lead to starvation or emigration of the grass carp and loss of control. Stocking over several years to build to the right fish density and set up multiple year classes of fish is a logical course of action but has not been successfully achieved anywhere yet. Even if control is achieved, as hydrilla is consumed, grass carp excrete nutrients that can fuel algal blooms, particularly cyanobacterial blooms. Properly managed, a grass carp program could lower hydrilla density to an acceptable level, but eradication is unlikely, and the trade-off will be an increased probability of algal blooms. Contingencies for control of algae and management of taste and odor may be necessary. Appendix D contains additional information about the use of grass carp for rooted plant control.

Efforts to use grass carp in Swift Creek Reservoir and Lake Gaston have been well documented. Hydrilla has not been eradicated in Lake Gaston, and herbicides have been used for supplemental control. Problems with filamentous cyanobacteria mats (Lyngbya) have arisen, possibly linked to hydrilla control efforts. Protection of desired plant assemblages has been found to require carp exclusion techniques to avoid loss of desired plants.

Grass carp have been the only hydrilla control applied to Swift Creek Reservoir, with varied success over the last 14 years. The goal of the Swift Creek Reservoir program has been to control hydrilla using the sterile grass carp to establish an ecosystem with a balance between aquatic plants and the biota found in healthy lakes and reservoirs. A mathematical model has been developed to determine proper grass carp mass to reach a 10 to 20 percent bottom coverage by hydrilla. Two major floods confounded this effort and disrupted the known grass carp biomass due to loss of fish over the dam. Overstocking grass carp in three years caused unintentional complete collapse of the plant community as well as hydrilla suppression. The ability to control hydrilla on a reservoir-wide scale was demonstrated, but the goal was not to collapse the entire plant community while controlling hydrilla, and nearly complete loss of plants has caused grass carp to starve or seek to leave the reservoir.

Resurgence of hydrilla has occurred after each plant community collapse within about 3 years. Increased algae, particularly cyanobacteria, has been documented, and while the water authority is well prepared to deal with more algae, management costs will increase as a result. Undesirable changes in the fish community of Swift Creek Reservoir have also occurred, although the addition of grass carp is not the sole cause. Chesterfield County Utilities constructed a carp barrier on the dam and are hopeful to recover from the flood damage and again approach the goal of a balanced ecosystem.

For Swift Creek Reservoir or any waterbody where control of hydrilla over nearly all the reservoir area is desired, grass carp represent a potentially valuable control agent, but management with biological controls is not easy and does not typically yield consistent results. As there is no intention to control hydrilla in the large upstream reaches of Chesdin Reservoir, this approach is less applicable. Where control in just localized areas is desired, grass carp will be less useful unless the area can be sequestered, and the grass carp can be contained in target areas.

Keeping hydrilla at a low density would involve stocking grass carp at a level that would suppress all vegetation, and keeping grass carp in selected target areas is virtually impossible. Stocking enough grass carp to suppress hydrilla over the whole reservoir would be expected to result in algae and related water quality changes unfavorable to potable water supply use, necessitating additional controls and/or treatment by the utility. The suppression of aquatic vegetation overall will create stress on stocked grass carp, resulting in attempts to leave the reservoir in search of food elsewhere. Floods have also resulted in downstream movement of grass carp, necessitating expensive outlet controls to keep grass carp in the target waterbody. Based on experience to date in Virginia, environmental agencies do not appear to be inclined to approve grass carp stocking in Chesdin Reservoir, creating a permitting challenge as well as management complications.

Recommendations for Hydrilla Control in Chesdin Reservoir

Given that a large area of hydrilla infestation within Chesdin Reservoir is not being targeted for control, increasing the risk of reinfestation of any managed area, and given that any control effort cannot be allowed to adversely affect water supply quality, the only hydrilla control technique that can be given an unconditional endorsement is the use of benthic barriers. Inert materials placed over areas of hydrilla growth offer effective and flexible control, limited maintenance needs, and minimal water quality impact. Barriers can be moved, removed, or reapplied as needed without any significant threat to water quality in the reservoir or concern over distance from the water supply intake. The cost is manageable for areas less than an acre but prohibitive over large areas. Benthic barriers are therefore a localized control, suitable for creating boating lanes or creating open water in shallow areas used for swimming or docking.

Alternative controls present issues with potential adverse impacts on water quality or low benefit to cost ratio where repeated application is expected. Probably the best alternative to benthic barriers is offered by herbicides containing diquat. Diquat is fast acting, has provided substantial control over hydrilla in other cases, and is less expensive than fluridone or florpyrauxifen-benzyl. Any of these three herbicides could be tried, but in each case, those involved should plan on sequestering the target area with a curtain to maximize exposure of hydrilla and minimize movement of the herbicide out of the target area. Testing for the herbicide outside the target area and, where detected, at distance intervals leading to the water supply intake, should be conducted to document containment or decay/dilution that prevents detectable herbicide from reaching the intake area. If it is found that herbicide is getting out of the treatment area at detectable concentrations within a quarter mile of the intake, later treatment should not be allowed. If it is found that no detectable herbicide is leaving the target area, treatment without sequestration, but with continued monitoring, could be considered. The presence of streams in target areas is likely to be an important factor in herbicide travel.

It cannot be assumed that a single treatment with any herbicide will provide lasting hydrilla control. The likely presence of seeds, tubers, and/or turions will allow hydrilla resurgence within a year in most locations and necessitate retreatment. Reinfestation from upstream is also likely. Consequently, any herbicide application will be a temporary solution and multiple applications represent a risk to the water supply. That risk may or may not be manageable, but where such use is desired, controls and monitoring will be needed at considerable additional expense and the likely negative public perception of herbicide use in a drinking water supply will require public outreach and reassurance that drinking water quality is being adequately protected.

Dredging could provide control of hydrilla and overall improvement of conditions in target areas, removing soft sediment that supports plant growth, harbors seeds, tubers and turions that allow hydrilla resurgence, demands oxygen from the overlying water, can contribute to turbidity with wind or wave action, and represents a loss of depth over original reservoir conditions. However, dredging is a very expensive endeavor with many possible adverse environmental impacts. A thorough evaluation of dredging feasibility is needed and controls on dredging are likely to be necessary to acquire permits to allow such a project to proceed. Ideally, a temporary dam could be created and the target area drained and allowed to dry, allowing conventional excavation equipment to remove sediment. Dredging under wet conditions or hydraulic sediment removal will require additional controls and expense and may not be feasible.

The potential for hydrilla to recolonize if dredging is not complete or even a small amount of sediment enters the area from the watershed makes dredging less desirable than most other techniques for the control of hydrilla at such a large cost. However, the improvement in overall conditions in any target area would be welcome if adverse impacts of the process can be avoided, permits can be obtained, and the large cost can be sustained.

Grass carp do not appear to be a viable option for Chesdin Reservoir. Feedback from environmental agencies has not been positive, given experience elsewhere, so this approach may not be permittable.

However, even if permits were granted, grass carp cannot be kept in target areas alone and supplying enough grass carp to make a difference throughout the reservoir would be expected to have negative water quality impacts unacceptable to the water supply function of the reservoir.

Appendix A: Benthic Barriers

How It Works

Benthic barriers, or bottom covers, limit light for rooted plants and create a physical barrier that restricts growth. Aquatic plant control by benthic barriers relies on the same concepts as "weed barrier" use in landscaping or gardening. Benthic barrier is usually used for two purposes: 1) to eliminate pioneer infestations of invasive species where localized collateral damage is acceptable and 2) to minimize aquatic vegetation in a small area designed for uses with which plants conflict (e.g., swimming or boat access).

Natural materials including clay, sand, and gravel have been applied to existing lake bottoms to create a layer of substrate less favorable to plant growth, although plants often root in these materials eventually, and environmental regulations make it difficult to gain approval for deposition of fill material. A variety of solid and porous barriers have been used to cover sediment and retard plant growth. Polyethylene, polypropylene, fiberglass, nylon, and various plastics have been developed over the last half century and experience has demonstrated efficient application approaches. Manufactured benthic barriers are negatively buoyant materials in sheet form which can be placed on the lake bottom to limit light, physically disrupt growth, and allow unfavorable chemical reactions to interfere with further development of plants and even mat-forming algae.

Porous weave benthic barrier (Aquascreen)

Barriers placed before significant plant growth has occurred can prevent such growths as long as the surface of the barrier does not support rooted plants. Placing barrier after seeds, turions, or winter buds have germinated but growth is limited can help suppress current growth and exhaust plant reserves, eventually leading to fewer plants when the area is uncovered. Placing barrier on mature plant growths may provide control but response is variable by species and there is an increased likelihood that plants will regrow after the barrier is removed.

Non-porous benthic barrier with sleeves for rebar weights (LakeBottomBlanket)

Benthic barriers can provide highly effective plant control on a localized scale. Benthic barriers are not selective and properly applied barrier can prevent nearly all forms of rooted plant growth and eliminate existing growths over one to two months. Once barrier is removed, recolonization will begin and renewed plant growth varies with time of year, plant species, and presence of seeds, turions or other reproductive forms in the previously covered area. Benthic barriers can be efficiently deployed in small areas such as dock spaces and swimming areas to minimize rooted plant growth. The creation of access lanes through dense plant growths and enhancement of structural habitat diversity with benthic barriers is also practical. It is unusual to apply benthic barrier to more than an acre or two in any one lake, however, because the cost of materials is high and application effort is substantial.

There have been difficulties with the deployment and maintenance of benthic barriers, limiting their effectiveness over the broad range of field conditions, but these can usually be avoided by proper planning and implementation. Problems of prime concern include long-term integrity of the barrier, "billowing" (i.e., lifting of the barriers off the bottom) caused by trapped gases, accumulation of sediment on top of barriers, and growth of plants on top of or through barriers. Successful use is related to selection of materials, the design and quality of the installation, and ongoing maintenance. Guidance for barrier use can be offered as a result of considerable experience:

- There is a trade-off between cost and barrier longevity; where a barrier is to be moved or removed for cleaning and replaced it is best to purchase strong material that will last for years.
- Porous barriers will be subject to less billowing but can still trap gas and will allow settling fragments of some plant species 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 if not properly vented and anchored; small slits or holes punched at regular intervals can alleviate gas accumulation.
- Plants under the barrier will usually die within a month, although two months of coverage achieves maximum plant reduction, 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 barriers restricts recolonization and germination from seeds, winter buds, or turions.
- Maintenance is needed to avoid plant growth on top of barriers; porous barriers will usually need annual cleaning, while non-porous barriers can usually go two years before cleaning is needed.
- Placing a single barrier panel is relatively easy and will provide plant control within its footprint, but placing multiple panels end to end or side by side greatly increases the needed effort, as lining up the panel edges can be challenging without using divers.
- Use of bricks, stones, small sandbags or other weights will hold the barrier in place but requires individual weight retrieval to remove the barrier for cleaning and maintenance; use of attached or built-in weights supports "one piece" manipulation but will make the barrier heavier overall and require more effort to handle or remove.
- Barrier width in commercially available products has typically been 7 to 14 feet and length has usually been between 25 and 100 feet; smaller pieces are easier to manipulate but having more pieces to place in an area increases the needed effort; balance application ease with desired coverage.
- Currently available barriers are durable and should last at least 10 years with proper installation and maintenance; most can be cut with a knife or scissors or punctured with sharp objects, but few can be ripped and nearly all will support some degree of foot traffic.
- Proper deployment may be difficult to accomplish over dense plant growth, particularly emergent plants with stronger stems; application in spring before plant growth becomes substantial requires less effort but must be conducted in cold water or with lowered water level.
- Unless the panel is in a frame that ensures it remains rigid along its edge, overlapping panels by about 6 inches is necessary to prevent plants from growing between panels.
- Sites with many stumps, boulders or other underwater obstacles are poor candidates for benthic barrier use, while sites with considerable sediment input may also be undesirable candidates.
- Areas subject to fluctuating water elevations, heavy boat traffic, or strong wave action may pose challenges to keeping the barrier flat and firmly affixed to bottom sediments.

Important considerations for the installation of benthic barriers include the need for nearly complete elimination of plants, size of the area to be treated, bottom features and possible obstructions, cost of the product, application and maintenance costs, and possible impacts to non-target organisms in the installation area. Proper deployment is a function of manpower and planning by the installer. Careful consideration of site conditions is essential to maximize effectiveness, as barriers must remain in place for at least a month to kill most target plants. Relocated barrier will require less maintenance, especially if flipped on reinstallation, although deployment effort may increase.

Benthic barrier with plants growing beyond its edge

Scuba divers normally apply barriers in water deeper than about 8 feet, which greatly increases labor costs. Most applications are in water <8 feet, however, and can be done by boat with support by snorkelers where panels need to be abutted or overlapped. Where drawdown is conducted, barriers can be placed in the drawdown zone prior to refill if the sediment supports foot traffic.

Where the barrier is to be applied and then weighted or staked in place, it can be rolled 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 and then staked or weighted. Where the barrier has attached weights when being deployed (e.g., rebar inserted in sleeves sewn into the barrier), it can often be folded accordion-style and paid out off a boat over the target area. With smaller barrier panels it is possible to flip the barrier in place or onto an adjacent area after at least a month, limiting maintenance and extending coverage within a season.

How long benthic barrier is left in place beyond the time necessary to kill target plants is a function of the use of the area in which it is installed and the type of barrier. Where barrier is placed in a beach setting in water shallow enough for people to stand, the barrier is often placed at least a month before swim season begins and is removed at the start of the season. People tend to prefer the feel of sandy natural substrate and foot traffic will continue to minimize plant growths, whereas in the absence of the barrier people tend to avoid areas where plants are growing. Where installed in deeper parts of swim areas, or around docks, or to create boating or swimming lanes to deeper water, installation for the whole use season is typical. Where an invasive species is targeted, barrier should be left in place long enough to ensure complete elimination of that target species, often approaching two months, with follow up actions to prevent its recolonization. In some cases, barrier is left permanently and is either cleaned in place or left to have plants grow on top of it where an invasive species has been eliminated and colonizing plants are desirable species.

Benthic barrier in a shallow swimming area in May, to be removed in June

Barriers can usually be removed in early August without significant plant growth before the end of the recreational season, allowing work to occur in warmer water and when lake-related labor is often more available. Some older forms of benthic barriers, such as burlap or felt-like materials, were never meant to be removed and fall apart easily after a few seasons; these and similar materials are not recommended for temporary installations.

Benthic barrier used to create a swimming lane in plant-infested water within a swim area

Benthic barrier can be installed by professional lake management firms but there is nothing especially technical or complicated in the installation and homeowners or knowledgeable members of lake associations, fishing organizations, or other conservation groups can handle installation if well organized. On a lakewide basis, it is best to coordinate among property owners and installation sites to achieve success most efficiently and it is advantageous to have one permit process cover all installations within a given waterbody.

Possible Benefits

- Complete elimination of plants in target area with proper application and maintenance.
- Most barrier materials are re-useable, allowing coverage of multiple areas over time with the same material.
- Creates edge effect, habitat diversity, and quality enhancement when portions of dense assemblages are covered.
- May foster an improved plant assemblage after removal, through naturally occurring seeds in the sediment or selective planting, but likely to require follow up actions like hand harvesting.

Possible Detriments

- Non-selective technique; all plants under a barrier will usually be killed.
- May kill non-mobile invertebrates under barrier.
- Low oxygen may develop under barriers and may allow release of reduced compounds from sediment, although upward transport is expected to be very limited.
- Eliminates access to sediment for fish and wildlife; could affect spawning and feeding.
- Effectiveness usually declines without labor-intensive maintenance.
- Invasive species may be as likely as native species to recolonize when barrier is removed without follow up effort.

Information for Proper Application

- Mapping of area to be covered by barrier, with information on plant types and density, portion of entire lake plant growth zone targeted, and type of barrier to be installed.
- 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.

Factors Favoring or Disfavoring the Use of this Technique

- Favored when the target area has dense plant growths of undesirable species that confict with designated use of the area (e.g., public swimming or boating access).
- Favored when the target area is small (<1 acre) and relatively free of obstructions (e.g., stumps, logs, boulders, pilings, and moorings).
- Favored where long-term control is sought over a small area with recognition of necessary maintenance needs.
- Favored where a desirable plant assemblage is expected to develop or can be encouraged by planting after barrier removal.
- Disfavored if the target area represents a substantial portion of the plant growth (littoral) zone for the whole lake (>10% is reasonable but the upper threshold may be dictated by the NOI OOC).
- Disfavored where barrier placement could negatively impact a protected species.
- Disfavored where there are many underwater obstructions or high sediment inputs.
- Disfavored in shallow water with strong wave action or intensive boat traffic.

Benthic barrier used to suppress invasive species along shoreline and in shallow water

Performance Guidelines and Monitoring Needs

- Map the vegetation and other resources in the target area; avoid barrier use over 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.
- Leave barrier in place for at least one month.
- Develop a maintenance program that monitors and maximizes barrier effectiveness; avoid gaps in targeted coverage, sediment accumulation, and rooting of plants through porous barriers.
- Monitor the plant community before and after barrier application.
- Monitor water quality above and near the barrier if the installation is large (>1 acre or >10% of littoral zone); focus on oxygen profiles and pH.

Appendix B: Dredging

How It Works

Dredging involves the removal of sediment. Conventional dry, conventional wet, and hydraulic/ pneumatic dredging are each addressed here, although planning and impact considerations will vary by approach. Dredging increases depth and restores lake volume where infilling from watershed erosion and organic inputs and/or internal generation of organic matter has occurred. Dredging can be an effective lake management technique for the control of excessive algae and rooted vascular plants by multiple mechanisms. Removal of organic sediment can reduce oxygen demand and improve the overlying water quality in multiple ways. Dredging may be considered true restoration, as it removes accumulated sediment and "re-sets" the lake to a less eutrophic state, although it does not address ongoing watershed sources and the collateral damage to lake biota can be substantial. Dredging of a small part of a lake, such as an inlet area where sediment accumulates, may have minimal adverse impacts and can prevent later problems as the sediment spreads into the rest of the lake. Dredging most of a lake could have major effects on biota that have to be balanced with the benefits of sediment removal.

Dredging is mainly conducted to recover depth in a lake, usually after sediment inputs from the watershed have accumulated to the point where habitat and lake uses have become impaired. Dredging on a large scale for other purposes, including reduction of nutrient reserves or plant control, is rarely conducted due to cost, impact, and permitting issues. The types of dredging, potential benefits and detriments within lakes, and many other application considerations are covered

Dredging increases depth and potentially changes the nature of the sediment-water interface. With increased depth a light limitation can be imposed, changing the types of plants (based on shade tolerance, pigment composition and related ecology) or the quantity of plants that will grow at the new, deeper depth. A dredging-mediated change to coarser substrate, usually sand and gravel but sometimes rock, will also limit plant growth and shift the assemblage to species able to establish roots in the new, coarser sediment. Where nuisance plant growths occur as a function of accumulation of hospitable sediment, dredging can limit such growths.

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.

Dredging for plant control will necessarily occur in the littoral zone, the area where light penetrates to the bottom and allows plant growth. This is a very active biological zone; the sediment is not a barren expanse of lake bottom, but rather a productive area with invertebrates living in or on the sediment, more invertebrates living on or among the plants, fish spawning, feeding, or seeking shelter among plants, and reptiles, amphibians, and birds all using the area as habitat. If the growths are invasive species or native forms at such a high density that human uses and habitat for some aquatic species are compromised, dredging can improve conditions, but the percentage of the littoral zone affected is an important consideration and not all impacts will be positive.

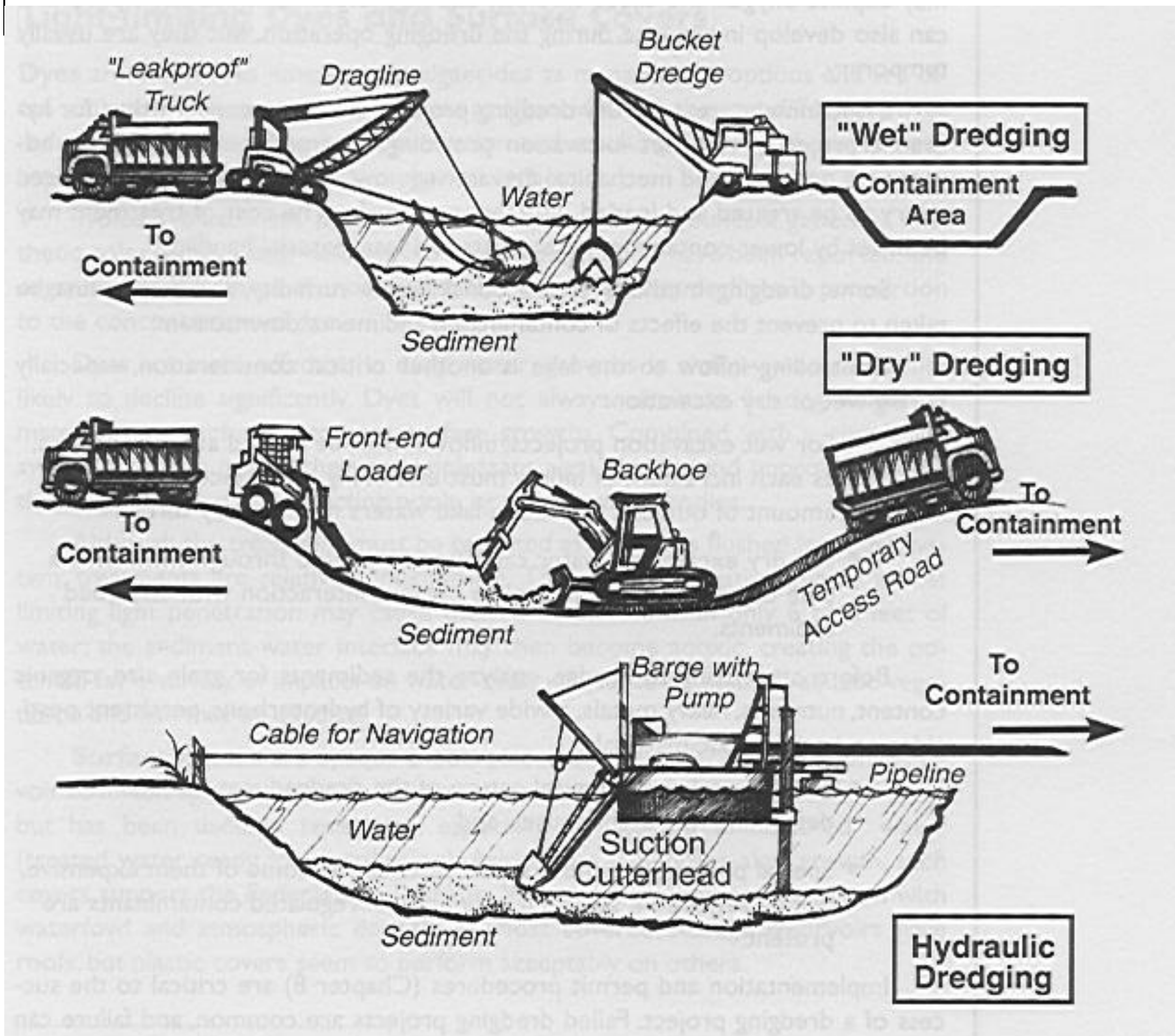
The removal of sediment by dredging can remove the plants themselves along with seeds, turions, winter buds, and root systems from which plants grow each year. This will effectively reset the dredged area in terms of plant community features, and what grows subsequently will be a function of the new conditions of depth and substrate, migration of plants from areas not dredged, new invasions, or active planting and other management to shape the plant community. The key rule in plant management is that where light penetrates to a hospitable substrate, plants will grow. If dredging limits light or makes the substrate less hospitable, fewer plants can be expected. Yet plants are integral to most properly functioning aquatic ecosystems and the encouragement of desirable plants is worth considering. Dredging can be a valuable component of an “aquascaping” program but does not constitute a complete program by itself.

The changes in types of plants will not always be beneficial; some invasive species and even some nuisance native species are able to grow at substantial depth and can grow on sandy to gravelly substrates. The density of any plant growth will likely be reduced as the water gets deeper and the sediment becomes coarser, but it is rare to removal all “soft” sediment and some regrowth is to be expected. The change in sediment features will have a strong impact on the invertebrate fauna, eliminating or diminishing habitat for some species. Shifts in plant and invertebrate populations will in turn affect use of the area by fish, reptiles and amphibians. The impact on water-dependent birds is highly variable; improved access through plant density reduction can be a benefit, while changing food resources may be a detriment. Habitat is an important consideration and large scale changes may not be acceptable.

As part of an overall plant control program that acknowledges the ecological value of the littoral zone, dredging must be complemented by additional actions. If plants have become overly abundant due to sediment inputs from the watershed, sources should be identified and addressed. This will be especially true where a delta forms at an inlet due to inadequate upstream erosion control. Dredging to remove accumulated sediment, particularly where it supports invasive species, should be accompanied by upstream work to minimize the need for future dredging. If a small area is dredged relative to the size of the littoral zone, undesirable impacts can be minimized unless the dredged area is a critical spawning site or other important and limited habitat type. Knowledge of the fish and wildlife associated with any area targeted for dredging is important to project planning and impact assessment. Yet where there is ample shallow water underlain by organic substrates and hosting dense aquatic plant communities, exposure of coarse substrate and reducing plant density in a limited area through dredging can improve overall habitat diversity and value.

Localized dredging projects usually seek to remove sediment from a target area like an inlet, cove, swim area or marina, while projects involving most of a lake are usually intended to enhance overall lake use, reclaiming depth, removing contaminated sediment, improving water quality, and/or controlling rooted plants or algae. It is generally better to remove all problem sediment from a smaller area than to remove just some of the material over a larger area, but getting all target sediment out of any area can challenging. Dredging usually targets “soft” sediment, typically synonymous with organic deposits or possibly sand or clay inputs from storm drains or tributaries. Knowing how much sediment to remove involves careful study and detailed testing of sediments for physical and chemical properties. There are many factors that govern dredging success, and a dredging feasibility study is usually necessary to cover the range of issues involved with planning, designing, and permitting a dredging project. Sediment quantity and sediment quality are the overriding influences on cost.

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



Key Considerations for Dredging

Reasons For Dredging:
Increased depth/access
Removal of nutrients/other contaminants
Control of aquatic vegetation
Reduction in oxygen demand

Volume Of Material Removed:
In-situ volume to be removed
Distribution of volume among sediment types
Distribution of volume over lake area (key sectors)
Bulked/dried volumes (immediately vs ultimate)

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

Dewatering Capacity of Sediments:
Dewatering potential
Dewatering timeframe
Containment needs

Regulated Resource Areas:
Wetlands (includes lakes)
MESA listed species
Areas of Critical Environmental Concern
Outstanding Resource Waters
Great Ponds

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

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

Uses Or Sale Of Dredged Material:
Desirable sediment alterations (value enhanced)
Possible beneficial uses
Possible sale

Existing and Proposed Bathymetry:
Mean depth
Maximum depth
Depth contours

Physical Nature of Removed Material:
Grain size distribution
Solids and organic content
Settling rate/residual turbidity
Bulking/drying factors

Chemical Nature of Removed Material:
Metals levels
Petroleum hydrocarbon levels
Nutrient levels
Pesticides levels
PCB levels
Other organic contaminant levels
Other contaminants of concern

Flow Management:
Possible peak flows
Expected mean flows
Provisions for controlling water level
Implications for dredging approach

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

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

Other Mitigating Factors:
Protective watershed management
Economic setting
Sociological setting
Political setting

Removal Costs:
Engineering and permitting costs
Dredging and dewatering costs
Disposal and monitoring costs

Dry dredging

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 lakes 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 of Dunn's Pond in Gardner with conventional excavation equipment

Control of inflow to the lake is critical during dry excavation; water can often be routed through the lake in a sequestered channel or pipe, limiting interaction with disturbed sediments. Even then, the material may need to be placed somewhere outside the lake to dry before ultimate disposal. If an excavated area or natural upland depression in available, one-step disposal may be facilitated, but most projects involve temporary and permanent disposal steps.

Dry dredging of Dunn's Pond in Gardner complete, with removal to "hard" bottom

Wet dredging

Wet dredging may involve 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 <30% solids unless sand and gravel deposits are being removed. Clamshell dredges, draglines, and other specialized excavation equipment are used in what is usually a very messy operation. Excavated sediment must usually be deposited in a sequestered area adjacent to the pond or into water-holding tanks or other structures until dewatering can occur. This approach is most often practiced when water level control is limited. This technique is applicable to ocean harbors but is usually not preferred in lakes other than small, isolated ponds unless there is no choice.

Clamshell dredge used in wet dredging operations

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 some bucket dredge designs greatly limit the release of turbid water and have been approved for use in potentially sensitive aquatic settings.

A more advanced form of wet dredging, hydraulic dredging usually involves a suction type of dredge with a cutter head. Agitation combined with suction removes the sediments as a slurry usually containing <20% solids by volume. 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 that can be augmented by polymer addition. The supernatant water can be released back to the lake or some other waterway with proper permitting. 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

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. A slurry can be pumped multiple miles along a suitable route with booster pumps if there is land to be reclaimed but cost factors often dictate having the containment area close to the lake.

Hydraulic dredging: large cutterhead barge

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.

Hydraulic dredging containment area for Nutting Lake in Billerica – empty (above) and full (below)

Pneumatic dredging

Pneumatic dredging, in which air pressure is used to pump sediments out of the lake at a higher solids content (>50%) is possible but not commonly employed and has not been used in New England. 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.

Possible 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 achieved.

- 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, especially lowered oxygen demand, for improved water quality.
- Opportunity to establish structures to enhance the fish community (dry dredging).

Possible Detriments
- All possible negative impacts of drawdown if the lake is lowered to facilitate dry dredging.
- Reduction or loss of benthic biological components where sediment is removed or disturbed.
- Altered food web, at least temporarily, but with possible long-term improvement.
- 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
Key factors include:
- Sediment quality, which will determine disposal options and cost.
- Sediment quantity, which determines disposal volume needs and greatly affects cost.
- What type of sediment is underneath the material to be removed.
- Sensitive biological resources and regulated resource types, which affect project goals and permitting.
- Ability to control the lake level and safely pass inflows, which affects choice of dredging method.
- Equipment access and related impacts.
- Dewatering and ultimate disposal areas, possible beneficial uses of dredged material.

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

Dredging is probably the most complicated lake management activity in terms of planning and permitting. Except at the smallest scale, it involves more testing, more approvals, and greater cost than any other in-lake action. Professional help is strongly advised when considering a dredging project, and a dredging feasibility study is almost always essential.

Factors Favoring or Disfavoring the Use of this Technique

- ♦ Favored where there is a justifiable need to increase depth in the lake.
- ♦ Favored where studies have demonstrated the impact of internal nutrient loading on the lake or the presence of other contaminants in the sediment that are impacting lake biota or uses.
- ♦ Favored where the oxygen demand by sediment is causing oxygen impairment in the water column.
- ♦ Favored where rooted plants, algal mats, or planktonic algae dependent on the surficial sediments are impairing recreation and habitat value.
- ♦ Favored where suitable, sufficient containment/disposal areas are available close to the lake.
- ♦ Disfavored where protected species or resource areas make it difficult to avoid adverse impacts from dredging.
- ♦ Disfavored where sediments are contaminated based on regulatory concentration thresholds and require special handling and disposal at increased cost.
- ♦

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

Dredging containment area in Menotomy Rocks Park in Arlington when full (above) and when restored (below) to previous activity field status

Performance Guidelines and Monitoring Needs

- ♦ Address the many considerations for dredging; 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 organic sediment.
- ♦ Remove sediment to expose inorganic material if plant control or reducing oxygen demand is a project goal.
- ♦ Restore or rehabilitate all access, temporary containment, and final disposal areas.
- ♦ Monitor downstream flows and water quality during dredging.
- ♦ Monitor water quality for any discharge from a containment area
- ♦ Monitor recovery of lake biota and in-lake conditions relative to project goals (e.g., depth increase, water clarity, plant control, water quality enhancement).

Appendix C: Herbicides

How It Works

Types of Herbicides

Herbicides, along with algaecides, are a subset of what are termed pesticides, substances that can be used to kill target organisms. Herbicides contain active ingredients that are intentionally toxic to target plants. Herbicides also contain auxiliary ingredients that aid application or increase effectiveness and which may or may not be toxic themselves. Consequently, different formulations may contain different percentages of active ingredient and various auxiliary compounds (also called adjuvants) that influence results, both intended and unintended.

Herbicides are typically classified as contact or systemic. Contact herbicides are toxic to plants 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, turions or other reproductive structures are also not likely to be affected, but with proper timing and multiple treatments, growths can be much reduced.

Systemic herbicides tend to work more slowly than contact herbicides because they need 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, turions, or other reproductive structures will require additional treatments as with contact herbicides, as previously formed reproductive structures are not impacted.

Many herbicides have both contact and systemic properties; definitive classification as contact or systemic is not completely reliable. For example, low dose treatment with diquat, considered a contact herbicide, may result in more complete plant death, while high dose treatment with triclopyr, a systemic herbicide, may kill the exposed plant tissues before enough herbicide can be absorbed and translocated to kill the root system.

Effects of herbicides

Active ingredients are intended to interfere with essential plant growth processes and cause structural or metabolic failure. Any plant subject to the process(es) under attack may be impacted, so herbicides are not highly specific in their targets from the perspective of mode of action. Plants within a genus and often within a family are likely to respond similarly. Plants of greater taxonomic dissimilarity may vary in their structural features and metabolic processes, such that differential impact from an herbicide is possible and therefore some specificity can be attained for some herbicides. Actual results will depend on many factors including: the concentration applied, the timing of application, plant density, and the nature of the assemblage where the application is made.

Results from experimental tanks at a research station where different doses are tested prior to registration of an herbicide should be a reasonable indicator of field results but cannot replicate all possible conditions and some variation in response is to be expected. The dilution and flushing offered by the target waters, the decay rate of the herbicide, and even the genetics of the target population of plants will affect results. Experience in MA provides practicable knowledge of the degree of control exerted by specific active ingredients over various target plant species, but variation is still to be expected.

Herbicides are intended to kill target plants. Advances in selectivity have been achieved through new or altered formulations, reduced dose, or timing and location of application. However, 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. More often the herbicide is matched to the dominant species, usually an invasive species, and the dose, timing, and location of application are set to limit inadvertent impacts to other species. 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. Application decisions are therefore a matter of perceived risk vs. reward and require a careful evaluation of resources and anticipated effects. Clearly stated and explicitly defined goals should be set with an appropriate monitoring program to provide actual data for results, determine if goals are met, and allow program adjustment as warranted.

Impacts to animal life can be direct, as with a toxic effect, or indirect, as with loss of oxygen when many targeted plants decay at once or the habitat is changed by loss of plants. Cases of fishkills relating to lowered oxygen from mass die-off of treated vegetation have been recorded, all related to contact herbicides used on dense plant assemblages. Direct toxicity has rarely been observed. Current treatment protocols applied by licensed applicators have been improved to minimize risk.
There does remain concern over possible toxicity, especially sub-lethal effects, for fish and wildlife exposed to herbicides at sensitive points in their life cycle. Not all life stages of all species have been studied and detailed monitoring of potentially affected populations is not routine. The impact on organisms with smaller body size (e.g, young birds, fish fry), high preening rates (e.g., muskrat, waterfowl), or high rates of transfer across membranes (e.g., gills for certain aquatic invertebrates) could be more severe than for other organisms and may go undetected. The risk from repeated treatments (i.e., annual or more often) would seem higher than for less frequent herbicide applications. The label dictates maximum rates of application for each herbicide, but caution should be exercised where sensitive life forms might be threatened by a planned treatment.

Where toxicity is not documented, the primary issue for herbicide treatments is change in habitat. There are aquatic and water-dependent organisms that are favored or disadvantaged by any mix of plant species at any given level, so any change in the assemblage from an herbicide treatment will benefit some species and not others. The scientific difficulty of documenting no loss of habitat for any species creates complications, but overall habitat value for the complete suite of species present or appropriate to the water resource can be improved with well-planned herbicide use. Where a change in the plant community of most or all of a lake is intended with herbicide use, more evaluation of habitat shifts may be required. It is a common policy that invasive species do not constitute “habitat” for fish and wildlife, but significant change of native plant assemblages must be viewed in terms of habitat alteration.

Herbicidal active ingredients, target species, and use restrictions

Active Ingredient	Common Aquatic Product Names	Primary Mode	Primary Target Aquatic Plants	Application and Water Use Restrictions
Copper	Komeen, Nautique, Harpoon, Current	Contact	Potamogeton, Vallisneria, Najas, more often for algae control	Maximum application rate = 1 ppm as Cu, treat no more than half the target waterbody with at least 14 days in between treatments. Contact with water and use for irrigation generally discouraged for 24 hr.
Diquat	Reward, Weedtrine, Diquat, Tribune	Contact	Wide range of aquatic plants, Myriophyllum, Potamogeton, Ceratophyllum, Najas, Elodea, Utricularia, Hydrilla	Maximum application rate = 0.5 gal/ac-ft, up to 2 gal/ac maximum = 0.4 ppm diquat cation. Treat no more than half target waterbody at one time with at least 14 days before any additional treatment. No restriction on fishing or swimming but up to 5 days until use for potable supply or irrigation can resume unless concentration is <0.02 ppm.
Endothall	Aquathol, Hydrothol	Contact	Wide range of aquatic plants, Myriophyllum, Hydrilla, Potamogeton, Ceratophyllum, Vallisneria, sometimes Chlorophyta (filamentous green algae)	Maximum application rate = 5 ppm as endothall acid. Treat no more than half the waterbody and not within 600 ft of any active potable water intake. Drinking water standard is 0.1 ppm.
Flumioxazin	Clipper, Propeller, Flumigard	Contact	Lemna, Wolffia, Hydrilla, Cabomba, Ceratophyllum, Najas, Myriophyllum, Potamogeton, Trapa, sometimes Chlorophyta (filamentous green algae)	Maximum application rate = 0.2 ppm as flumioxazin. Treat no more than half the waterbody, previously untreated areas may be treated after 10-14 days, but only one treatment per 4 years. No consumption, swimming, or fishing restrictions, but up to 5 days needed before water can be used for irrigation.
2,4-D	Navigate, Weedar, Clean Amine, Platoon, DMA4, Aquacide	Systemic	Myriophyllum, Trapa, Nuphar, Nymphaea, Brasenia; historically also Ceratophyllum, Persicaria, Utricularia, but rarely used in MA now	Maximum application rate = 2 gal/ac-ft = 1.5 ppm. No more than 2 applications/yr at least 21 days apart. Up to 7 days before water can be used for irrigation or concentration <0.1 ppm. Not typically allowed in waters where any connection to potable water intake or wells is possible.
Fluridone	Sonar, Avast, Fluridone	Systemic	Myriophyllum, Hydrilla, Cabomba, Najas, Elodea, Lemna, Wolffia, sometimes Potamogeton, Nuphar, Nymphaea, Brasenia, Vallisneria to reduce growth	Maximum application rate = 150 ppb, 90 ppb for ponds <10 ac, but most applications are <30% of maximum. Applied concentrations must be <20 ppb within 1320 ft of potable supply intakes. Irrigation of sensitive vegetation after 7-14 days or concentration <1 ppb. No restrictions for swimming or fishing.

Herbicidal active ingredients, target species, and use restrictions (continued)

Active Ingredient	Common Aquatic Product Names	Primary Mode	Primary Target Aquatic Plants	Application and Water Use Restrictions
Glyphosate	Rodeo, Round-Up Custom, Aquaneat, Glyphosate	Systemic	Emergent and floating leaved species, including Phragmites, Typha, Lythrum, Nuphar, Nymphaea, Brasenia, Nelumbo, Persicaria	Applied as a spray, usually 1-8% concentration with sticking agent added, 1 gal provides 4 lbs of glyphsosate in acid form with limit of 0.94 gal/ac, equates with maximum applicatio rate of 1.7 kg/ac or 421 mg/m2. Not to be applied within 1/2 mile of potable water intake. No restriction for use of water post-treatment.
Imazapyr	Habitat, Imazapyr, Ecomazypyr	Systemic	Emergent and floating leaved species, including Nuphar, Nymphaea, Nymphoides, Nelumbo, Trapa, Typha, Phragmites, Persicaria, emergent forms of Myriophyllum, but rarely used in MA due to irrigation restrictions and non-target impacts	Applied as a spray, 0.5-5% concentration with sticking agent added, 1 gal provides 2 lbs of imazapyr in acid form with limit of 0.75 gal/ac Cannot be applied within 1/2 mile of active potable water intake. Treated water cannot be used for irrigation for 120 days or until concentration is <1 ppb. No restrictions for swimming or fishing.
Imazamox	Clearcast, Imox	Systemic	Emergent or floating leaved species, including Phragmites, Typha, Nuphar, Nymphaea, Nelumbo, Nymphoides, Persicaria, Brasenia, Trapa, emergent forms of Myriophyllum	Maximum application rate = 0.5 ppm. Also applied as 1-5% spray for emergent vegetation with limit of 1 gal/ac = 1 lb/ac in acid form. Not to be applied within 1320 ft of active potable intake and concentration must be <50 ppb at any intake for use. No irrigation use until concentration is <1-50 ppb, depending on vegetation type. No restriction for swimming or fishing.
Triclopyr	Renovate, Triclopyr	Systemic	Myriophyllyum, Nuphar, Nymphaea, Nelumbo, Brasenia, Lythrum, Phragmites, Persicaria	Maximum application rate = 2 gal/ac/yr = 6 lb active ingredient/ac/yr. Can be applied as spray or injected into water. No irrigation use until concentration is <1 ppb or 120 days after treatment. No restrictions on potable water use, swimming, or fishing.
Florpyrauxifen-benzyl	ProcellaCOR EC	Systemic	Myriophyllum, Nymphoides, Nelumbo, Brasenia, Hydrilla, Trapa, Certatophyllum, but only EC formulation registered for use in MA and applied only for Myriophyllum control	Maximum application rate = 0.13 lb/ac-ft treated (25 prescription dose units), but use in MA is <0.026 lb/ac (<5 PDU). Any additional application to same area after >14 days. No use for irrigation for up to 35 days. No restrictions for human potable consumption, swimming, or fishing. Use of treated water or composted, treated plants for livestock not recommended.

Effectiveness of herbicides on algae and non-native vascular plant species that may be the target of herbicide treatment

Functional Group and Genus or Appropriate Taxon	Scientific Name of Target Species	Common Name of Target Species	Diquat	Endothall	Flumioxazin	2,4-D	Fluridone	Glyphosate	Imazapyr	Imazamox	Triclopyr	Florpyraux-ifen-benzyl
Algae												
Chara/Nitella spp	Chara/Nitella spp	Muskgrass/Stonewort	P		P					P		
Chlorophyta	Chlorophyta	Filamentous green mats	P		P							
Chlorophyta, Chrysophyta	Chlorophyta, Chrysophyta	Planktonic algae										
Cyanobacteria	Cyanobacteria	Blue-green algae										
Non-Native Vascular Plants												
Submergent												
Cabomba	Cabomba caroliniana	Fanwort		P	C		C					
Egeria	Egeria densa	Brazilian waterweed	C				P					
Hydrilla	Hydrilla verticillata	Hydrilla	P	P	P		C					P
Myriophyllum	Myriophyllum aquaticum	Parrotfeather	C	P	P	C	P		P	P	C	C
	Myriophyllum heterophyllum	Variable watermilfoil	C	P	P	C	P				C	C
	Myriophyllum spicatum	Eurasian watermilfoil	C	C	P	C	C				C	C
Najas	Najas minor	Spiny/European naiad	C	C	P	P	C			P		
	Najas gaudalupensis	Southern naiad	C	C	C	P	C			P		
Potamogeton	Potamogeton crispus	Curlyleaf pondweed	C	C	C		C			C		
Utricularia	Utricularia inflata	Swollen bladderwort	C		C		C					
Floating leaved												
Nelumbo	Nelumbo nucifera	Indian lotus		P	P			C		P	C	C
Nymphoides	Nymphoides peltata	Yellow floating heart	C		P	P			P	P		C
Trapa	Trapa natans	Water chestnut	P		P	C	P	P	C	C	P	C
Emergent												
Lythrum	Lythrum salicaria	Purple loosestrife						C	C		C	
Phragmites	Phragmites australis	Common reed						C	C	C	P	
Key to herbicide effectiveness:	P = Partial - multiple treatments may be needed for more complete control. C = Control - while 100% control is rare, >90% control is expected.											

Effectiveness of herbicides on native vascular plant species that may be the target of herbicide treatment (continued)

Functional Group and Genus or Appropriate Taxon	Scientific Name of Target Species	Common Name of Target Species	Diquat	Endothall	Flumioxazin	2,4-D	Fluridone	Glyphosate	Imazapyr	Imazamox	Triclopyr	Florpyraux-ifen-benzyl
Native Species												
Submergent												
Ceratophyllum	Ceratophyllum demersum	Coontail	C	P	C	P	C			P		P
Elodea	Elodea canadensis	Waterweed	C				C					
	Elodea nuttallii	Slender waterweed	C				C					
Myriophyllum	Myriophyllum humile	Low watermilfoil	C	P	C	C	P				C	C
Najas	Najas flexilis	Bushy naiad	C	C	P	P	C			P		
Potamogeton	Broadleaf Potamogeton spp.	Broadleaf pondweeds	P	C	P		P			P		
	Thinleaf Potamogeton spp. (e.g., pusillus, berchtoldii, spirillus)	Thinleaf pondweeds	C	C	P		P			P		
Utricularia	Utricularia spp. (e.g., purpurea, macrorhiza)	Bladderwort	C				C			P		
Vallisneria	Vallisneria americana	Water celery	P	P			P					
Floating leaved												
Brasenia	Brasenia schreberi	Watershield			P	P	P	C	P	P	C	C
Lemna	Lemna spp (e.g., minor)	Duckweed	P		C		C					
Nelumbo	Nelumbo lutea	American lotus			P	P		C	P	P	C	C
Nuphar	Nuphar spp (e.g., variegata)	Yellow water lily			P	P	P	C	C	P	C	
Nymphaea	Nymphaea odorata	White water lily			P	P	P	C	C	P	C	
Nymphoides	Nymphoides cordata	Little floating heart	C		P	P	P		P	P	P	C
Persicaria	Persicaria amphibia	Water smartweed				P	P	C	P	P	P	
Wolffia	Wolffia spp. (e.g., columbiana	Watermeal	P		C		C					
Emergent												
Pontederia	Pontederia cordata	Pickerelweed	P					C	C	P	P	
Sagittaria	Sagittaria spp. (e.g., latifolia, graminea)	Arrowhead	P					C	C	C	P	
Typha	Typha spp. (e.g., latifolia)	Cattail	P					C	C	C	P	

Key to herbicide effectiveness: P = Partial - multiple treatments may be needed for more complete control. C = Control - while 100% control is rare, >90% control is expected.

Time of year of the application is an important consideration for efficacy of treatment for target species and impacts on non-target species. For example, glyphosate is used on emergent and floating leaved plants and will be more effective later in the season when plants are translocating food to the root system. Imazapyr, used on the same species, can be effective over a greater time range within the growing season but has greater non-target species impacts. As another example, fluridone is very effective on invasive Eurasian watermilfoil but requires a long contact time (60-90 days) which may be difficult to achieve near an inlet or in a lake with high flow through and short water detention time at the time of intended application (usually spring). Florpyrauxifen-benzyl (ProcellaCOR) also controls Eurasian watermilfoil and requires only a few days of contact time to be effective, which may limit the impact of flushing and dilution yet minimize impacts to other non-target species. The timing of treatment can matter to certain non-target organisms, such as species of pondweed that begin growth later or die back sooner than many invasive plant species or fish that spawn in a narrow time window in spring. Consultation with a licensed applicator, Certified Lake Manager, and/or state fish and wildlife agencies can be beneficial in evaluating options.

Control of submergent vegetation vs. nearshore emergent plants requires different approaches and poses different risks of impact. Submergent species are generally treated by herbicides added to the water while emergent species are most often treated with herbicides sprayed directly onto \plant surfaces above the water. Different fish and invertebrates, or at least different life stages of each, tend to utilize submergent species vs. emergent species, so exposure and risk of impacts varies. More herbicide enters the water with submergent treatments and more herbicide may wind up on non-target terrestrial vegetation with emergent plant treatment. Most submergent treatments are done in spring or early summer, while most emergent treatments are performed in late summer. Treatment of floating leaved vegetation tends to be intermediate to approaches used for submergent and emergent vegetation, with a wider range of herbicides available. Consideration of differences in timing and location of treatments for different growth forms of vegetation is therefore warranted in planning and permitting.

Aquatic plant control can have impacts on water quality, at least in the short-term, but there is no strong evidence that it leads to long-term impacts to lake water quality. Any impact on biochemical reactions including oxygen demand, phosphorus cycling, and algae bloom formation will be a function of scale. With a large-scale plant control treatment affecting plant growth over most of a shallow lake, water quality impacts are more possible. The pH might be lowered by reduced photosynthesis, phosphorus may be temporarily more available, and any control of benthic algae growth from shading will be reduced.

Oxygen levels are of primary concern in most waterbodies, and the effect of herbicide treatments can be variable, mostly as a function of the size of the treated area. Any oxygen impacts are likely to be transient, but if a large portion of a lake with a dense plant assemblage is treated for overall reduction in plant biomass, the risk of oxygen depression increases. Treatment planning should minimize the potential to contravene water quality standards and monitoring should track conditions until post-treatment oxygen stabilizes.

Loss of shading or antagonistic chemical (allelopathic) restriction of algae by plants may foster greater algae growth, especially by filamentous, mat-forming algae, but sometimes by planktonic forms. This may lead to significant shifts of primary production from bottom vegetation to phytoplankton in the water column. This flipping between ecological dominance by vascular plants and that by algae has been described as alternative stable states and the influence of climate change has also been implicated. Yet such shifts are not likely in a lake where the plant growth zone does not cover most of the lake; it is a shallow lake phenomenon. Further, unless plant control targets the whole plant community, the degree of change in plant cover and biomass will be much less than that required to induce major changes in water quality and biological features. Targeted plant control in lakes deep enough to stratify is very unlikely to result in any measurable water quality change, but this remains something to consider in shallow lakes where the plant community occupies most of the lake bottom or where inputs of nutrients from the watershed are high.

Herbicides, like nearly all other plant control options, are unlikely to provide complete control of the target species from a single application; this is akin to taking medicine for some serious ailment – one dose is unlikely to work. Plant control is better viewed as a maintenance activity, hopefully with a decreasing frequency of treatments, but still likely to be needed from time to time. Many effective plant control programs involve more than one technique in an adaptive manner as the plant community and control needs change. The exact combination of herbicides and other techniques to manage a lake will vary with target species, non-target species, target area, lake features, regulatory constraints, and affordability and can be unique for each lake. There is no "one size fits all solution".

There is some potential for aquatic plants to develop resistance to specific herbicides. Resistance arises from the process of genetic selection for plants with some means to reduce herbicide impact and should not be confused with plant tolerance, which is the existence of traits throughout the population that limit herbicide impact. Resistance was developed by hydrilla to fluridone and a species of duckweed to diquat in Florida where the same area had been treated with the same herbicide every year for many years. Resistance has not been documented to have developed elsewhere to date. Where treatment involves mainly spot applications at locations that change each year and represents a small portion of the plant growth area, development of resistance has not been a significant threat. Additionally, resistance is less likely for herbicides that attack cell membranes and multiple physiological processes as opposed to those that tend to impact one specific process like synthesis of a key enzyme or pigment. Yet as the potential for resistance to develop does exist, the simplest advice is not to treat the same area annually with herbicides with the same mode of action for an extended period of years.

Regulation of herbicides

Every registered herbicide has an EPA-approved label, which is more than an identifying sticker with some instructions for use. Labels are legal and regulatory documents that can be downloaded from the manufacturer and dictate where, how, and when the specific product can be used, likely target organisms, appropriate concentrations, and any use restrictions. Herbicides must be approved for use in most states by a designated state agency and may have supplemental labels or other restrictions for use. Approval signifies that the potential benefits of proper use of the product outweigh possible detriments but does not mean that there can be no negative side effects.

Herbicide resources

Reviews of herbicides and their use include Cooke et al. 2005, a book on lake management, and Gettys et al. 2020, a book on aquatic plants. Cooke et al. 2005 does not include some currently used herbicides, but it does summarize control experience and possible impacts of treatment as understood at the time. Gettys et al. 2020 (www. aquatics.org/bmp.html) is the 4th edition of this aquatic plant control handbook with specific management recommendations for selected invasive species and a chapter on common concerns expressed about herbicide use with plain language explanation of risks and related considerations.

Those considering herbicide 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 and plant species. As the composition of the plant assemblage is very important to developing a herbicide application plan and evaluating results, it is critical that plants and in the treatment area are correctly identified. Aquatic plants can be difficult to identify, although most of the invasive and native nuisance varieties can be learned.

Active herbicide ingredients applicable in VA for hydrilla control

There are five herbicidal active ingredients that might be applicable for hydrilla control in Chesdin Reservoir, but two (Endothall and Flumioxazin) tend to have a lot of non-target impacts and would not typically be used in a water supply unless there were no other options. This leaves diquat, fluridone, and florpyrauxifen-benzyl as legitimate options for hydrilla control in Chesdin Reservoir.

Diquat dibromide

Diquat works as a desiccant and defoliant against broadleaf and grassy species and is generally non-selective. However, one potentially important observation is that diquat has been able to control certain perennial plants like Eurasian watermilfoil and hydrilla without direct contact with the root crowns. It was assumed that recovery would occur after application of contact herbicides like diquat, but diquat appears to have some systemic properties. Successful control beyond a year or two has been achieved some lakes.

Diquat acts fairly quickly and degrades before it can move very far within a waterbody, providing localized control with limited threat outside the target zone if there is limited flow through that target area. Use of diquat to control vegetation in limited target areas within a waterbody or as a follow up to lakewide treatment with another herbicide such as fluridone is therefore an applicable strategy.

Diquat acts mostly by contact, with some recent evidence of systemic action, is relatively non-selective, but may leave many root systems that may generate regrowth. It is often used for spot treatment of limited areas, especially as a follow-up to more selective lakewide treatment with another herbicide but is also used where other herbicides are less effective.

Fluridone

Fluridone is a systemic herbicide that interferes with the plant's ability to photosynthesize. The vast majority of fluridone treatments over the last two decades have applied concentrations near the lower end of the labelled rate, often <10 ppb (termed low-dose treatment). A newer pelletized formulation with reliable slow release of fluridone has also provided control in more rapidly flushed areas or in smaller targeted areas, especially for Eurasian watermilfoil and hydrilla. Wagner and colleagues evaluated data from over 100 low-dose treatments for impacts to non-target plant species. In general, native assemblages recover in no more than 2 years to a single treatment with fluridone.

Fluridone is a systemic herbicide; it is translocated throughout the plant and kills all parts except seeds, turions, and certain winter buds. It is used at relatively low doses (routinely <20 ppb) and can be used selectively through adjustment of dose, application timing, and duration of exposure. Fluridone is very diffusive and requires extended contact time (>60 days) for best results. Booster treatments or slow release pellets can be applied if the target area flushes too often.

Response of aquatic species richness (the number of species present.) to low dose fluridone tends to vary with the number of native species present at the time of treatment. Where invasive species have depressed native species richness, increases are observed, while where native species richness is high prior to treatment there is a slight depression of richness for up to five years following treatment. In terms of overall native plant assemblages, low dose fluridone treatments have minimal lasting effect while depressing target species such as Eurasian watermilfoil, fanwort, hydrilla, and curlyleaf pondweed.

Florpyrauxifen-benzyl

Florpyrauxifen-benzyl was developed and approved most recently of the available herbicides for hydrilla control. Florpyrauxifen-benzyl, more technically 2-pyridinecarboxylic acid, 4-amino-3chloro-6-(4-chloro-2-fluoro-3-methoxy-phenyl)-5-fluoro-, phenyl methyl ester, is an arylpicolinate systemic herbicide intended for use for foliar application to emergent aquatic vegetation or direct application to water to control submergent vegetation. As a synthetic auxin it produces effects on the plant including alterations in cell wall elasticity and gene expression, and non-productive tissue growth that results in leaf curl and disruption of the plant phloem, interfering with transport of nutrients and causing death in days to weeks.

Florpyrauxifen-benzyl is the newest aquatic herbicide. It is a systemic herbicide and has been very effective against Eurasian watermilfoil with very limited impacts on many native species. It requires a relatively short contact time at a relatively low dose.

Target species include invasive hydrilla, all invasive watermilfoils, and floating heart. It is marketed under the tradename ProcellaCOR. There is a limited track record for this herbicide, but it requires only a few days of contact time, making it valuable for more complete control of aquatic plants in areas with shorter detention time. It has been very effective against species of milfoil (Myriophyllum spp) but has achieved mixed results with hydrilla, with seemingly lower effectiveness on monoecious strains of hydrilla. ProcellaCOR acts much faster than fluridone, however, making it a useful tool where throughflow cannot be controlled. It also has less impact on many non-target species.

Possible Benefits

- Can minimize invasive species abundance.
- Can reduce nuisance growths of native species to facilitate water-dependent human uses and enhance open water habitat.

Possible Detriments

- May harm some non-target species; some non-target impacts can be minimized by proper planning, but some cannot be avoided.
- Rarely provides extended control of annual species that propagate by seeds, turions, or winter buds.
- Complete elimination of target species is rare; long-term control requires a multi-year program, usually with multiple control methods applied.

Information for Proper Application

- Correctly identified plant species in the target area, allowing determination of herbicide and dose to be used and planning to minimize non-target impacts.
- General plant mapping and knowledge of any ecologically sensitive areas, especially where protected species are involved.
- For large or repeated efforts, more detailed vegetation mapping with estimates of cover or biomass which aid planning and tracking of results.
- Acreage and volume of the area(s) to be treated to allow calculation of product needed to deliver appropriate dose.
- Water body uses to facilitate determination of any use restrictions during and after treatment.
- Consideration of all user groups and any conflicts with intended vegetation control.

Factors Favoring or Disfavoring the Use of this Technique

- Favored where undesirable plant species dominate, especially invasive species.
- Favored where overall density of macrophytes is excessive throughout the littoral zone.
- Disfavored where susceptible, state-listed plant species or other sensitive receptors are present.
- Disfavored where existing vegetation is desired for fish and wildlife habitat.

Performance Guidelines and Monitoring Needs

- Map the distribution of the target species and any protected non-target species in the lake to facilitate assessment of results.
- Track weather where dilution and flushing are factors in herbicide effectiveness.
- Apply in accordance with all label instructions and restrictions.
- Inspect and clean all equipment before entering or leaving the lake and target area.
- Test for herbicide concentration periodically if intended exposure time is long enough to warrant booster treatment.
- Compare pre- and post-treatment plant communities; level of detail and duration of monitoring period depends on size of target area, sensitivity of non-target resources, and plans for follow-

up treatment or other controls, but monitoring should generally occur in the same tme period of successive years for long-term programs at points on established transects or a grid for best comparison.

- Monitoring for state-listed rare species, if required by, may require different approaches than those for general vegetation or wildlife purposes, as these may not be adequately represented in transect or grid surveys and may be harder to identify.
- Track oxygen levels if amount of vegetation expected to die within a two-week period could depress oxygen, often a concern during hot weather or drought where the target area is a large portion of the lake.

Appendix D: Vascular Plant-Eating Fish

How It Works

Fish that consume plants can potentially keep plant growths under control, but as biological agents, high variation in results is to be expected. The best known of the herbivorous fish is the grass carp (*Ctenopharynodon idella*), which consumes a wide range of rooted aquatic plants and is used in some states for plant control. As described below, the highly variable results, the non-selective nature of herbivory, and the potential for fish to move to other waters and survive for an extended period of time, potentially causing damage to non-target plant populations, is why grass carp and other non-native herbivores are often prohibited by state law and regulations.

Grass carp, *Ctenopharyngodon idella*

Only seven states allow stocking of sterile, diploid grass carp and a genetic triploid version, incapable of reproduction, is most often specified where stocking is allowed. Outlet controls are usually mandated to minimize escape from the target waterbody but are rarely completely effective. Aquatic vegetation control results have been highly variable and fish abundance or biomass along with dietary preference are the primary factors in degree of plant control. Projects with a goal of complete plant control will involve enough grass carp (usually 20/vegetated acre) to virtually eliminate all plants, leading to starvation or escape by the grass carp and a resurgence by plants unless grass carp are restocked.
Projects intending to control just certain
n species or to reduce plant abundance without elimination will involve an intermediate number of grass carp and have proven very difficult to manage successfully. Intermediate grass carp abundance does not guarantee that fish will not congregate and eliminate plants in certain areas while not impacting other areas, nor is it expected to provide control in only selected areas. Grass carp do have dietary preferences, and while they will consume nearly all aquatic plants if alternatives are lacking, a focus on invasive or unwanted plant species is not to be expected. Managing a biological control mechanism is quite complicated.

Grass carp do prefer hydrilla as a food source, however, so stocking grass carp for the control of hydrilla has been pursued in multiple lake systems. The use of grass carp for hydrilla control in Lake Gaston on the NC and VA border is one of the better documented cases. Targeted invasive species have been much reduced but not eliminated and some native plant species remain, although areas of native species are fenced off to prevent consumption by grass carp. However, drawdown and herbicides have also been used in the plant control effort at Lake Gaston and considerable effort goes into tracking results and making adjustments to enhance control.

Grass carp have been stocked in Swift Creek Reservoir since 2010 with variable results. Stocking at the maximum allowable rate in VA resulted in complete elimination of aquatic vegetation within 2 years. Resurgence of hydrilla occurred within 3 years. Attempts to build a stable, multi-year population of sterile fish by stocking smaller numbers of fish each year met with public opposition, as hydrilla control was slow. Lack of vegetation may have starved some fish and floods allowed some fish to escape downstream. Electrofishing is not a very effective means to monitor grass carp population, so knowledge of how many fish were in the reservoir was limited and overstocking occurred twice more in the next decade, leading to vegetation crashes and increased turbidity in the reservoir. While there is potential to gain some intermediate level of control over hydrilla by careful grass carp stocking, successful cases cannot be found and it is not possible to have grass carp target just selected areas within a reservoir.

Use of grass carp in Ball Lake in CT controlled Eurasian watermilfoil but the plant community is minimally diverse, with coontail becoming dominant after grass carp were stocked. Water clarity was poor before grass carp stocking and remained poor after stocking. In four other CT lakes where grass carp were stocked (Waubeeka, Taunton, Candlewood, and Squantz), vegetation was dramatically reduced, including both targeted invasive species and native plants. A substantial decrease in water clarity was observed in one of the four lakes. The conversion of plant biomass into grass carp biomass comes with high release of nutrients into the water column that can support algal blooms.

Fish that consume plants have appeal in a control program as a function of seemingly lower cost and prolonged control, but the disruption of lake ecology and unreliable results make them less desirable in most cases.

Possible Benefits

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

Possible Detriments

- 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

- Assess the plant community and determine if control is achievable at the desired level.

- Assess the fish community and determine possible adverse impacts of adding grass carp.
- Stock at the recommended rate; this should be lower than the maximum allowable and increased only when adequate plant data have been collected to show that more control is needed.
- Be prepared to counter adverse impacts on water quality; this could mean in-lake treatments to minimize algae blooms or increased treatment of water withrawals to meet intended uses (e.g., irrigation, potable supply).

Factors Favoring or Disfavoring the Use of this Technique

- Favored where undesirable plant species are part of the preferred diet of stocked fish.
- Favored where overall density of macrophytes is excessive throughout the littoral zone.
- Disfavored where loss of all vegetation must be avoided.
- Disfavored where increased turbidity is not tolerable.
- Disfavored where the fish community depends on substantial vegetation.

Performance Guidelines and Monitoring Needs

- Map the distribution of the target species and any protected non-target species in the lake.
- Determine an appropriate stocking density.
- Place proper controls at any outlet to prevent downstream fish passage.
- Monitor the plant community multiple times each year to assess changes; revise the stocking plan as needed.