Aquatic Pesticide Monitoring Program

Review of Alternative Aquatic Pest Control Methods For California Waters

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DISCLAIMER AND ACKNOWLEDGEMENTS

This report is the result of feedback by some members of the Aquatic Pesticide Monitoring Program Steering Committee that there is a need for thorough documentation on alternative aquatic pest control methods for California waters. This work is intended as an educational tool, including detailed discussion of alternative methods. This review does not evaluate conventional chemical pesticides; therefore, it should not be considered a guideline on all available aquatic pest control methods. No policy or regulation is expressed or intended by this report.

We thank the APMP Steering Committee and Interested Parties for providing feedback and direction on this literature review. Thanks are also due to all the aquatic plant managers, scientists, regulators, and NGOs who agreed to be interviewed and provide literature and unpublished reports for this review. Any errors or omissions in presenting alternative pest control efforts are the responsibility of the authors, rather than those interviewed. David Spencer, George Forni, Lars Anderson, and Robert Leavitt provided constructive review comments on portions of this review, Joe DiTomaso and John Madsen constructively reviewed the entire document, and Roger Mann assembled some of that information in the Feasibility Screening (Appendix C). Amy Franz and Seth Shonkoff assisted with document review and formatting. The California State Water Resources Control Board is acknowledged for funding this review.

INTRODUCTION

Aquatic plant and algae infestations can reduce the utility of water bodies for irrigation, aquaculture, potable water, navigation, and recreation, as well as obstruct drainage canals, which are needed for flood control prevention. Millions of dollars are spent annually to control aquatic weeds and algae (Joyce 1992), and California agencies invest heavily in programs to control nuisance aquatic plants (e.g., CDBW 2001; CDFA 2003a). Over the next several decades, with increasing human population growth, demand for food and water will increase, exacerbating the need for efficient delivery of usable water in California and worldwide (Van Vierssen et al. 2001).

The purpose of this review is to evaluate aquatic pest control methods that may serve as alternatives to registered chemical pesticides (Table 1). These alternatives include biological, mechanical, and physical control methods, as well as preventive measures. The review also discusses chemicals not registered as pesticides, including phosphorus-binding agents, acetic acid, and Aquashade.

Biological methods include the introduction of insect species and sterile grass carp, as well as microbial biocontrol agents, enzymes, and the addition of organic material. Mechanical control methods include harvesting, cutting, shredding, pulling, rolling, rotovation, diver dredging, the placement of barriers to inhibit growth, and excavation. Physical control methods include shading, aeration, and water level drawdown. Manual cutting, pulling, and rolling are geared towards small-scale projects, obstructed areas, or individual waterfronts. Harvesting, rotovation, excavation, and dewatering are used in larger scale aquatic weed removal (Table 1).

This document was written to discuss plant management methods that may be usable in California waters. Wherever possible, local case studies are described, and local environmental conditions and regulations are referred to. For readers desiring further information, several excellent reviews of aquatic plant control methods are readily available on the World Wide Web. Madsen (2002) provides a general review. Gibbons et al. (1999) provides recommendations for implementation of aquatic plant management plans. Systma and Parker (1999) review methods that are appropriate for irrigation canals. The identification of aquatic weeds and other information on their biology are described in DiTomaso and Healy (2003).

Table 1. Methods available for control of aquatic pests in California waters.

Physical and Mechanical Control Methods	Biological Control Methods
Mechanical Harvesting	Triploid Grass Carp
Mechanical Cutting	Other Herbivorous Fishes
Rotovation and Rototilling	Fish Biomanipulation
Hydroraking	Terrestrial Herbivorous Mammals
Weed Rollers	Gastropod Mollusks
Lake Sweepers	Insects
Diver-operated Suction Dredging	Non-Insect Crustaceans (for mosquito control)
Sediment Removal	Predatory fishes (for mosquito control)
Shading	Commercially Available Biocontrol Agents
Piping	Microbial Pathogens (e.g., cyanophages)
Bottom Barriers	Fungal Pathogens
Manual Removal	Organic Material Amendment
Water Level Manipulation	Acetic Acid
Channel Clearing	Plant Competition
Mechanical Excavation	
Exposure to Extreme Environmental Conditions	**Preventive Measures**
Aeration, Oxygenation, and Water Circulation	Early Detection
Nutrient Removal	Quarantine
	Regulation
Non-conventional Chemical Controls	Education and Outreach
Calcium based Products	Riparian Buffer Strips
Aluminum based products	Retention Pond or Wetland Construction
Nitrate	Watershed Best Management Practices
Aquashade	
Salt (Sodium Chloride)	

Aquatic plant control typically involves a balance of multiple management objectives. Different water body users may have varying definitions of how much submerged aquatic vegetation is acceptable (Van Nes et al. 1999). This can be particularly important because some management objectives can be incompatible. For example, reducing macrophyte biomass can result in increased algal blooms, and vice versa (Scheffer et al. 1993; Scheffer, 1999). Success of many control methods could be improved by the timing of application to the nuisance species. For example, water hyacinth control agents should be applied when the plant carbohydrate stores are at their lowest which generally occurs in the spring. Eradication when plants are young and shoots and leaves are small may also increase rates of success (Madsen et. al 1993).

This review synthesizes past and present knowledge of alternative management options, providing a wide range of potential tools for controlling aquatic plants and algae.

Nevertheless, each combination of plant species, water body, and stakeholder needs will respond best to a particular set of management options. Often times, significant progress can be achieved with alternative techniques on the control of relatively small infestations. However, large infestations may be most effectively treated with conventional pesticides, either alone or in combination with alternative plant control methods (Madsen 2002). It is important to not limit the available options in vegetation management and to choose carefully which ones are best applied for certain scenarios, considering the managed species, ecological system, natural resource values, and stakeholder priorities.

To determine the best management options, aquatic resource managers are encouraged to develop aquatic plant management plans that best address all user goals (Gibbons et al. 1999). If a practitioner wishes to decide among a specific suite of management options, they may want to formally compare their feasibility and cost effectiveness, using the Aquatic Plant Management Economic Methodology prepared as part of this project (Mann 2003).

Some of the methods described in this review are also used to control mosquito larvae in California waters. Water level manipulation has a long use history in mosquito control, as larva production is elevated in stagnant standing waters. Mechanical removal of aquatic or wetland vegetation could reduce larval production in some cases. Additionally, biological control is commonly used to control mosquito production; mosquitofish (*Gambusia affinis*) and other animal species may be introduced to water bodies, where they prey on larval mosquitoes.

REVIEW DESIGN

An evaluation of plant control methods for potential use in California should include all methods and technologies available throughout the United States. This study includes a detailed evaluation of methods documented in scientific journal literature, agency technical reports and grey literature. Additionally, telephone or in-person interviews were conducted with 77 practitioners in California and other states to point out methods currently successfully applied in specific management circumstances.

Literature Review

An extensive review of recent literature and survey papers was conducted. This included keyword searches using selected library search engines (e.g., the Web of Science, Biosis) and review of relevant articles in the past several years of relevant journals. For example, The Journal of Aquatic Plant Management (http://www.apms.org/japm/japmindex.htm) was reviewed since 1990, and Lake and Reservoir Management since 1996. The World Wide Web was also surveyed for gray literature using keyword searches on web search engines. An excellent source of gray literature regarding plant management is the Aquatic Plant Information Retrieval Service (APIRS) at the University of Florida (http://plants.ifas.ufl.edu/search80/NetAns2/). Additionally, papers available from the U.S. Army Corps of Engineers Waterways Experiment Station Digital Archives were downloaded and reviewed. Finally, several frequently published research scientists in the field were contacted with reprint requests. Of the published papers, grey literature, and web documents evaluated, 177 were included in this report and cited in the references section.

Practitioner Survey

To augment the findings of the literature review with late breaking information from the field, practitioners were surveyed within California and other states. Practitioners were asked whether they knew of any novel techniques for control of aquatic pests that would serve as alternatives to application of chemical pesticides in specific management circumstances. Interviews generally ranged in length from 15 to 60 minutes, depending on the time constraints of the interviewee and the information they had to share.

Appropriate practitioners and experts for interviews were identified using publications of articles regarding non-chemical plant control methods, relevant reports and information on the World Wide Web, attendance at the Western Aquatic Plant Management Society conference, listings on the APMS and NALMS websites and recommendations through already established contacts. Contact information of all practitioners interviewed is available in **Appendix B**.

BIOLOGICAL CONTROL METHODS

Biological control involves using plant, animal, or fungal species or components to reduce the survival, growth, or reproduction of the nuisance species. This includes use of herbivores, such as grass carp or insects that consume parts or all of the nuisance plant species. Bacterial and fungal pathogens are also used. These cause disease to the nuisance plant species, thereby reducing survival and recruitment. Additionally, biological materials, such as bacteria, enzymes, barley straw, organic matter amendments, may be added to the system to reduce growth of nuisance plants or algae, without preying on them or causing disease. The proposed mechanisms for non-predatory biocontrol methods include competition for resources, and production of natural substances that inhibit the growth of the nuisance species. The development of biocontrol agents has been limited due to production difficulties, unresolved regulatory questions, virulence issues and lack of capital investment (Watson 2003).

Biological control is often more successful when multiple methods are integrated. Plants weakened by insect damage or sublethal doses of chemicals are often more susceptible to pathogens. In water hyacinth management, for example, multiple insect species, insects combined with grass carp, or pathogens combined with chemical treatment are often more effective than individual treatment methods alone (Gopal 1987).

Pros and Cons of Biocontrol

Biocontrol for reduction of nuisance plants in aquatic systems has both positive and negative attributes (Charudattan et al. 2002). A positive aspect of biocontrol is that control agents are often host specific, so effects to non-target species may be reduced. Control agents can also reproduce in response to increases in nuisance species density often without reapplication of the agent. Development and registration (where necessary) of biocontrol agents is generally less expensive than chemical agents. Additionally, the ecosystem impacts under biocontrol can be more gradual, thereby allowing the system to adjust to loss of a species.

However, biocontrol can have many potential disadvantages. An important risk is involved when new species are introduced as biocontrol agents. To be considered successful, these species are expected to persist indefinitely in the environment where they are used, and may spread to new locations. Therefore, if there are any adverse effects resulting from the biocontrol agent, these effects may be difficult or impossible to control. Adverse effects of biocontrol agents could include loss of habitat for some fauna, competition with native species, and the production of toxic metabolites that are released to the environment. Other drawbacks include unpredictable success and rates of control that are slower than with chemical methods. Resistance in host species is unlikely to develop but can occur. Finally, agents that work in one area may not be suitable in all ecosystems. Climate, interference from herbicidal application, hydrological conditions, and eutrophication of the system can influence the effectiveness of biocontrol agents (Hill and Olckers 2001). The growth of nuisance weeds can be suppressed with the use of biocontrol agents, but not fully eliminated.

Triploid Grass Carp

The grass carp, also known as the white amur (*Ctenopharyngodon idella*), feeds on aquatic plants and can therefore be used as a biological tool to control nuisance aquatic plant growth. To reduce the potential for unintended consequences, grass carp must be sterilized for use in waters of the United States. Once grass carp are stocked in a water body, it may take several years for them to control the plant growth and decrease weeds to about 20% of the earlier plant cover (Washington State Department of Ecology 2001). If practitioners stock enough fish to achieve control within the first few years, this can eventually result in detrimental effects to non-target plants, as the fish increase in size (e.g., Colle and Shireman 1994). If possible, it would be more cost-effective to stock a smaller number of fish, and wait for them to grow sufficient size to control the plant problem (Stewart and Boyd 1999).

A wide range of field applications and scientific studies has demonstrated that grass carp can effectively reduce growth and biomass of undesirable vegetation (e.g., Leslie et al. 1994; Pauley et al. 1994; Santha et al. 1994; Van Vierren et al. 2001). However, success with grass carp may vary from site to site. Sometimes identical stocking rates result in no control, adequate control, or even complete elimination of all underwater plants. Therefore, before introducing grass carp to a water body, it must be determined whether complete elimination of all submerged species could be tolerated.

Many researchers and aquatic plant managers think that grass carp should only be stocked when complete elimination of all submersed plant species could be tolerated.

As with any large-scale ecosystem manipulation, grass carp introduction may cause significant environmental impacts to a water body. Elimination of submerged plants by grass carp foraging could result in increased turbidity, water column nutrients, and phytoplankton production (Scheffer et al. 1993; Colle and Shireman 1994; Scheffer 1999). If all aquatic vegetation is removed, waterfowl, amphibians and aquatic mammals may also be adversely impacted (Brakhage 1994). In light of the fact that grass carp, once introduced, are extremely difficult to remove from a water body (e.g., Colle and Shireman 1994), caution should be exercised when considering new waters for grass carp introduction.

Case study results vary widely in overall impacts of grass carp introduction to native plant and animal communities. Overstocking can result in disturbance to the existing fish community, resulting from vegetation habitat removal. In two Florida lakes heavily stocked with grass carp, all submerged vegetation was wiped out, resulting in impaired water quality and declines in sensitive native fish species (e.g., Colle and Shireman 1994). In contrast, when grass carp were carefully stocked in eight Oregon and Washington lakes, dissolved oxygen improved and other fish populations were not affected (Pauley et al. 1994). By reducing dense monotypic vegetation, and increasing underwater structural diversity, grass carp introduction may even increase abundance of other fish species (Killgore and Kirk 1998; Killgore et al. 1998).

California Department of Fish and Game has implemented a number of restrictions to reduce the probability of negative consequences of grass carp use. First of all, grass carp may only be used in water bodies that are isolated from the 100-year floodplain of major California rivers (Marty Muschinske, *pers. comm.*). Due to the risk of adverse impacts on adjacent water bodies, stocked water bodies should be isolated or have screened inlets and outlets (Washington State Department of Ecology 2001). Screens to inlets or outlets are generally only approved by CDFG where they do not interfere with anadromous fishes, e.g. steelhead or salmon runs. Additionally, grass carp must be sterilized, a process achieved by causing fertilized eggs to retain three sets of chromosomes (triploidy). The risk of inadvertent release of fertile grass carp (e.g., Webb et al. 1994) is reduced by testing the blood of juvenile fish to confirm triploidy.

In California waters, stocking costs include the purchase price of the fish (generally about $8-15/fish), purchase cost for the permit ($100 application fee), a one-time stocking fee of 15$/fish paid to CDFG, and an annual regulatory fee of $7.50/fish also paid to CDFG. Inquiries can be submitted to the local region office of CDFG or to Marty Muschinske, of the Eastern Sierra/Inland Desert region, who currently has the most experience with the program (Marty Muschinske, *pers. comm.*). Applications are evaluated by the local region office. Stocking rates for Washington lakes generally range from 9 to 25 eight to eleven inch fish per vegetated acre. This number will depend on the amount and types of plants as well as water temperatures (Washington State Department of Ecology 2001). One-year-old fish (less than 225 grams body weight) have much lower plant feeding rates than larger fish (Pine et al. 1990), so if small fish are stocked, foraging rates may increase considerably with fish size.

For any given water body, it can be difficult to determine the optimal number of grass carp to stock. In the 1980s and 1990s, stocking rates varied widely among U.S. water bodies (Stewart and Boyd 1999). The optimal stocking rate is generally higher in Oregon and Washington than in southeastern United States (Pauley et al. 1994), suggesting that cooler water bodies in northern California would require higher stocking rates than warmer southern California waters. Currently, a number of California practitioners often report simply stocking a fixed number of fish per year, based on the general observation of successful weed control (Paul Saunders, *pers. comm.*; Ron Derma, *pers. comm.*).

For practitioners wishing to more accurately estimate the appropriate number of fish to achieve adequate control, the Waterways Experiment Station (WES) of the United States Army Corps of Engineers has developed a grass carp stocking rate computer model called AMUR/STOCK (Madsen et al. 1998). AMUR/STOCK was developed to help aquatic plant managers evaluate proposed stocking rate strategies. Practitioners would input data on water body temperature, plant biomass and growth rate, number of grass carp initially stocked, and grass carp feeding preference. The model would then determine the required rate of restocking and the plant area controlled (Stewart and Boyd 1999). AMUR/STOCK is available as part of the Aquatic Plant Information System CD-ROM, which can be ordered for free from the U.S. Army Corps of Engineers Website (U.S. ACE 2001; http://www.wes.army.mil/el/aqua/apis/apishelp.htm)

Grass carp are more effective at removing some plant species than others. Highly preferred species include *Egeria densa*, *Hydrilla verticillata*, common elodea (*Elodea canadensis*), and duckweeds (*Lemna* spp. and *Spirodela* spp.). Non-preferred species include coontail (*Ceratophyllum demersum*) and milfoils (*Myriophyllum* spp.) (Stewart and Boyd 1999). Success has been reported in controlling water hyacinth using a combination of grass carp and weevils (Gopal 1987). Eurasian watermilfoil is not a preferred food source and grass carp will consume most other aquatic species before eating it (Washington State Department of Ecology 2001). Also, grass carp may consume submerged species before eating floating species in the same water body (Santha et al. 1994).

A number of practitioners in California water bodies have reported positive experiences with grass carp. Use of grass carp has been successful for southern California irrigation district delivery channels, where the primary management objective is water conveyance, and complete elimination of all vegetation is acceptable. For example, grass carp have been an important tool in controlling *Hydrilla verticillata* (hereafter, hydrilla) in the Imperial Valley, CA. In the Imperial Irrigation District, hydrilla infested areas have been reduced from over 600 miles of irrigation canals, reservoirs, drains, private ponds and deliveries to less than 0.75 miles in a single drain. While triploid grass carp remain the main weapon against hydrilla, an integrated method of fish, mechanical, and manual methods is being used to eliminate the final <1% of the hydrilla infestation (Mike Mizumoto, *pers. comm.*). A total of 13,908 triploid grass carp have been stocked into the Imperial Valley waters. By 2000, hydrilla was reported to be eliminated from all sites except one drain (Mizumoto 2001). The Bard Irrigation Districts and Coachella Valley Water District also report very positive experiences using grass carp in irrigation canals (Ron Derma, *pers. comm.*; Paul Saunders, *pers. comm.*). In the Bard Irrigation District, recent set up costs for a six mile irrigation canal included the purchase and permitting for 300 fish, and the installation of a concrete grate to reduce the risk of fish escape (Ron

Derma, *pers. comm.*). Finally, a number of southern California and Central Valley golf courses have stocked grass carp to control vegetation in their ponds (Paul Beaty, *pers. comm.*). These include the Tulare County Recreation Department and the Woodridge Golf Course (just outside of Lodi) (Marty Muschinske, *pers. comm.*).

Grass carp have also been successfully employed in Arizona canals used for drinking water conveyance, where chemical pesticide application was discontinued. The Salt River Project (SRP) delivers a million acre-feet of water annually to 250,000 acres in central Arizona through approximately 130 miles of canals and 120 miles of laterals. Water usage in the SRP system has shifted from primarily agricultural use to use as a drinking water source. As a result, environmental regulations prohibit the use of most chemical herbicides. Magnacide H (acrolein) and chelated elemental copper are currently the only used chemicals. SRP has used grass carp to control extensive aquatic weed growth in most of the canal systems for ten years and has found them to be "environmentally friendly and cost effective." Weed growth and fish populations are monitored and fish are moved to maintain effective weed control throughout the system. Grass carp have been shown to adequately control aquatic weed growth in the SRP (Maldonado 2001).

Other Herbivorous Fishes

In addition to triploid grass carp, common carp and tilapia have been added to ecosystems to reduce aquatic vegetation. However, these species are not perceived to be successful and are not recommended for use as biocontrol agents. Common carp stir up the bottom of water bodies, and are generally considered to be a nuisance species. Anecdotal reports of use of tilapia in the Coachella Irrigation District (southern California) indicated that they did not control growth of aquatic plants and were constantly getting stuck in irrigation drains (Paul Saunders, *pers. comm.*). Tilapia is prohibited in California north of Los Angeles County and CDFG does not recommend they be used for aquatic vegetation control.

Fish Biomanipulation

In addition to the use of herbivorous fish, water resource managers can also reduce aquatic plant growth by changing the abundance of fish higher in the food web.

This method, often referred to as biomanipulation, is typically used to control growth of nuisance planktonic algal blooms and has been most successful in small lakes when combined with nutrient input control (John Madsen, *pers. comm.*). Fish biomanipulation may also be appropriate in water bodies characterized by large populations of small fish that eat zooplankton. In these lakes, the heavy grazing by planktivorous fish can cause low zooplankton abundance, and a consequent reduction in zooplankton grazing rates on algae. In these circumstances, it may be possible to indirectly control algal production by manipulating the "top" of the food web. Specifically, managers reduce the population of smaller fish. Freed up from the predation pressure by the small fish, the zooplankton in the lake increase in size and foraging rate. This greater grazing by zooplankton consequently reduces the overall abundance of algae in the water body, improving water clarity (Carpenter et al. 1987; Carpenter and Kitchell 1988). The water body manager can reduce the small fish population either by directly removing the fish from the water body (e.g., Annadotter et al. 1999) or by adding a large population of predatory fish, which are expected to forage heavily on the smaller fish, thereby reducing their population (Kitchell 1992). This is most successful when omnivorous, benthivorous fish are controlled at the same time (John Madsen, *pers. comm.*).

Fish biomanipulation is a difficult management method to implement effectively. It typically requires a good understanding of the community structure and chemistry of the water body. It is only successful in water bodies with certain community structure types. If predatory fish are added to the water body, severe fishing restrictions may be necessary to maintain the high populations (Kitchell 1992). Additionally, many factors can influence algae growth, causing success to vary considerably from year to year (Carpenter et al. 1987). Nevertheless, biomanipulation has been reported to substantially improve lake water quality in lakes where other methods have failed (e.g., Annadotter et al. 1999).

We know of no examples of fish biomanipulation attempted in California waters. It may be an appropriate method for consideration in drinking water reservoirs, where human access and fishing are limited, and there is a good scientific understanding of the limnology of the water bodies.

Terrestrial Herbivorous Mammals

Terrestrial herbivores may be used to control emergent and riparian vegetation. Goats may be corralled into an area where control is desired using electric fencing, and allowed to forage there until vegetation is reduced. A number of private companies currently offer goat grazing as a vegetation control option, and irrigation districts such as Reclamation District 999 do include goat grazing in their control methods (Bob Weber, *pers. comm.*). Although terrestrial herbivores serve as alternatives to chemical pesticide application, water quality may be adversely impacted by the movement of soil and sediment following disturbance, as well as goat excretion. One of the Aquatic Pesticide Monitoring Program demonstration projects evaluates the cost-effectiveness and water quality impacts of goat grazing.

Gastropod Mollusks

Introduction of snails or sea slugs is a biocontrol option that has been researched for certain aquatic infestations. Cooke et al. (2001) reported that small research experiments indicate that snails grazing on biofilm algae may be useful for improving growth of desirable aquatic plants. Presumably, the use of these grazing snails would increase aquatic vascular plant biomass, thereby resulting in reduced nutrient availability for floating nuisance algae, and ultimately improvement in water quality (Scheffer et al. 1993; Scheffer, 1999). Researchers are currently evaluating a number of sea slug species for potential biocontrol of the marine invasive plant, *Caulerpa taxifolia*. Although the slug is very promising as a biocontrol agent, there is considerable political ambivalence regarding the introduction of a non-native biocontrol species in marine waters (Meinesz 1999). Therefore, use of gastropods has not been developed for commercial biocontrol application. Snails were extensively researched for biocontrol of hydrilla, but were found to be an ineffective control method, and thus were not commercially developed (Bill Haller, *pers. comm.*). Interest in development of snails as a biocontrol agent has been limited due to the environmental risk associated with purposeful introduction of prolific generalized herbivores. Additionally, there is concern that snails can serve as vectors for certain fish parasites (McCann et al. 1996). Thus, although gastropod mollusks may have potential for use in biocontrol, there is yet to be an example of successful field-scale application.

Insects

Another alternative in biological control is the release of insects that specialize in feeding on particular nuisance plant species. In other states and countries, insects have been developed for biological control of a number of aquatic and emergent plants that occur in California waters. These include hydrilla, Eurasian watermilfoil, water hyacinth, giant salvinia, and purple loosestrife. In California, insects have been evaluated for biological control of hydrilla and water hyacinth, but not for Eurasian watermilfoil or purple loosestrife. Currently, the weevil, *Cyrtobagous salviniae*, is being evaluated for long-term control of giant salvinia (*Salvinia molesta*) on the Colorado River and adjacent irrigation drains (Olson 2003).

Biological control using insects has had limited field application in California waters, but has been reportedly successful for plant management in some other states. In Florida and Louisiana, biological control of water hyacinth has been successful using two weevil species of the genus *Neochetina* and one moth of the genus *Sameodes*. However, large-scale reduction of water hyacinth (50-70% reduction in plant growth) often took years to occur (Bill Haller, *pers. comm.*). Another concern is that even though plant height and flowering might be reduced, the expansion of the plant mat could still occur (John Madsen, *pers. comm.*).

In California, insects have been tested for control of water hyacinth and hydrilla. In an effort to control water hyacinth in the Sacramento-San Joaquin Delta, three species of insects were released in 1982. Recent surveys have shown that one of the species (*Neochetina bruchi*, the water hyacinth-eating weevil) has spread throughout the Delta, but the populations are not of sufficient size to effectively control the hyacinth. Currently, a research collaboration among CDBW, CDFA, and the USDA is underway to understand the factors limiting the success of insect biocontrol in the Delta (USDA and CDBW 2003).

Two insect species have been evaluated for control of hydrilla in California, the hydrilla tuber weevil (*Bagous affinis*) and the Asian hydrilla leaf mining fly (*Hydrellia pakistanae*). Laboratory and field studies have determined that both species feed on hydrilla tissue and have the potential to reduce hydrilla densities (Godfrey and Anderson

1994; Godfrey et al. 1994; Godfrey et al. 1995). However, hydrilla eradication in the state is currently achieved using chemical application, grass carp, hand removal, and sediment dredging for tubers.

Biological control has shown some success in controlling Eurasian watermilfoil in other states, though the control agents have not been introduced in California. The milfoil weevil (*Euhrychiopsis lecontei*) appears to be able to control Eurasian watermilfoil, causing significant biomass reduction in the laboratory (Creed and Sheldon 1993) and in the field (Creed and Sheldon 1995). This insect exposes vascular tissue of the stem when feeding on Eurasian watermilfoil and causes the collapse of the plant. Sheldon and O'Bryan (1996) have shown that the weevil preferred Eurasian watermilfoil. Their data from the six years following a Eurasian watermilfoil decline in a Vermont lake show that watermilfoil has not regained its dominance, while native plant density has increased. The increase in native plant density may result from poor egg hatching and recruitment on non-target plant species (Sheldon and Creed 2003).

Biological control using insects or other invertebrates does not appear to hold much promise for *Egeria densa*. Many organisms were tested to control *Egeria densa* (including snails), but generally showed little success (Bill Haller, *pers. comm.*).

Often times, insect population growth may not be sufficient to achieve biological control in weed-infested areas. Evaluation of feasibility is often required on a site-specific basis. For example, the milfoil weevil appears to have much lower densities in waters with cooler temperatures, and might not be suitable for regions with colder summer climates. Another important consideration is the potential for effects on non-target species or other unintended consequences of the insect introduction (Sheldon and Creed 2003). Non-native insect species, once introduced to a new region, could potentially spread rapidly and adversely affect local ecosystems. They could potentially impact non-target vegetation and cause loss of habitat for some fauna. Site-specific research on the specific impacts of a particular biocontrol insect should be conducted before that agent is introduced to California waters.

Predatory Animals For Mosquito Control

A number of predatory fishes and invertebrates are available or in development for controlling mosquitoes. These organisms prey upon mosquito larvae or pupae, thereby reducing reliance on chemical pesticide application for mosquito control. In California, mosquitofish (*Gambusia* spp.) are readily available for mosquito control. *Gambusia* are very effective predators on mosquito larvae, with some species even able to reduce mosquito populations in dense beds of aquatic plants (Lounibos et al. 1992). Additionally, a number of predatory fish and invertebrate species are currently being applied on a pilot or local basis by various California Mosquito and Vector Control Districts (Karl Malamud-Roam, *pers. comm.*).

In addition to mosquitofish, at least three fish species are currently being studied for biological control in California waters: guppies (*Poecilia reticulate*), Sacramento perch (*Archoplites interruptus*), and three-spined stickleback (*Gasterosteus aculeatus*) (Miller 2003; Schon 2003a, b). The Sacramento-Yolo Mosquito and Vector Control District (SYMVCD) has stocked guppies in 286 mosquito sources, comprising 670 acres. Permitting for guppies was relatively easy for guppies in northern California waters, because they do not survive the cold winters and are therefore unlikely to have long-term adverse impacts on native wildlife. They are relatively easy to culture and more tolerant of adverse environmental conditions than mosquitofish, making them appropriate for stocking in dairy lagoons and acidic creeks (Schon 2003a). SYMVCD has had limited success with three-spined stickleback. Although they can be cultured and do consume mosquito larvae in the laboratory, the sticklebacks are not effective at consuming mosquito larvae in many field conditions (Schon 2003b). Sacramento perch are still in the development and testing phase for mosquito control by the Contra Costa Mosquito and Vector Control District. They have been successfully raised and consume mosquito larvae in the lab, but large-scale experiments or field applications have yet to be conducted (Miller 2003).

An additional fish genera, the pupfish (*Cyprinodon* spp.) has been proposed for evaluation, but practical use for mosquito control is restricted due to special status (Su 2003a). In the Coachella Valley (southern California desert), a species of tadpole shrimp (*Triops newberryi*) has been extensively evaluated in laboratory studies. The tadpole shrimp shows promise for mosquito control in ephemeral habitats. Tadpole shrimp have a number of desirable traits for mosquito control in intermittently wetted habitats; they prey on mosquito larvae, have a desiccation resistant life stage, grow quickly, and have high reproductive capacity. Nevertheless, they have yet to be evaluated in large-scale field applications (Su 2003b).

Commercially Available Biocontrol Agents

Biological agents such as bacteria, viruses, and enzyme solutions are commercially available to aid in the improvement of water quality. These agents are touted to increase water flow by reducing/eradicating algal, and to some extent, macrophyte growth. Few field and lab experiments have been completed to test the efficacy of commercial microbial products. Commercial microbial products generally contain a mixture of bacteria and enzymes. The microbial products are typically applied to the system to augment the system's bacterial populations. The theory is that increased bacterial concentrations will limit the availability of nutrients necessary for algal and macrophyte growth and reproduction. The bacteria, theoretically, utilize the same nutrients (nitrogen and phosphorus) as the photosynthesizers and therefore act as competitors for growth.

Biocontrol agents are readily available as commercial formulations. Examples include Aqua 5™ , 1998 LakePak™, WSP® , Algae-Tron™ , and PK-700, all of which are relatively inexpensive to purchase. Nevertheless, the success of biocontrol agents to reduce primary producer (planktonic) populations is not well established. Few studies are available testing the effectiveness of these methods. The available peer-reviewed studies indicate that microbial control methods are not effective for control. Some laboratory research has piloted new methods, such as culturing and expanding the bacterial fauna from individual lakes. But the practicality and cost-effectiveness of these methods for field application remains to be tested. Mesoscale experiments are necessary to see if laboratory results can be replicated in the field.

A recent laboratory and field study provided evidence that commercially available biocontrol agents were generally not effective for control of algal growth (Duvall et al. 2001; Duvall and Anderson 2001). In the laboratory study, there was no significant decrease in chlorophyll-a concentrations in the treated systems, compared to control systems where no microbial product was added (Duvall et al. 2001). In the field study, lake mesocosms treated with commercial microbial product were measured for bacteria concentrations. One out of the three commercial products applied showed a significant increase in bacteria concentrations when compared to the controls but none of the commercially treated mesocosms showed a significant decrease in chlorophyll-a concentrations when compared to controls (Duvall and Anderson 2001). A study by Queiroz and Boyd (1998) also indicated no relationship between addition of bacterial agents and chlorophyll concentration in the water body. Bacterial inoculate were added to catfish aquaculture ponds. There was no significant difference in chlorophyll-a concentrations between treated and control ponds and no difference in bacterial populations between treated and control ponds. The treated ponds produced a higher net production of catfish than the non-treated ponds, but the reason for this was unclear.

Plant Pathogens Currently In Development

Plant pathogens for the control of hydrilla and Eurasian watermilfoil have shown progress over recent years but remain in the research phase. So far, only laboratory tests in aquariums and small ponds have been conducted, and the methods are not available for widespread application. The use of the pathogen *Fusarium graminearum* in control of *Egeria* species is in the pre-commercial evaluation phase (Charudattan and Dinoor 2000). The fungus *Alternaria eichhorniae* has shown some success in control of water hyacinth in Africa but rapid colonization by the fungus is necessary for long-term control (Reeder 2003). Species of *Rhizoctonia* have the ability to kill plants but there is no host specificity and non-target plants can also be affected.

Since the 1980s, the Corps of Engineers (USACE) has been researching plant pathogens to control hydrilla in the Southeastern U.S. A fungal pathogen species from Texas (*Mycoleptodiscus terrestris*) holds promise for future control but is not yet commercially viable (Judy Shearer, *pers. comm.*). So far, only laboratory testing in aquariums (up to 67,000 l) and small pond testing have been conducted since the USACE does not have the permit required for larger scale fieldwork. Whether these agents will be successful in flowing waters or large-scale applications remains to be tested. New methods have been developed to bind the organisms to plants. These new formulations include flour or starch and oil that apply buoyancy and keep the fungus attached to hydrilla. The USACE is working with the SePRO Corporation on patenting the microbial herbicide (Judy Shearer, *pers. comm.*).

Hydrilla has also been evaluated for integrative control combining fungal agents with herbicides. Laboratory studies indicated that use of *Mycoleptodiscus terrestris* in combination with the herbicide fluridone reduced hydrilla biomass by more than 90% and was more efficacious than these treatments individually (Netherland and Shearer 1996; Nelson and Shearer 2002). Mesocosm studies had similar results (Nelson et al. 1998). Sublethal amounts of herbicide were applied which would also minimize the impact on non-target species if used in natural environments. Shearer and Nelson (2002) found that application of a combination of *M. terrestris* and the chemical herbicide endothall also reduced hydrilla biomass in lab experiments. Shearer (2002) also noted that stressful conditions, such as herbicidal application in non-lethal doses, may weaken a plant and compromise a plant's defenses, thereby making it more susceptible to infection by the fungus.

Integrative control has been evaluated for water hyacinth using multiple insects or insects in combination with bacterial pathogens (Gopal 1987). Co-introduction of *Neochetina eichhorniae* and *Orthogalumna terebrantis* reduced plant density by 45% and petiole length by 35% over a 50-week experimental period. Integrative control has also been applied to water hyacinth management. The pathogen *Cercospora rodmanii* and *Neochetina eichhorniae* eliminated 99% of water hyacinth (Charudattan 1984, as reviewed in Gopal 1987).

The permitting process for plant pathogens is fairly extensive, which can delay and limit development of these alternatives. Endemic plant pathogens need to be registered with EPA before release in the environment. The registration process requires intensive host specificity and toxicity testing. After that is accomplished, the pathogen species gets a label, just like a chemical, with established maximum applications rates and use restrictions. Costing about $2 million, plant pathogen registration is less costly than chemical registration (about $20 million) (Judy Shearer, *pers. comm.*). Further development and registration of plant pathogens has been slowed by lack of funding and interest on the part of major corporations or venture capitalists (Rahavan Charudattan, *Pers. comm.*; Judy Shearer, *pers. comm.*).

Pathogens For Mosquito Control

Pathogens have also been studied for mosquito control. The microbial organism, *Lagenidium giganteum* shows promise for reducing larval populations of *Mansonia* mosquitoes. In a study by Cuda et al. (1997), *L. giganteum* reduced the emergence of adult mosquitoes, and appeared to generate self-sustaining populations in test pools. This pathogen has specific water quality requirements and is only likely to be effective in relatively unpolluted water bodies.

Cyanobacteria Control Agents Currently in Development

In laboratory and microcosm experiments, specialized biological control agents have shown success in the control of nuisance cyanobacterial blooms. Methods under development include cyanophages, bacteria, and cell culture isolates (reviewed in Sigee et al. 1999). However, many of these agents are still in the research phase, and it may be years before they become available to practitioners.

Cyanophages (viruses) may be useful in controlling cyanobacterial blooms. Cyanophages are host specific, so a variety of species would be necessary for biocontrol. Ultimately, the cyanobacteria species may become resistant to the cyanophages, rendering the control method ineffective in the long term. Bacteria can kill cyanobacteria by producing extra cellular products that lyse cells (i.e., cause them to “blow up”). Some fungal species can produce an antibiotic that also harm cyanobacteria, but physical proximity between fungi and cyanobacteria is necessary. Isolates from cultures of the aquatic fungus, actinomycetes, have shown inhibitory effects against cyanobacteria. The isolates are collected from environmental samples and isolated in the lab. *Streptomyces exfoliatus* was successful in lysing genera of major bloom species such as *Anabaena, Microcystis* and *Oscillatoria*. Microcosm studies show that *S. exfoliatus* was successful in lysis of lake phytoplankton and a reduction of algal populations. Protozoans reduce cyanobacterial cells by grazing. Lab experiments have shown that certain protozoan species graze on genera of oscillatoria and anabaena. Microcosm experiments have shown a reduction in algal populations.

Organic Material Amendment

Organic materials, such as peat, and barley straw, have been used for control of rooted aquatic plants and algae. Theoretically, control is achieved by reduction of nutrient availability to the nuisance species or release of chemicals that impede growth. Organic material amendment results tend to be system specific, creating a need for small-scale pilots prior to widespread application in a specific water body.

Field studies have shown that sediment amendment with peat or barley straw may reduce hydrilla production (Spencer et al. 1992). A number of laboratory studies have demonstrated that natural or human-altered increases in sediment organic matter content can reduce growth of Eurasian watermilfoil (Barko et al. 1986; Gunnison and Barko 1989). The chemistry of added organic materials can affect their ability to reduce aquatic plant growth; organic material may inhibit plant growth or stimulate plant growth, depending on the nitrogen content of the added organic materials (Spencer et al. 1992). The use of organic additions, including barley straw, for the control of hydrilla has not been widespread.

Barley straw has gained popularity in recent years for algae control via word-of-mouth successes, but research indicates that it only works in certain management circumstances (Lembi 2002). The activity of barley straw is usually described as preventing the new growth of algae, rather than killing algae already present. It is thought that fungi decompose the barley in water, which causes lignin- and tannin-derived polyphenolic compounds to be released, preventing the growth of algae. This method is most successful in well oxygenated water bodies where the decomposition of barley is not disrupted (Boylan and Morris 2003). Martin and Ridge (1999) and Terlizzi et al. (2002) suggest that decomposing barley may inhibit the growth of a limited number of algae and dinoflagellate species under both laboratory and field conditions. Barley straw has also shown some success in the control of cyanobacterial growth (Barrett et al. 1996). Because effectiveness of barley straw to control algae will vary from site to site, small-scale pilot studies should be conducted before investing significant time or effort in whole-lake applications.

Managers can also add barley straw to sediments, in an effort to control growth of rooted aquatic plants. Other materials, including sand, gravel, and peat, have also been added to sediments to alter plant growth (Barko et al. 1986; Spencer et al. 1992). Plants grow best with a certain amount of nutrients in the sediment (Barko and Smart 1986). Addition of barley straw, peat, or other organic material may inhibit aquatic plant growth by bringing the nutrient density and concentration out of the ideal range (Systma and Parker 1999). As with floating algae, the ability of barley straw to control growth of rooted aquatic plants varies among studies and locations. Parker and Sytsma (1998) found good evidence that addition of barley straw reduced *Potamogeton* growth in Oregon irrigation canals. In contrast, Spencer et al. (1992) found that barley straw or peat can actually increase hydrilla growth in California soils. Water hyacinth and other free-floating plants that prefer acidic water for nutrient uptake may also benefit from organic additions to the water body (John Madsen, *pers. comm.*). As with control of algae, small-scale pilot studies should be conducted to evaluate effectiveness before applying at a management scale.

Although barley straw may be a viable algae control method, it has uncertain legal status for use by public water body management practitioners (Lembi 2002). The EPA states that a pesticide is “any substance or mixture of substances intended for preventing, destroying, repelling, or mitigating any pest.” However, no company has ever registered barley for use as a pesticide as it has not gone through the testing required for registration. Therefore, barley cannot be sold as a pesticide to control algae. Its use in private ponds or lakes is allowed under the facet that it qualifies as a “home remedy”, its use as a commercial algaecide in larger or public bodies of water is not supported by the EPA (Lembi 2002). Despite the non-qualification of barley straw as an official pesticide, it is still widely sold on the commercial market, approved by the New York State as a method to improve the quality of garden ponds (Lembi 2002).

Acetic Acid

The addition of dilute acetic acid to the propagules, root crowns, or tubers of aquatic weeds has shown to be a successful growth inhibitor (Spencer and Ksander 1995a, 1995b, 1997, 1999; Parker and Sytsma 1998). Submersed aquatic plants, such as hydrilla, rely on subterranean vegetative propagules, such as tubers, turions, or winter buds for reproduction. These propagules enable the plant to survive periods of unfavorable conditions. The addition of acetic acid to these propagules at the appropriate time in their life cycles was shown to limit growth of these weeds. The growth of both hydrilla and sago pondweed (*Stuckenia pectinatus*) can be decreased as a result of exposure to dilute acetic acid (Spencer and Ksander 1995a, 1995b, 1997, 1999; Parker and Sytsma 1998). Acetic acid sediment amendment will only be effective in channels with little or no standing water; therefore, natural or artificial water level drawdown is generally necessary for this method (Parker and Sytsma 1998).

At this time, we know of no California field practitioners who use acetic acid to control growth of rooted aquatic plants. Field studies have shown that it was effective in a Yuba County canal (Spencer and Ksander 1999), though cost effectiveness for widespread application has not been determined (David Spencer, *pers. comm.*). Preliminary research trials by the USDA-ARS and the Invasive Spartina Project have also shown that acetic acid may hold promise for killing rhizomes of smooth cordgrass (*Spartina alterniflora*) (Anderson 2003). A sanitary district in Humboldt County has been evaluating acetic acid for control of floating vegetation in some of their treatment ponds. An ongoing APMP demonstration project is underway to evaluate its effectiveness and environmental impacts in control of duckweed (*Lemna* spp.) growth (Mark Bryant, *pers. comm.*). In Kansas, acetic acid can be an effective contact herbicide for common weeds in agricultural field plots (Lee DeHaan, *pers. comm.*). As with barley products, acetic acid has not been registered or formally tested for use as a pesticide, so it has uncertain legal status. Increased acidity in the water body may have severe effects on non-target aquatic organisms.

Management Considerations For Organic Material Amendment

All of the organic material amendment techniques can be difficult to apply at large management scales. Barley straw added to the water column tends to float on the surface, which can lead to homeowner complaints. Attempts to contain the barley straw in sacks can reduce effectiveness (Tom Jordan, *pers. comm.*). Commercial products, such as barley pellets, barley straw bales, “pond pads”, and barley extract are readily available (Jane Sooby, *pers. comm.*). They can be purchased on the World Wide Web or ordered through pond management magazines, such as Doctors Foster Smith (www.DrsFosterSmith.com) or Water Gardening (www.watergardening.com). A half pound of barley straw ranges in cost from \$5-\$15, and marketers claim this amount can be used to treat 500 to 1000 gallons for approximately 6 months. Barley hay can also be purchased in bulk from agricultural sources for only \$1 - \$3/bale. In urban areas, storage may not be readily available for bulk quantities (Tom Jordan, *pers. comm.*). Sediment amendment is typically applied in dewatered systems, because materials like barley straw tend to float. Development of techniques to produce barley straw slurries or other easily spread materials may improve application efficiency and effectiveness (Parker and Systma 1998; Systma and Parker 1999). Although acetic acid is relatively inexpensive to purchase, it can be dangerous to handle in concentrated form. Concentrated acetic acid can cause burns to skin and eyes, requiring protective clothing, and appropriate environmental conditions for use (Parker and Sytsma 1998).

Plant Competition

Nuisance aquatic plant impacts may be reduced by introduction or augmentation of other plant populations. The more desirable plants may compete with nuisance species, thereby impeding their growth and spread. Nevertheless, the addition of competing plants remains a highly experimental procedure with limited field applications or assessments of effectiveness (Holdren et al. 2001). The best results will be seen when the nuisance plant is controlled before the native plant is added in order to prolong the effectiveness of the initial control technique (John Madsen, *pers. comm.*).

In a Massachusetts lake, native *Chara* sp. was experimentally planted in areas harvested for Eurasian watermilfoil. The researchers found that areas with transplanted *Chara* plants remained resistant to milfoil invasions over the duration of the two-year study (Monnelly et al. 2003). For selected Wisconsin water bodies, The Nature Conservancy plants shoreline areas with wild rice, a native emergent plant. The replanting efforts are perceived as successful methods of reestablishing native vegetation (Hannah Spaul, *pers. comm*.). Spikerush (*Eleocharis* spp.) has had some success in crowding out nuisance plant species in many aquatic systems, including irrigation drainage canals (Sytsma and Parker 1999). Spikerush has a low growth habit and negligible effect on water flow, which are desirable characteristics. There is also some evidence that these plants secrete a growth inhibitor that is absorbed by surrounding plants. Slender spikerush (*Eleocharis acicularis*) may be more suited for California water bodies.

PHYSICAL AND MECHANICAL CONTROL METHODS

This section includes all methods that involve destruction or removal of nuisance plants by physical or mechanical methods. Mechanical methods include harvesting, cutting, rotovation, weed raking, hand pulling, dredging, channel clearing, and excavation. All of these methods involve direct damage to the target nuisance species (typically aquatic plants) by physical removal or destruction. Physical methods also involve physically manipulating the water body or immediate plant environment to reduce survival or growth of the nuisance species.

Mechanical Harvesting

Mechanical harvesters are large machines which cut and collect aquatic plants. They remove the upper portion of the plant and are able to cut five to ten feet below the water surface. The weeds collected by the harvester can then be transferred to an upland disposal site. Harvesting immediately removes surface mats of plants and opens up the area, which can help maintain boat lanes. Due to the size of the machines, only larger areas with a sufficient depth are suitable for this treatment. The same area may need to be treated twice or more per growing season to maintain control of the nuisance weed (Kimbel and Carpenter 1981; U.S. Army Corps of Engineers 2002).

Mechanical harvesters are currently available in California, with several contractors offering these services and harvesters available for purchase from local and national companies (Appendix A). Several companies commercially produce harvesters, including Aquarius Systems (http://www.aquarius-systems.com) and Aquamarine (www.aquamarine.ca). PMC Production, a California based company, produces harvesters commonly used by local contractors (http://www.pmcproduction.com/). Miller Aquatic Technologies actively markets some of their harvesters as cost effective for management on canals, small ponds, and other narrow and shallow waterways (http://www.milleraquatics.com/harvesters.html).

In other parts of the country, harvester technology has developed to provide specialized responses to local plant management concerns. For efficient control of plant problems in the very large waterways of Florida, large-sized harvesters have been developed. Harvesters used in Florida reach up to 95 feet in length and work very efficiently in large-scale projects (Bill Haller, *pers. comm.*). Although such large harvesters may not be appropriate for many California water bodies, they may be useful for managing *Salvinia molesta* in the Colorado River.

A significant problem with mechanical harvesting is the often rapid regrowth of the plant after harvesting. In a study of Eurasian watermilfoil control in a Minnesota lake, total shoot biomass and plant abundance was only reduced for six weeks following the harvest (Crowell et al. 1994). Plant growth rates were higher in the harvested areas than unharvested areas. As a result of the rapid regrowth, harvesting must be conducted multiple times in a growing season to achieve adequate control. For example, in a Wisconsin lake, monthly or bi-monthly harvesting was most successful for controlling Sago pondweed (Madsen et al. 1988), a plant common throughout California (DiTomaso and Healy 2003). In some water bodies, multiple harvesters must be operated daily during the growing season to fight off the constant plant regrowth (e.g., Lake Minnetonka Conservation District 2002). Local municipalities, such as the City of Oakland, often purchase and maintain their own harvesters to achieve this constant control.

Sometimes, specialized mechanical harvesting innovations can increase control efficiency, thereby reducing frequency of harvesting required. In particular, cutting at the base of the plant stem can dramatically reduce regrowth rate. In Wisconsin, a mechanical harvester was modified with a blade that could cut Eurasian watermilfoil to within 0.6 m of the sediment surface (Unmuth et al. 1998). Long-term control was achieved in deep waters (greater than three meters), where 46% of cut channels persisted for three years after the study. Control was less effective in shallow waters (less than three meters), with only four percent of channels remaining clear. One of the Aquatic Pesticide Monitoring Program demonstration projects will evaluate a mechanical cutter designed to remove plants at the root, which may also reduce plant regrowth rate (Ross Holton, *pers. comm.*).

Timing and frequency of harvesting may also affect the regrowth of the nuisance species. In Wisconsin, harvests in autumn are likely to cause strong reductions in

Eurasian watermilfoil total non-structural carbohydrates (carbohydrates used for future growth), and consequent regrowth rate (Kimbel and Carpenter 1981). In a Florida study, repeated clipping of hydrilla stems significantly reduced rate of producing reproductive tubers. Tuber reduction was more pronounced when plants were clipped prior to formation of a dense canopy. This result suggests that repeated harvesting during tuber forming time-periods may reduce hydrilla recruitment (Fox et al. 2002).

Disposal is a very difficult issue with wide scale harvesting applications such as the Sacramento-San Joaquin Delta (Cynthia Gause, *pers. comm.*). Disposal costs constitute almost 25% of the annual harvesting budget for control of Eurasian watermilfoil in Tahoe Keys (Greg Tischler, *pers. comm.*) In Florida, large harvesting machines dispose the plant material in areas of the same water body since launching and on-land disposal would dramatically increase cost (Bill Haller, *pers. comm.*). CDBW has met with substantial permitting difficulty in their efforts to dispose of plant material on levees or other locations near Delta water bodies. For example, the Central Valley Regional Water Quality Control Board (CBRWQCB) mandated that they obtain written approval from individual landowners, prior to disposing of plant materials on levees. The CBRWQCB also determined harvested plant materials to become waste discharges once removed from the water, creating difficulties in NEPA and CEQA permitting (Cynthia Gause and Marcia Carlock, *pers. comm.*). Although not insurmountable, permitting issues do delay the implementation of harvesting projects in sensitive areas like the Delta.

The Waterways Experiment Station (WES) of the Army Corps of Engineers has developed computer programs to assist managers in developing effective mechanical harvesting plans. The HARVEST program, developed by WES, will simulate the cutting, collection and transport of a nuisance species in an aquatic system (Madsen et al. 1998). It has been used in California to determine the current production capacity of harvesters operating on Big Bear Lake, and to identify locations where new offloading sites could be developed to increase harvesting efficiency (ReMetrix 2001). HARVEST is available for free by ordering a CD-ROM copy of APIS (Aquatic Plant Information System) from WES. APIS is an interactive CD-ROM that provides information on aquatic nuisance species, their distribution, and the current control methods available (U.S. Army Corps of Engineers 2001; http://www.wes.army.mil/el/aqua/apis/apishelp.htm).

Peer reviewed studies are lacking on the cost-effectiveness and environmental impacts of harvesting in California waters. However, a number of successful harvesting programs currently exist in California. One example is mechanical harvesting of Sago pondweed in Clear Lake, CA. At three locations in Clear Lake, mechanical harvesting was conducted in a combined area of about eight acres. Approval was obtained from the Lake County Department of Agriculture to assure that there would be no interference with active hydrilla control. It was reported that a boat that followed the cutter retrieved about 80% of the cut weeds. The only observed fish mortality was one small catfish. The subsequent clean up was messy, as about 15 cubic yards of fragments were removed from the shoreline. Overall, it was stated that mechanical harvesting was an effective method for nuisance control with immediate results (Lake County Water Resource Division 1999). Mechanical harvesting programs are also actively employed by the Tahoe Keys Property Owners Association (Greg Tischler, *pers. comm.*) and the City of Oakland (for Lake Merritt; Richard Bailey, *pers. comm.*). Many estuarine and inland water bodies, such as Lake Van Ness (City of Visalia), Winchester Lake (Reclamation District 999), Westlake Lake (City of Westlake), and San Mateo Lagoon (city of San Mateo) are managed by contracts with private contractors (Dave Najara, *pers. comm.*; Tom McNabb, *pers. comm.*; George Forni, *pers. comm.*; Bob Weber, *pers. comm.*).

Harvesting and removing cut plant material may be preferable to leaving plant material in place in eutrophic (high nutrient) systems, because it may decrease the amount of nutrients available for primary production. Carpenter (1980) predicted that half of the flux of dissolved total phosphorus (DTP) and dissolved organic material (DOM) from the littoral zone (shallow area) to the pelagic zone (open water) is from the decay of aquatic plants. The prediction, based on a eutrophic hard water lake in Wisconsin, suggests that aquatic plants can compose a substantial pool of nutrients that mechanical cutting would free up for algal growth. Harvesting of macrophytes removed 37.4% of the annual phosphorous inputs and 16.4% of nitrogen inputs to a eutrophic lake in Wisconsin during a late August harvest (Carpenter and Adams 1977). This may decrease within-lake nutrient levels but does not decrease the external loading of nutrients to a water body. Although harvesting may decrease within-lake nutrient levels, algae production may continue to remain high due to high external loading or nutrient release from sediments.

The price per acre of mechanical harvesting may range from $500-800, excluding mobilization, and the cost for equipment purchase ranges from $35,000 to $110,000 (Washington State Department of Ecology 2001). Regular harvesters can remove plants at rates of approximately one to four acres per day, depending on the size of the machine and plant density (John Madsen, *pers. comm.*). Larger water bodies with widespread infestations may require several harvesters to achieve plant control (e.g., Lake Minnetonka Conservation District 2002). Disposal options and fees are another consideration. Sometimes permits have to be obtained to dispose the plant biomass and disposal fees apply for landfill sites.

Environmental Effects of Mechanical Harvesting

Mechanical harvesting operations can have impacts on water quality, fish survival, and future distribution of problem weeds. Unlike many mechanical control methods, the environmental impacts of harvesting have been evaluated extensively in numerous studies.

Water body nutrient concentrations may be reduced by the harvesting and removal of plants (Carpenter and Adams 1977). Harvesting may initially increase the turbidity and dissolved solid concentration of a system (Alam et al. 1996). In some cases, harvesting may have no short-term impacts on water quality. For example, Carpenter and Gasith (1978) found no significant difference in particulate phosphorus, total Kjeldahl nitrogen, DOC, BOD or dissolved reactive phosphorus between control and cut plots in a eutrophic lake. In the longer term, harvesting can reduce internal loading of dissolved phosphorus that occurs via natural macrophyte senescence (Carpenter 1983). Nevertheless, the amount of nutrients removed in a typical harvesting program is usually much less than the total rates of internal nutrient recycling and external loading to a water body (John Madsen, p*ers. comm.*). In contrast, chemical application may increase internal phosphorus loading by plant senescence (Carpenter and Adams 1978). Ultimately, harvesting may slow succession of highly eutrophic lakes (Carpenter 1981).

Harvesting is not recommended for fast moving waters, due to the potential risk of spreading an invasive plant species. Harvesting is also not advisable in water bodies with early infestations of plants that spread by fragmentation. Plant species of particular concern include Eurasian watermilfoil (*Myriophyllum spicatum*), parrotfeather (*Myriophyllum aquaticum*), hydrilla (*Hydrilla verticillata*), and Brazilian egeria (*Egeria densa*) (John Madsen, *pers. comm.*). There is evidence that standard harvesting operations release viable fragments of *Egeria densa* in the Delta (Anderson et al. 2000). If fragments of plants are not captured by the harvester, they can be hand collected to eliminate the possibility of spreading the plant parts to new areas. If all available niches are infested already, harvesting is an option to be considered to reduce plant biomass, while leaving the bottom part of the plant intact for habitat as well as sediment stabilization. In Clear Lake, permits from the Department of Food and Agriculture will only be issued for harvesting in areas more than ¼ mile away from sites infested with hydrilla (Nate Dechoritz, *pers. comm.*).

Mechanical harvesting can have both negative and positive effects on aquatic life. Harvesting can result in direct mortality to and removal of fish, invertebrates, and turtles (Mikol 1985; Booms 1999; Madsen 2002). Booms (1999) estimated that 39,000 fish and 700 turtles were removed during the harvesting of a Wisconsin lake from May thru mid August. Unmuth et al. (1998) estimated that 36 fish/hectare were removed in a harvest. Nevertheless, these removals of small fish and invertebrates may have limited impacts on the overall populations. For example, Armitage et al. (1994) found no significant difference in macroinvertebrate richness or abundance between stream areas treated with chemicals or by harvesting. Monahan and Caffrey (1996) found that mechanical cutting reduced macroinvertebrate community composition and abundance more than chemical treatment but abundance increased rapidly after cutting and there were no observable effects to fish.

Part of the effect of harvesting is the alteration of underwater habitat. Garner et al. (1996) indicate that after cutting, reduction in available plant cover causes declines in fish growth and *Cladoceran* densities. When applied to create habitat variation, harvesting can positively affect growth of some fish species. For example, when channels are created to enable access of predatory species, harvesting can reduce stunting of smaller fish. Olson et al. (1998) found that creating deep lake channels by harvesting increased the growth rates of some age classes of bluegill and largemouth bass. Another strategy to create variation in habitat is to harvest in alternating sections of a water body with alternating years. For example, in a river or canal where water delivery is needed, a channel may be cut adjacent to opposite banks on alternating years (Garner et al. 1996).

Harvesting may also impact plant diversity in lake systems. Species diversity was found to be greater in unharvested areas than harvested areas in Lake Wingra, Wisconsin (Nichols and Lathrop 1994). Long-term monitoring of harvested lakes in Wisconsin showed a decrease or no change in the number of native species and a decline or no change in the watermilfoil frequency (Helsel et al. 1999).

Mechanical Cutting

Mechanical weed cutters can cut plants several feet below the water surface or can cut emergent plants above the water surface. The distinction between mechanical cutting and mechanical harvesting is that while harvesters remove cut plant material from the water body, mechanical cutting machines do not remove the cut plant material. Therefore, the cutters can operate demonstrably faster compared to harvesters. Generated floating plant fragments may be removed from the water to prevent them from re-rooting or drifting. Clean up can be accomplished using a weed rake or specially designed nets. As with harvesting, areas may need to be cut several times during the growing season.

In limited circumstances, cut plants may be left in the water to decompose. This significantly reduces control costs because removal, off-loading, and disposal are not required in these situations. This method usually requires shredding of the plants into small pieces. It is only appropriate for species not likely to spread by fragmentation, or in dense infestations requiring rapid control. However, the cut vegetation may increase water column nutrient concentrations and turbidity (James et al. 2002).

Recent mechanical cutting technologies not readily available in California waters include “juicers” and highly efficient mechanical shredders. Several demonstration models have been developed of the “juicer” or “grinder”, which grinds the cut plant material to a fine pulp and thereby is believed to create non-viable fragments. The addition of nutrients to the water column may be a concern (William Haller, *pers. comm.*;

John Madsen, *pers. comm.*). Most models of this system are prototypes that are not widely available for commercial use. One model, "the Crusher," will be evaluated as part of an APMP (Aquatic Pesticide Monitoring Program) demonstration project in 2004.

Shredding machines may be a cost-effective, large-scale operating alternative to harvesters. The shredded plant material is left in the water, and effects of decomposing plants to the water chemistry have to be studied. Commercially available shredders include the Swamp Devil (Aquarius Systems; http://www.aquarius-systems.com) and the Cookie Cutter. The Cookie Cutter is effective for destruction of extremely dense stands of wetland or emergent vegetation. It is a barge with two hydraulically driven knifelike blades, which spin rapidly, shredding a three-foot swath of vegetation in its path, and even grinding through soft sediments. It may create access and available habitat for shorebird nesting, but may also aid seed and fragment dispersal (U.S. Army Corps of Engineers 2001). Additionally, a prototype shredder designed for water hyacinth control (the Terminator; http://www.aquasolutionsusa.com/) can be hired for large projects. In Vermont, a shredding approach was conducted to control waterchestnut (*Trapa natans* L.) and generally killed the plants without adversely affecting water chemistry or causing nutrient problems (Ann Bove, *pers. comm.*). The effects of shredding on water quality in Delta water hyacinth stands is being evaluated by the APMP (NCAP Annual Report 2003, Greenfield et al 2003).

As with mechanical harvesting, mechanical cutting should not be conducted in circumstances where infestations are likely to spread. This includes fast moving waters, in addition to early infestations of species that spread by fragmentation. When shredding machines are used on species that spread by fragmentation (e.g., *Egeria densa,* Eurasian watermilfoil, hydrilla), there is substantial risk that the shredded material will spread to other locations and actually increase infestation. Therefore, mechanical shredding without removal is generally more appropriate for species that do not always spread by fragmentation, such as water hyacinth. In closed water bodies with complete weed coverage, shredding may be useful on any aquatic species for controlling plant biomass and achieving boat access (Madsen 1997; John Madsen*, pers. comm.*).

As with mechanical harvesting, effects to other aquatic organisms should be considered. Most literature to date has focused on effects of mechanical harvesting, with little evaluation of effects on ecosystems where cut plants were not removed from the water body. A mechanical shredding study found no significant difference in macroinvertebrate benthic community density, diversity, or richness after shredding of waterchestnut in a Vermont lake (Fiske 1999). Further research is warranted on the effects of cutting operations to animal populations.

In California, mechanical cutting is frequently performed by resorts, marinas, and other relatively small lakeshore recreation managers to maintain access to their site. An example is the Soda Bay resort of Clear Lake, which performed cutting weekly from June 15th through September 29th 1999. The resort had cutting equipment that attached to a boat and cut to a depth of five feet. After cutting, the fragments were removed from the water with rakes and pitchforks, distributed for composting at another privately owned location, and used for garden mulch (Lake County, Water Resource Division 1999). This use of low-tech, relatively inexpensive, but labor-intensive methods, is typical of mechanical cutting operations conducted by lakeshore commercial enterprises.

Many agencies and companies build their own mechanical cutting boats for plant management in local ponds and canals. For example, Environmental Waterworks, an Orange County contractor, has built and operates a mechanical cutter that is operated on a boat 20' long, 5' wide, and weighing 600 pounds (Steve Walters, *pers. comm.*). Solano Irrigation District also constructed its own mechanical cutter, which it uses for weed control in selected irrigation ponds. Small boat operated cutters are appropriate for isolated small ponds such as those found in golf courses, where cut materials can be pushed to the banks and removed manually. Specialized underwater weed cutters can also cut weeds in water as shallow as ten inches and as deep as five feet.

Mechanical cutting by hand held brush cutters has also been used experimentally on *Spartina alterniflora* in a Washington state bay. Cutting with herbicide application was more effective than cutting or application alone. This method reduced stem density and stem height when measured at the one-year post treatment mark but did not eradicate the plant (Major et al. 2003). *Spartina alterniflora* is threatening the native *Spartina* species in the marshes in and around San Francisco Bay, and integrated approaches, such as mechanical cutting with herbicide applications, are currently in development for its control (ISP 2003). Mechanical cutting was also utilized on the nuisance weed waterchestnut (*Trapa natans* L.) in lakes in New York state. Cutting experiments reduced seed production, though some seeds were still produced (Madsen 1990; Methe et al. 1993).

With the exception of specialty shredders like the Terminator, Swamp Devil, and Cookie Cutter, manual cutting is relatively inexpensive. Portable boat-mounted cutting units cost from $400 to $3,000. Specialized underwater cutters cost about $11,000. These tools are commercially available but can also be constructed in homemade fashion. Since no expertise is needed to operate these tools, costs can be limited to the purchase of cutting implements. Disposal fees may apply (Washington State Department of Ecology 2001).

Rotovation, Rototilling and Hydroraking

Rotovation and rototilling are methods for chopping up and disturbing plants, focusing on the base of the plant, including submerged portions. A rotovator is a barge-mounted rototilling machine that lowers a tiller head about eight to ten inches into the sediment to dislodge plant root crowns. Whereas rototilling could only be used with emergent vegetation, rotovation can also be used to control submerged vegetation. Unlike harvesters, rotovators do not have the capability to collect the uprooted plant material and the buoyant root masses float to the surface. The plant material may then be removed by a harvester following the rotovator, manually collecting plant material from the water surface, or raking along the beaches. However, the risk of spreading the infestation due to a large number of plant fragments is still high. Since the entire plant is removed from the sediment, rotovation can often reduce plant biomass throughout the growing season, sometimes even for two seasons (Gibbons et al. 1987).

Water bodies suitable for rotovation include larger lakes or rivers with sufficient depth. Rotovation may not be appropriate in salmon-bearing waters, since it causes increased short-term turbidity. Additional risks include the potential impact of contaminants released from the sediment as well as the resuspension of various nutrients to the water body. Rototilling can be used for control of emergent wetland vegetation, such as *Spartina*, cattails, and bulrush.

A rotovation attachment is available as part of the Aquamog mechanical system. The Aquamog has an excavator arm which accepts a number of different attachments. The rotovation attachment for the Aquamog is 10' wide, weighs about 2,000 pounds, and has 4 rows of spring steel tines that are off-set to increase efficiency at dislodging aquatic plants (BBMWD 2003).

In Washington, the Willapa National Wildlife Refuge uses rototilling, in combination with targeted chemical spraying to control invasive *Spartina alterniflora*. Spraying during low tide with rototilling during the winter appears to work well (Jonathan Bates, *pers. comm.*). Oregon has used rotovation to control Eurasian watermilfoil (Sytsma and Parker 1999). Winter tilling to a sediment depth of 4-6 inches reduced stem density by 80 – 90% for 2 to 3 years of control.

As with mechanical harvesting, the risk of spreading viable plant fragments must be considered for rotovation and rototilling. For example, when *Spartina* stands are rototilled, viable rhizomes may be released and wash out to other areas with tidal movement (Vanessa Howard, *pers. comm.*). The potential for spread of viable *Spartina* fragments to new locations has not been studied for locations such as San Francisco Bay.

Hydroraking is a similar method to rotovation. In hydroraking, a heavy-duty metal rake is attached to a hydraulic arm, and then dragged across the lake bottom to dislodge buried plant material. As with rotovation, management considerations include disposal, and the potential for spreading of plant fragments, turbidity, and disturbance to bottom habitat (Holdren et al. 2001; Ann Bove, *pers. comm.*).

Costs for rototilling, rotovation, and hydroraking vary according to treatment scale, density of plants, machinery used, and other site constraints. Contract costs for rotovation range from $1,200 – $1,700 per acre. Disposal fees may also apply (Taylor and Gately 1998).

Weed Rollers and Sweepers

Weed rollers and sweepers are relatively new methods to control nuisance weed infestations in small locations. Weed rollers include a long metal cylinder (up to 30') attached to a dock or piling on one end. A motor drives the cylinder forward and backwards in a 270-degree arc from the attachment point. The cylinder compresses young plants and soil in the area. Fin-like blades on the roller remove taller plants from sediment and may remove roots. For weed control, use once per week should be sufficient (Washington State Department of Ecology 2001).

The use of rollers may disturb bottom dwelling organisms and spawning fish. Plant fragmentation of nuisance weeds may also occur (Washington State Department of Ecology 2001). Furthermore, in soft bottom areas, sediment disturbance can be significant (Terry McNabb, *pers. comm.*). Concern has also been expressed about the use of weed rollers on sediments high in organic matter. The Minnesota Department of Natural Resources regulates management of aquatic vegetation and requires permits for the use of weed rollers to protect littoral habitats (Minnesota Department of Natural Resources 2004).

The Lake Sweeper is an automatic weed control device that may be used in similar areas to the weed roller. Like weed rollers, the Lake Sweeper is attached at one end to a dock or other fixed location and consists of a 24' – 42' metal pole that moves forward and reverse in a 270-degree arc. A pump provides the force to move the floating pole back and forth. Instead of rolling along the sediment, the Lake Sweeper floats along the lake surface, with a series of lightweight rakes dragging behind it. According to the manufacturer, these rakes can kill a variety of submerged aquatic plants within 3 to 5 days by gradually weakening the plants. The Lake Sweeper may be an economically viable management option for small, high use locations. Purchase cost for a Lake Sweeper is approximately $2,000. Installation is said to be simple and operating costs are reported by the manufacturer to be very low (Kretsch 2003). Contact information for the manufacturer (Lake Restoration, Inc.) is available in Appendix A. The potential for the Lake Sweeper to increase rate of release of viable plant fragments has not been independently evaluated.

Diver-operated Suction Dredging

Diver dredging is a mechanical control technology for plant removal, in which divers use pump systems to suction plants and roots from the sediment. The pumps are mounted on barges or pontoon boats and the diver uses a long hose with a cutter head to remove the plants. The plants are vacuumed through the hose to the support vessel where plants are retained in a basket and sediment and water are discharged to the water body. A silt curtain can be deployed to the treatment site to control turbidity (Washington State Department of Ecology 2001).

The cost of diver dredging can vary depending on density of plants, type of equipment used, and disposal requirements. Nevertheless, it is typically a costly control option. State regulations on contract divers for dredging work are stringent and prevailing wage rates are high. Two divers and a tender are needed. Costs can range from a minimum of $1,100 per day to upwards of $2,000 per day with actual removal rates varying from approximately ¼ to one acre per day (Taylor 1998).

Considered a selective technique, driver dredging is particularly well suited for low-level, early infestations of noxious weeds. It can also be used to assist in long-term maintenance following herbicide treatments. Diver dredging is not recommended for control of aquatic beneficial plants (WDFW 1997). It has shown success in controlling noxious species, such as Eurasian watermilfoil. For example, suction dredging increased the number of native plant species one year after dredging and reduced the biomass of Eurasian watermilfoil in an oligotrophic lake (Boylen et al. 1996).

Sediment Removal

Sediment dredging has been used to remove nutrient rich sediment from irrigation canals. Plant propagules can also be removed when large amounts of sediment are dredged. Increased turbidity and suspended sediments can occur with this method. In a field study, plant biomass had a patchy distribution in areas where sediment was dredged compared to control sites (Sytsma and Parker 1999).

Shading and Piping

Shading may reduce plant/algal growth by limiting the amount of photosynthetically available light. Shading can be established by shade fabrics, canal bank vegetation, or piping (putting irrigation underground) for irrigation systems (Sytsma and Parker 1999). Piping and shading can also reduce water loss due to evaporation. High storm water runoff and extensive maintenance requirements can be problems associated with these methods. Aquashade, a chemical product added to waters to reduce light penetration, is another shading method; it is discussed in the "Non-Conventional Chemicals" section of this review. Shading is also one of the mechanisms of control for bottom barriers, described below.

Experimental studies have evaluated shading as a control method with varying degrees of success. Field experiments in English drainage channels showed that low shade (white geotextile material with 38% PAR reduction) and high shade (black geotextile material with 92% PAR reduction) had no significant effect on curly pondweed (*Potamogeton crispus* L.) biomass (Sabbatini and Murphey 1996). Filizadeh and Murphey (2002) provided evidence that shading may be effectively combined into integrated methods. In this study, shading combined with application of the herbicide, diquat, significantly reduced biomass of Sago pondweed (*Potamogeton pectinatus* L.). The combination of cutting, shading and diquat had better control on plant biomass than any of the methods tested individually (Filizadeh and Murphy 2002). Pondweeds are distributed throughout California, including the Bay region and Central Valley (DiTomaso and Healy 2003).

For irrigation delivery canals, replacement of the canal by piping is an effective, long-term shading option. Pipes up to 36 inches in diameter can be readily installed in existing canal beds, and are likely to be able to transport 15 to 20 cfs. Pipes also provide for significant water conservation by eliminating seepage and evaporative losses. However, pipes are very costly to install, and not always appropriate for control of storm water flows (Sytsma and Parker 1999).

Bottom Barriers

Bottom barriers are semi-permanent materials that are laid over the top of the plant beds. They are analogous to using landscape fabric to suppress the growth of weeds in yards. By eliminating the sunlight from the area, bottom barriers interfere with photosynthesis, causing covered plants to die.

Although bottom barriers may kill and remove plants originally present, once the barriers are removed, the nuisance species often rapidly recolonizes. This has frequently been observed for Eurasian watermilfoil. In one study, Eurasian watermilfoil re-colonized 44% of grid squares within 30 days of benthic barrier removal (Boylen et al. 1996). In Lake George, New York, and in a Wisconsin study, Eurasian watermilfoil rapidly re-colonized sites after barriers were removed, indicating a continuing need for control after removal (Eichler et al. 1995; Helsel et al. 1996).

Bottom barriers have had some success in lakes in Wisconsin, New York, and Washington, but were not reported successful in Clear Lake, California. In Lake George, New York, no plants remained after use of a PVC barrier (the Palco™ barrier), but there were plants under mesh screen (Aquascreen™) barriers (Eichler et al. 1995). In Wisconsin, Palco™ liners completely eliminated all plants under the barrier (Helsel et al. 1996). In a 700-acre Seattle-area reservoir, bottom barriers were used to control a new infestation of milfoil plants. In this system, the bottom barriers were part of a successful eradication program that did not use herbicides (Zisette 2001).

In California waters, bottom barriers are being used in a variety of management circumstances, including some integrated control and innovative methods. The Invasive Spartina Project is conducting experimental evaluations of bottom barriers constructed of biodegradable fiber cloth for control of new *Spartina* infestations. Use of these biodegradable materials reduces the possibility that bottom barrier material will pollute the ecosystem, because barriers can be difficult to retrieve (Erik Grijolva, *pers. comm.*). In offshore waters of the southern California coast, bottom barriers are currently part of an integrated program to eradicate the noxious algae, *Caulerpa taxifolia*. In this program, plants are covered with vinyl containment tarps, and solid chlorine pucks are placed under the barriers. This combination of chemical and non-chemical stressors has been successful in eradicating this hardy species (Bill Paznokas, *pers. comm.*). Bottom barrier pilots in Clear Lake have been less successful. Bottom mats, installed at a Clear Lake resort, had sediments and vegetation growing on top of them within a year, and the area had to be mechanically harvested (Lake County Water Resource Division 1999).

Bottom barriers are more difficult to install in water bodies where currents or strong tides occur. The installed fabric can loosen, float to the surface, and cause danger to boat traffic or swimmers. Because of this, bottom barriers may be difficult to maintain in tidally influenced areas of the Sacramento-San Joaquin River Delta, estuarine areas, and coastal areas.

Bottom barriers will result in the loss of habitat for benthic organisms due to the loss of the bottom vegetation. A physical and chemical evaluation of sediment conditions under synthetic fabric barriers showed that invertebrate density declined up to 90%. Benthic barriers apparently blocked sedimentation and caused an increase in NH_4 and a decline in dissolved oxygen to near zero beneath the fabric. Community effects were reported to be more severe in warm water. However, biotic conditions recovered quickly after barriers had been removed (Ussery et al. 1997). Nevertheless, the impact would be limited to the area where bottom barriers are applied, and would be unlikely to have widespread impact on a large water body.

Bottom barrier material costs vary depending on the type of material used. Costs can range from $0.1 – $0.6 per square foot; costs for professional installation are an additional $0.25 - $.50 per square foot. Bottom barriers are generally not a cost effective method to control infestations covering large surface areas. They are appropriate to control growth in specific areas, such as adjacent to marinas and docks.

Bottom barriers and covers may be used for irrigation canals. Lining irrigation canals with concrete or geotextile material can reduce the substrate available for plants to root (Sytsma and Parker 1999). Sediment deposition may reduce the long-term effectiveness of this procedure.

Manual Removal

Many programs involve manual removal of plants from the lake bottom. Typically, care is taken to remove the entire root crown and to not create fragments. In deeper waters, divers are often needed to reach the plants. Depending on visibility in the water, sediment type, and restriction on plant fragmentation, manual eradication methods may not be suitable for certain water bodies.

Hand removal has several advantages and disadvantages over more sophisticated methods of aquatic weed control. In shallow waters, or with floating plants, it requires little skill or equipment to manually remove aquatic plants. Therefore, the method can be employed by volunteers, untrained workers, or inmates, and large capital expenses are not required. With proper training, the method can be employed to selectively remove specific weeds, while limiting disturbance to desirable plants. The disadvantage to hand removal is that it is slow and labor intensive, and is therefore not generally appropriate for controlling large or dense infestations or eradicating plants with extremely rapid growth. One example of a manual removal effort that failed was a multi-agency pilot effort to control giant salvinia (*Salvinia molesta*) in the lower Colorado River. In this project, several dozen volunteers from various agencies used nets to scoop out many tons of salvinia. Because of the inability to remove all plant material, the great abundance of remaining plant material, and the extremely rapid vegetative regrowth, the project was considered a complete failure and was discontinued (Laura Crum, *pers. comm.*). In general, the method will prove most successful with early infestations or to maintain control in limited areas.

A hand-pulling program has been established for hydrilla control in several California water bodies. For example, in the Yuba canal, one CDFA Associate Biologist has been spending approximately five full months per year conducting hand removal of approximately 30,000-40,000 individual hydrilla plants. Plants were disposed of by drying and placing in a closed container in the trash. In the Yuba canal, the hand removal was conducted in combination with application of the copper herbicide Komeen™ to the water column. This integrated pest control method was reasonably effective at reducing hydrilla growth, resulting in a statistically significant reduction in tuber density over the sampling years (Ross O'Connell, *pers. comm.*).

A number of California agencies have expressed interest in conducting hand removal programs but have reported a surprising degree of difficulty with permitting issues. The CDBW intends to implement a hand-pulling program for water hyacinth in the Delta to augment current chemical control efforts. In this program, plants would be disposed of cost-effectively, by placing them along levee banks (USDA and CDBW 2003). This program has had difficulty obtaining the necessary permits for implementation. It did receive approval from USFWS and NOAA-NMFS, but has been hindered by difficulty obtaining NEPA and CEQA approval from the Regional Water Quality Control Board. Approval has been hindered by the concern that hand removal efforts may stir up the water body, creating a discharge of nutrients from the disturbed plants. Additionally, it was determined that landowner approval must be obtained to dispose of removed material on any levee banks (Cynthia Gause, *pers. comm.*).

According to the 1994 Integrated Aquatic Vegetation Management Plan Manual, hand-pulling expenses can run between $500 and $2,400 per day (Gibbons et al. 1994). As with diver dredging, removal rates for hand pulling depend on plant density, visibility, and sediment characteristics. Use of volunteer labor could considerably reduce costs. Some volunteer manual removal programs are quite sophisticated. For example, to control Eurasian watermilfoil in Lulu Lake, Wisconsin, volunteer divers with The Nature Conservancy clip individual plants at the base, and volunteer canoers collect and remove the resulting fragments (Hannah Spaul, *pers. comm.*).

Water Level Manipulation

Aquatic weeds can sometimes be effectively controlled by dewatering water bodies. This may involve pumping or releasing water via a dam or weir. Drawdown is frequently used in wildlife refuges by federal or state wildlife agencies or local duck clubs. For example, three months of drawdown can control emergent wetland vegetation (cattails and bulrush) at the Kern National Wildlife Refuge in California (Dave Hardt, *pers. comm.*). It is also viable in some man-made reservoirs and irrigation canals. Nevertheless, many water bodies lack the water level control structures needed to achieve significant plant control (Washington State Department of Ecology 2001).

Water drawdown can have variable impacts on water quality and aquatic plant survival. Water drawdown may increase phosphorus release from the sediment upon rewetting (Klotz and Linn 2001). Alternatively, phosphorus loading may decrease by increasing benthic oxygen levels, which favors sequestering of phosphorus in the sediment (Coops and Hosper 2002). If there is sufficient water flushing, drawdown can reduce water column nutrient concentrations and algae growth (Holdren et al. 2001). However, drawdown can have varying impacts on different rooted plant species, with some nuisance species not harmed by the manipulation. In fact, aquatic plant biomass can even increase after drawdown (Wagner and Falter 2002). The impacts of drawdown to flora and fauna are severe and this method should only be applied to water bodies where short-term habitat impacts are acceptable to resource agencies.

In systems where water levels may be readily controlled, water level manipulation may be used to control the timing of aquatic plant infestation growth. For example, in irrigation drainage systems, it may be possible to add water prior to the irrigation season, allow aquatic plants to grow, and then remove the water to kill the plants. This method may reduce the capacity for plant growth during the irrigation season by reducing the pool of available nutrients (Lars Anderson, *pers. comm.*).

If a water level structure is in place, costs may be minimal (Washington State Department of Ecology 2001). In some cases, natural fluctuations in water levels resulting from drought can result in substantial die-off of invasive aquatic plants (Gene Martin, *pers. comm.*).

Channel Clearing or Excavation

In some cases, it may be cost-effective to remove plant and surface sediment material from a water-body. This may be achieved by a mechanical excavator or by flushing material downstream of a given site. It may also be achieved by chaining, in which a chain is dragged along the channel bottom between two heavy-duty vehicles. Removal of plants and sediments may also reduce future growth by reducing the abundance of seeds and the pool of available nutrients.

These methods are more appropriate for storm water or irrigation canals, because the water level may be relatively low, access to the entire water surface is relatively easy, and the habitat value is not considered to be important. There is the potential for increased turbidity downstream of the target site, and disposal of removed material may be an issue. Often times, these methods are easier in systems having a hard-bottomed substrate or a concrete base.

Excavation is a method commonly used throughout California for management of irrigation canals and other small waterways. The Los Banos Wildlife Area (managed by CDFG) uses it for control of water hyacinth and water primrose in some of their irrigation canals (Bill Cook, *pers. comm.*). Mechanical excavation is also used on a limited basis at the Merced and Solano Irrigation Districts. These districts use excavators to remove sediment, overlying vegetation, and perennial below ground structures. They prefer to use chemical control, finding it more cost-effective in most channels, but use excavation in channels where there is a risk of chemical release into tightly regulated natural waters. The Solano Irrigation District channel is concrete lined, making it possible to remove most of the sediment, thereby limiting plant growth (Bob Acker, *pers. comm.*; Mark Vale, *pers. comm.*).

The Richvale Irrigation District relies on mechanical excavation for aquatic plant control in both main and lateral irrigation canals. They switched to mechanical methods 20 years ago, to avoid permitting issues, recreational concerns, and inadvertent fish kills in the public recreation area downstream of the irrigation canals. A single excavator operator can clear about one mile of ditch per day and the plant removal is reported to be very effective. Regrowth with this method is slow; typically, a single site requires excavation only once every one to three years. Spoils are stacked along the edge of the canals, and either used to maintain the adjacent roads or transferred to the canal edge to reduce erosion. The system is relatively easy to apply in this region, because the channel bed is composed of hardpan (extremely compacted clay), but it is appropriate (and used) for irrigation canals in other regions. Several other agencies subcontract with the Richvale Irrigation District, to have their channels excavated, at the cost of $75/hour (Troy Kellet, *pers. comm.*).

Sediment excavation may also be used in lake restoration, though the expense of the method is significant and success rate varies among water bodies. Sediment excavation has been used in a New York lake to remove thick organic sediment and an infestation of curly pondweed (*Potamogeton crispus* L.) from the lakebed (Tobiessen et al. 1992). Dredging the sediment bed with a Mudcat Model MC-10 hydraulic dredge resulted in a sustained (ten year) decrease in biomass of pondweed at the dredged sites. Dredging may reduce light availability to bottom dwelling plants by increasing the depth of the water column. Sediment dredging was not successful at a highly eutrophic lake in Sweden (Annadotter et al. 1999). Despite removal of 25% of the sediment area, phosphorous was still being released to the water column.

Exposure of Plants to Extreme Environmental Conditions (Heat, Steam, Flame, Cold, or Electricity)

In theory, aquatic plant survival and growth may be inhibited by subjecting the plants to extreme environmental conditions. Steam applications, exposure to heated water, flame, or freezing conditions could all kill vascular plants. In dewatered areas, high voltage electricity could be used to kill plants. In practice, these methods have received little study or evaluation for field application. The limited studies of these methods do indicate promising results (reviewed in Sytsma and Parker 1999). For example watermilfoil fragments exposed to heated water for ten minutes were severely reduced. A New Zealand-based company (Waipuna; www.waipuna.com) has developed a commercially available system, which sprays heated water directly on plants and then covers it with an organic foam surfactant, which traps the heat and kills the plants. The method would be appropriate for vegetation control in riparian or dewatered areas; in some management circumstances, it is comparable in cost and effectiveness to glyphosate applications (Quarles 2001).

Gourd and Ferrell (2003a, b, c) evaluated use of propane flame treatment and steam spraying using commercially available equipment for weed control. In their studies, two early season applications with a butane flamer generally controlled perennial weeds in irrigation canals and ditch banks. In contrast to flaming, steam spraying did not achieve adequate control in the work of Gourd and Ferrell (2003a). Although flaming appeared to be more effective than steaming, it could only be used in locations having low wildfire risks, and where permitted by air pollution laws.

Another potential alternative control method is application of extremely cold material to aquatic plants. Liquid nitrogen or liquid helium could be sprayed directly onto exposed portions of floating or emergent plants. This method has never been attempted (Jeffrey Stuart, *pers. comm.*). In dewatered areas, plants could also be subjected to high voltage electricity. The human health risks of both these methods would be considerable (Lars Anderson, *pers. comm.*).

Aeration, Oxygenation, and Water Circulation

In water bodies where excess growth of nuisance algae is a concern, water quality can often be improved by physically mixing the water (circulation), or interspersing the water with surface air (aeration) or pure oxygen (oxygenation). When applied correctly, these methods can help maintain oxygen levels throughout the water body, and reduce algae production (Holdren et al. 2001).

Aeration, oxygenation, and water circulation can all help maintain oxygen levels in the hypolimnion, which ultimately reduces algae growth by reducing the rate of nutrient recycling into the water. Thermal stratification can create a barrier to full mixing of the water column, resulting in a hypolimnion that is anoxic. Nuisance phytoplankton blooms can occur in the epilimnion of aquatic systems as long as there are ample nutrients and light available. This is particularly a problem in aquatic systems that have excess nutrients. Anoxia in the hypolimnion and the sediment-water interface can enhance the release of phosphorus and nitrogen from the sediment into the water column. Eventual mixing will bring these nutrients into the photic zone where they stimulate primary production (Horne and Goldman 1994). When used effectively, aeration, oxygenation, or water circulation control the release of nutrients from the lake bottom, thereby reducing algal growth and consequent reliance on direct herbicide application.

Many municipal water districts and waste treatment operations in California currently use aeration and circulation to reduce production of algae and foul taste and odor producing compounds. For example, Marin Municipal Water District has several aerators established in their reservoirs to maintain water circulation (Larry Grabow, pers. comm.).

In aeration, water-air surface exchange is increased by mechanical means, which can increase oxygen content of low-oxygen waters (Fast and Boyd 1992). In oxygenation, pure oxygen is injected directly into the water. The advantages of oxygenation to the hypolimnion (vs. aeration) are 1) maintenance of thermal stratification and a cold-water environment for fish habitat 2) an increased solubility of oxygen in water over air 3) an increased transfer efficiency and 4) avoidance of excess nitrogen in the water column (Beutal and Horne 1999). Methods of oxygenation include side stream pumping systems, deep oxygen injection systems, and submerged contact champer systems. All three systems have been able to increase dissolved oxygen concentrations in water, and some can reduce internal loading of nutrients from sediment to the water column.

There are two primary types of aerators, 'splashers' that aerate by dispersing water through air, and 'bubblers' that aerate by dispersing air through water (Fast and Boyd 1992). These devices can be run electrically or by solar power. The Solar-Bee© aerator uses solar energy to pump water from depth and disperse it over the surface. Initial cost of the Solar-Bee© is higher than non-solar aerators, but the energy savings over the long term may make Solar Bee systems cost-effective.

Some California agencies report using physical pumping or recirculation of water as a method to control production of nuisance algae. The Tahoe Keys Property Owners Association has established a series of water circulation pumps to control the algae problem (Greg Tischler, pers. comm.). The manager of Alameda Lagoon has also reported success with water aeration units, for breaking up algal mats (Tom Jordan, pers. comm.). For very small water bodies, practitioners have even reported using a spray pump and fire hose system to break up and sink algal mats (Tom McNabb, pers. comm.). The method may interfere with algal growth via water disturbance and movement of the algae to portions of the water column that inhibit development (e.g., areas with reduced light availability). Recirculation may also be achieved by installation of water pumps or fountains.

Studies of Aeration in Aquatic Systems

Hypolimnetic aeration may be useful in lakes that have internal loading of nutrients from bottom sediments to the photic zone. A number of peer-reviewed research studies suggest that hypolimnetic aeration may be an effective method of controlling algal growth and related chemical parameters. Prepas and Burke (1997) studied hypolimnetic oxygenation of a deep eutrophic lake in central Alberta over a six-year period. The hypolimnetic oxygenation resulted in reduction of phosphorus release from sediments, hypolimnetic reductions in ammonia, increased oxygen levels in the hypolimnion and an increase in nitrate + nitrite in the hypolimnion. Concentrations of total phosphorous, inorganic nitrogen, and chlorophyll-a all decreased in the epilimnion during the summer months. Continual aeration was necessary to maintain these conditions. The cost of the project was $30,000 capital costs and $49,000/year for aeration.

Cowell et al. (1987) studied full lake aeration in a small sinkhole lake in Florida. The aeration completely eliminated thermal stratification in the warm months. Dissolved oxygen of the bottom waters increased significantly and turbidity, pH, alkalinity, total nitrogen, hydrogen sulfide, and iron decreased significantly. Although there were decreases in many of the nutrients, and a decrease in blue-green algae, neither primary production nor chlorophyll-a concentrations changed significantly. The authors concluded that continued aeration over a few years may be necessary to reduce primary production.

Aeration was not successful in removing total ammonia nitrogen from waters under laboratory conditions (Chiayvareesajja and Boyd 1993). In aquaculture ponds, aeration increased dissolved oxygen in bottom waters and reduced soluble reactive phosphorus but increased total phosphorus due to re-suspension of phosphorous from the sediment (Masuda and Boyd 1994).

In addition to altering nutrient flux from sediment to the water column, aeration may also aid in fish growth and reproduction. In an aerated eutrophic Florida lake, total catch/hour increased by 50% over a non-aerated period of the same lake (Leslie et al. 1986). The aeration system was able to completely turn over the 10.5-hectare lake every 7 – 11 days. Costs, including capital costs, were $436/month for the two-year aeration period.

Nutrient Removal

In lakes or impoundments with a high degree of nutrient recycling from the bottom sediments, it may be possible to remove nutrient-rich waters or sediment directly from the bottom of the lake. This method is uncommon, and requires a good understanding of the chemistry and nutrient budget of the lake. Removal of nutrient-rich water appears to be working in Devil's Lake, an important recreational lake in southern Wisconsin (Richard Lathrop, *pers. comm.*). Devil's lake is characterized by water very rich in phosphorus in the deepest portion of the lake, resulting from historic loads of phosphorus. Natural resource managers with the Wisconsin Department of Natural

Resources have set up a 20-inch diameter siphon pipe running from the deepest portion of the lake out to an intermittent stream channel. To maintain the lake-level, water is pumped from a nearby stream, low in nutrients. Because the water nutrient concentration is highest at the lake bottom, the expectation is that withdrawal of this phosphorus rich water should limit nutrient loading and resulting algal blooms over the next 15 years. The project is also expected to reduce incidence of swimmer's itch and mercury concentrations in sport fish, as indirect results of the reduced lake productivity (Wisconsin Department of Natural Resources 2001; Richard Lathrop, *pers. comm.*).

NON-CONVENTIONAL CHEMICAL CONTROLS

In addition to conventional herbicides and pesticides, there are other chemicals that can be utilized to reduce primary production in aquatic systems. These are typically used to control development of nuisance algal blooms. Nuisance algal blooms create unpleasant conditions in recreational water bodies and can create taste and odor problems in drinking water reservoirs. Although not well studied, alternative chemicals may also be used for control of benthic algae and floating and submerged vascular plants. The US EPA has so far only approved Aquashade for use in aquatic environments. The effects of many other non-conventional control methods are not well tested, particularly for use in the littoral zone and for control of rooted or free-floating vascular plants.

Research has been conducted to study the effects of certain chemicals on the release of nutrients from anoxic sediments of eutrophic lakes. Eutrophic lakes can have internal source loading of nutrients from sediment to the water column, especially when the hypolimnion and porewater are anoxic. Primary production can be reduced by reducing nutrient concentrations in the photic zone. Under anoxic conditions, phosphorous, an important nutrient for algal/plant growth, is released from the sediment to the water column. Certain chemicals can be added to eutrophic lakes that can bind phosphorous and precipitate it out of the water column into the sediments where it stays sequestered as long as oxic conditions continue (Horne and Goldman 1994). Jaynes and Carpenter (1985) found that the roots of certain macrophyte species can release oxygen directly into the sediment, thereby changing the redox potential to favor sequestering of phosphorus in the sediment. However, the net flux of phosphorus into eutrophic systems must be determined as senescence of macrophytes may also be a source of internal loading.

These chemical applications have generally received little attention in California waters. Both rigorous scientific studies and field trials should be undertaken to evaluate the effectiveness of these methods in California lakes and reservoirs. Currently, the Marin Municipal Water District, funded by the Aquatic Pesticide Monitoring Program, is evaluating the effectiveness of gypsum and alum for control of benthic algae in one of their reservoirs.

Calcium-based Products

Calcium based products, including lime ($Ca(OH)_2$), limestone ($CaCO_4$), and gypsum ($CaSO_4$) are frequently used for control of aquatic algae and submerged aquatic plants. Several studies have documented reduced plant growth as a result of lime application. Repeated treatments (over a seven year period) to hard water eutrophic lakes in Canada reduced photic zone phosphorous and chlorophyll-a concentrations and average macrophyte biomass was reduced (Prepas et al. 2001). Single applications of lime gave short-term (< 1 year) control of phosphorous and long-term control (>1 year) of submerged aquatic plants (Reedyk et al. 2001).

Positive results have been observed in studies using iron gypsum ($Fe\text{-}CaSO_4$). Iron gypsum was effective in reducing hypolimnic total phosphorus (TP) by 90% and increased water clarity (secchi depth reading) from 50 to 270 cm in a Finnish eutrophic lake. One year after application, TP was reduced by an average of 62% for the entire water column (Salonen et al. 2001). Iron gypsum also reduced methane production and release, reduced release of phosphorous from anoxic sediment, and improved redox conditions in laboratory experiments utilizing sediments from a eutrophic lake in Finland (Varjo et al. 2003). The reduction of methane production is important because methane released from sediments can transport nutrients into the photic zone. Iron is important in adsorbing phosphorous in the sediment.

As compared to lime and iron-gypsum, limestone studies have had less positive results. Studies of limestone application in aquaculture ponds have shown mixed results in reduction of nutrients and algae production. In aquaculture ponds, limestone did not reduce TP or soluble reactive phosphorous (SRP) concentrations compared to controls (Masuda and Boyd 1994). Application in catfish ponds did not reduce TP, chlorophyll-a concentrations, or cyanobacterial abundance but oxygen production did decrease (Giri and Boyd 2000). Limestone application was not effective in reducing phytoplankton densities.

Aluminum based products

Alum ($Al_2(SO_4)_3$) is a salt that can precipitate phosphate out of the water column and sequester it in the sediment, thereby reducing phosphate availability to primary producers (Horne and Goldman 1994). In a French soft water eutrophic lake, SRP concentrations were reduced by alum, although alum was not added in sufficient amounts (due to potential aluminum toxicity) to reduce total phosphorus (Van Hullebusch et al. 2002). Despite low SRP, a bloom of the noxious algae species (*Microcystis* sp.) appeared. In the lab utilizing sediments from shallow eutrophic Swedish lakes, aluminum treated sediments released less phosphorous than untreated sediment. If sediment conditions are anoxic the dosing of alum is dependent on the concentrations of Fe-P (phosphate adsorbed to iron) as oxidation of Fe-P will release phosphate from the sediments to the water column. (Rydin and Welch 1998). Alum reduced SRP and turbidity in aquaculture ponds (Masuda and Boyd 1994), though repeated applications were necessary.

A 13-year follow-up study on a Vermont lake showed that one application of alum and sodium aluminate increased water quality. Summer photic zone total phosphorus and chlorophyll-a had decreased by 68% and 61%, respectively, since pre-application measurements. Weight loss occurred in large yellow perch for the first three years following application and the macroinvertebrate density decreased by 90% one year after treatment. The macroinvertebrate density recovered in all areas with some densities exceeding pre-treatment numbers (Smeltzer et al. 1999). Alum treatment was effective for a range of 8-11 years in polymictic lakes and a range of 13-20 years in dimictic lakes (Welch and Cooke 1999).

Nitrate

Nitrate has also been utilized to reduce internal loading of phosphorous from sediments to the water column. Sondergaard et al. (2000) injected low doses of nitrate into the hypolimnion of a thermally stratified eutrophic lake. Hypolimnetic dissolved organic phosphorous was reduced by 23 – 52% during the treatment years. Dissolved nitrate was more effective than granulated nitrate.

Many of the above chemicals are successful in sequestering nutrients in the sediment by precipitating nutrients out of the water column and sequestering them in the sediment. How these chemicals may affect aquatic and benthic organisms still needs to be addressed. For example, the iron in iron gypsum compounds can be harmful to animals. In lab studies of effects on zooplankton, particulate iron caused mortality and decreases in reproduction (Randall et al. 1999).

Aquashade

Aquashade is an EPA registered chemical that controls growth by filtering out photosynthetically available radiation (PAR) in the range of blue-violet and red-orange. Several contractors use Aquashade for control of algal growth in California waters. It is commonly used in recreational lakes and ponds, when homeowners are interested in reduced algae or aquatic plant growth. However, certain municipalities choose not to apply it because local stakeholders think it creates an unnatural appearance in the water body (Craig Crawford, Santa Clara County Department of Parks and Recreation, *pers. comm.*). In California, the Central Valley Regional Water Board has received a small number of applications to use Aquashade and calcium products for nuisance vegetation control. They did not instruct the applicants to seek an NPDES permit but are still awaiting guidance from the State Water Board on this issue (Emily Alejandrino, *pers. comm.*).

The limited available experimental research suggests that Aquashade is an effective method of controlling aquatic algae. Lab experiments have shown that applications of Aquashade in varying concentrations reduce the transparency of the water and increase the light extinction coefficient (K_d) over control locations. Aquashade absorbs light in the spectrum of 550 – 650 nm (Madsen et al. 1999). In the lab, application of Aquashade did not affect the oxygen uptake rates of the crayfish, *Orconectes propinquus* (Spencer 1984), suggesting that it is not toxic to crayfish. Additional research on how Aquashade affects plant/algal growth is necessary to see under what circumstances this method is successful.

Salt (Sodium Chloride)

Aquatic plants generally have limited salinity regimes in which they can survive, and exposure to saline conditions will kill hydrilla, Eurasian watermilfoil, and other freshwater plant species (Twilley and Barko 1990). Exposure of water bodies or dewatered areas to solid salts (sodium chloride) could potentially kill plant beds and inhibit future growth. However, addition of salt in large quantities would likely kill native plants and animals, along with introduced plants.

We have identified two case studies of salt addition attempts for control of aquatic plants. The Mountain View Sanitary District, in California, added rock salt to mowed cattails that had experienced a natural dewatering event. The practitioners hypothesized that the combination of multiple stresses (recent mowing, drying, and salt addition) would kill the plants. But their experiment was hampered by difficulties in implementation, including insufficient penetration of treatment area, followed by flooding, which ultimately resulted in insufficient salinity for toxicity (Dick Bogaert, *pers. comm.*). The other case study is Capital Lake, in Washington State. The Washington Department of Ecology is currently considering controlling Eurasian watermilfoil in Capital Lake by reintroducing salt water (historically, it was a salt water lake), but there is concern that saltwater influx would damage the newly developing freshwater ecosystem (Condon 2003). In summary, the addition of salt probably has limited application for aquatic plant control.

NPDES Permitting Status of Non-Conventional Chemicals

Alternative chemicals such as gypsum, lime, alum, acetic acid and Aquashade may be better received by the public than conventional target-specific pesticides. Also, in many cases, they are relatively inexpensive to purchase. However, as with barley straw, the permitting status of these chemicals is not clearly established. Calcium products, iron, and alum all reduce primary production by sequestering nutrients, rather than direct mortality to aquatic plants. Because their mechanisms of action do not direct mortality to plants or algae, they are not herbicides, per se. Aquashade, as well, functions by reducing light penetration, and is not a direct herbicide. Acetic acid does act as a contact herbicide, and has not been permitted as such, so it may not be appropriate for use by public entities.

In California, the Central Valley Regional Water Board has received a small number of applications to use Aquashade and calcium products for nuisance vegetation control. They did not instruct the applicants to seek an NPDES permit but are still awaiting guidance from the State Water Board on this issue (Emily Alejandrino*, pers. comm.*).

PREVENTIVE MEASURES

In addition to methods for removing nuisance plants, algae, or nutrients from water bodies, there are a variety of proactive methods to keep the infestation or algal bloom from occurring in the first place. Nutrient loading to water bodies can be curtailed by watershed management strategies. Nuisance species introductions can be limited by a variety of preventive measures. Extensive reviews have been developed elsewhere on the range of options available for both watershed management (e.g., Holdren et al. 2001; Lee and Jones-Lee 2002) and prevention of alien species invasion (e.g., Wittenberg and Cock 2001; Madsen 1997). A brief summary of available preventive measures follows.

Early Detection

The spread of invasive species can be controlled by patrolling water bodies, detecting early infestations, and removing the invasives before they have a chance to spread (Madsen 1997; Wittenberg and Cock 2001). Early detection can reduce the environmental and economic costs associated with noxious weeds. For a given water body, fewer resources are needed to remove early infestations than widespread infestations. In many instances, the costs of early detection programs can be limited by enlisting volunteers from environmental non-profits. In coordination with local management agencies, The Nature Conservancy is setting up a volunteer early detection program to control the spread of Eurasian watermilfoil in Adirondack State Park waterways in New York (The Nature Conservancy 2003; Hilary Oles, *pers. comm.*). States with active weed watcher programs include Minnesota, New Hampshire, and Vermont (Madsen 1997).

Coordinated early detection programs have not been established to control infestations in California fresh waters, though such programs would be appropriate for a number of noxious weeds. California does have a border quarantine in effect for hydrilla (described below). The Department of Fish and Game is conducting visual and sonar inspections of high-risk areas for the marine invasive plant, *Caulerpa taxifolia* (Johnson 2001).

Quarantine and Regulation

In some cases, the federal or state government can pass legislation controlling the spread or possession of nonindigenous species, including aquatic plants. The state of California has established a quarantine policy that restricts the importation of noxious species, including a number of aquatic invasive pests. State regulators are able to reject the import of shipments infested with viable fragments or seeds from hydrilla, Eurasian watermilfoil, water primrose, *Salvinia* species, and other aquatic and terrestrial weeds. These restrictions occur at the roadside agricultural inspection stations at the borders with other states. In the case of hydrilla, shipments of aquatic plants, such as vegetation in fish shipments, are also prohibited in entry from areas with large hydrilla infestations, unless accompanied by a certificate verifying that no hydrilla is present. Other species, including water hyacinth and water lettuce are restricted only from transition to locations where they are rare or currently being eradicated (CDFA 2003b), and the enforcement mechanism for these restrictions is not clear.

In addition to quarantine, there are additional legal protections and enforcements that can be undertaken to restrict invasion of aquatic pests. For example, the State of Washington has a list of invasive aquatic plants that are banned from sale within the state. The Oregon State Department of Agriculture enforces these bans by inspecting nurseries and pet stores for the banned plants. Civil penalties can result from sale of these plants (Hamel and Parsons, 2001).

On the Internet, most invasive aquatic plants are readily available for purchase. A recent search of the internet found that twelve highly invasive plants were found listed for sale by wetland nurseries and water garden dealerships throughout the U.S. and internationally. This finding indicates a clear need to improve development and enforcement of laws needed to prevent further introduction of noxious weeds from commercial sale (Kay and Hoyle 1991).

Education and Outreach

For many noxious weeds, educational information can be provided to water body users, to help reduce the probability of unintentional introductions. This information could be provided in the form of brochures, web sites, and posters. Additionally, signs can be posted at water body boat launches, bait shops, or nurseries where aquatic plants are sold, identifying nuisance species likely to be inadvertently introduced. The expectation is that once people are educated about the problem plants and how they spread, people will be less likely to put them in natural waters. To achieve this, educational materials often discourage disposal of nuisance species in or near natural waters, transfer of nuisance species between waterways (e.g., on boat hulls or trailers), or intentional release of nuisance species into the wild.

Riparian Buffer Strips

Buffer strips alongside waterways can impede the inflow of effluents, thereby reducing eutrophication. Planting native perennial species at the perimeter of water bodies may aid in the absorption of nutrients. This may also help reduce soil erosion (Lembi, 2003). In Gainesville, Florida, a non-profit organization (Adopt-A-River) works closely with local wetland biologists and municipal employees to plant riparian buffer strips on a city creek. To control costs, they populated the strips with native plants dug up from storm water ditches from other locations (Fritzi Olson, *pers. comm.*). In southern Wisconsin, The Nature Conservancy has extensive planting programs for native prairie and savannah grassland species. These programs are undertaken to achieve the duel benefits of conserving native grass species and improving the water quality of nearby lakes and rivers (Hannah Spaul, *pers. comm.*). Riparian buffer strips are also used to control storm water phosphorus loading from residential developments (e.g., Woodard and Rock 1995). As with many watershed management techniques, the cost-effectiveness of buffer strips for controlling bioavailable nutrient loading has not been systematically evaluated for California waterways (Lee and Jones-Lee 2002).

Retention Pond or Wetland Construction

Establishing a settling or retention pond or a wetland at effluent sources can allow nutrients to settle or be processed before they reach water bodies. Retention ponds can be used in agricultural settings, as well as to reduce loading from urban storm water runoff sources (Holdren et al. 2001; Lee and Jones-Lee 2002). A 30-hectare wetland was constructed to filter out the effluent from a wastewater treatment plant in Sweden (Annadotter et al. 1999). The effluent previously drained directly into very eutrophic Lake Finjasjon. After the wetland become operative, the lake Secchi depth increased from 0.9 to 1.5 meters, chlorophyll-a concentrations decreased and total phosphorous decreased by 25%. The use of wetlands as filters has long been established.

Watershed Best Management Practices

There are many additional methods to reduce watershed loading of nutrients to water bodies. People may implement Best Management Practices, activities or structures to prevent pollution. In agricultural systems, fertilizer input rates can be tailored to the specific soil types and crop yields of individual plots, thereby reducing the likelihood of applying excess nutrients to the watershed. Soil erosion and corresponding P losses can be further reduced by contour farming, strip cropping, or setting up permanent vegetative cover. There are currently little data in California with which to compare the effectiveness of these methods for reducing loading of bioavailable nutrients (Lee and Jones-Lee 2002).

For water bodies surrounded by residential development, landowners can be encouraged to properly construct and maintain septic systems, and limit shoreline erosion, to reduce the risk of nutrient loading. In some cases, wastewater treatment facilities can be improved to reduce point source nutrient loading, and significantly improve overall water quality (Williams 2001). There are many resources available to develop a wide array of additional Best Management Practices (Holdren et al. 2001).

RELATIVE RELIANCE ON CONVENTIONAL PESTICIDES VS. ALTERNATIVE METHODS

There was variation among different regions and practitioners in the extent of conventional chemical versus alternative methods used. These differences result from local, regional, and statewide differences in legal restrictions, varying experiences with feasibility of alternative methods, and amount of resources available to specific organizations.

Not surprisingly, alternative methods are practiced most extensively in locations where conventional pesticides are banned, strongly opposed by the public, or extremely difficult to permit. For example, in the Adirondack State Park in New York, conventional pesticides are highly restricted, resulting in exclusive reliance on alternative methods. Within the park, local lake management agencies attempt to control Eurasian watermilfoil with hand harvesting, benthic barriers, grass carp, and suction harvesting, depending on the degree of infestation (Hilary Oles, *pers. comm.*). In less regulated areas of New York State, many lake management associations apply for permits to apply fluridone or other conventional chemical pesticides (Nancy Mueller, *pers. comm.*).

Vermont tends not to rely on chemical methods because of public perception, and because one of the major concern lakes, Lake Champlaign, is on the border of VT, NY, and Canada, making regulations for chemical use very complex and difficult to address. The costs would be high to deal with the regulatory challenge of applying chemicals. The predominant methods are mechanical harvesting and hand pulling, with lesser reliance on diver operated suction dredging and chemical application (Ann Bove, *pers. comm.*). Recently, however, Vermont approved the use of whole-lake fluridone treatment for the control of Eurasian watermilfoil in two Vermont lakes (Getsinger et al., 2002).

Sometimes, within states with heavy reliance on conventional chemicals, localized infestations can be effectively managed using alternative methods. The Ichetucknee River in Florida is a good example of a high profile area where public interest has been harnessed to develop an effective hand-removal campaign. In this river, a three-mile stretch of water lettuce infestation has been effectively controlled using hand removal alone. Chemical pesticide applications were ruled out because the river is extensively used for recreational water sports and is also perceived as having high natural value that needs to be protected. The local hand-removal program effectively capitalizes on the high popularity and strong sense of stewardship for the river. Nine times per year, the local management agency recruits a crew of between 15 and 90 volunteer laborers, who manually harvest the water lettuce. Additionally, a permanent staff member "nitpicks," laboring every day to remove young water lettuce plants from among native vegetation. This extensive coordination has resulted in successful control of a very hardy invasive species. Meanwhile, at the statewide level, Florida management agencies rely predominantly on conventional chemicals to control water hyacinth and other noxious invasives (Fritzi Olson, *pers. comm.*).

Despite examples of alternative successes, many regions and agencies rely predominantly or exclusively on chemical pesticides, based on previous experience that the chemical pesticides were more cost-effective. For example, in Delaware Bay, non-native *Phragmites* are controlled by glyphosate application. After initial public opposition to chemical application, research tests were undertaken to evaluate non-chemical methods, both separately, and in combination with chemical application. The test results indicated that only chemical application was effective, resulting in exclusive reliance on herbicide application for *Phragmites* control (Teal and Peterson 2003).

The majority of aquatic plant management activity in Florida entails application of chemical pesticides. Numerous insect species have been introduced for biological control with varying success, but mechanical control efforts are restricted to high use areas (e.g., alongside bridges), and locations with high water flow velocity. After decades of trial and error with biocontrol and mechanical control options, Florida practitioners predominantly rely on chemicals, based on funding and institutional limitations, and the experience that the chemical pesticides were more effective in most management circumstances (Florida Department of Environmental Protection 2003).

Reliance on chemical pesticides can extend to non-profit conservation organizations, such as The Nature Conservancy (TNC). The Ohio chapter of TNC spent many years attempting to control invasive emergent species such as reed canary grass and *Phragmites* using mechanical methods. A multi-year effort to interfere with vegetation growth by repeated cutting was unsuccessful. Eventually, TNC Ohio chapter came to the realization that their objective of preserving biodiversity on their sites could only be effectively achieved by judicious use of chemical herbicide applications. They did not have the staff or financial resources to continue mechanical efforts. Currently, they routinely use glyphosate, but attempt to minimize total chemical pollution by methods such as manually sponging individual plants with chemical, and applying chemical to cut stumps (Marleen Kromer, *pers. comm.*).

Some states, such as Indiana, use companies partially owned by pesticide corporations as plant management specialists, and also have very widespread use of chemical control methods. ReMetrix, a company that works closely with the state of Indiana, uses remote sensing and other GIS technologies to accurately quantify biovolume and distribution of introduced plants. ReMetrix is partially owned by a major chemical manufacturer.

GENERAL PERMITTING REQUIREMENTS FOR NON-CHEMICAL METHODS

Most mechanical methods require the completion of a 1600 permit application from the Department of Fish and Game (DFG). The Department of Fish and Game will issue a no-fee permit for harvesting projects. No project size limits apply. DFG will restrict aquatic weed control during fish spawning season and approvals will be given for that time on a case-by-case basis. The disposal of plant material may require additional permits (Lake County Water Resource Division 2002).

Mechanical harvesting might require an endangered species permit from the U.S. Fish and Wildlife Service or NOAA Fisheries for anadromous fish species or other listed species. In addition, a waste disposal permit for disposing the plant material after harvesting might have to be obtained from the Department of Public Works. A California Environmental Quality Act (CEQA) document is also sometimes required for potential environmental impacts.

Diver dredging projects may require a federal permit from the U.S. Army Corps of Engineers. The necessity for the Corps of Engineers permit is site dependent (Washington State Department of Ecology 2001).

To stock grass carp in California waters, a planting permit must be obtained from the Department of Fish and Game. Also, if inlets or outlets need to be screened, an additional permit may be required.

GENERAL DISCUSSION

We found considerable variation in the amount of research and application among the alternative aquatic pest control methods. Some methods, such as grass carp, mechanical harvesting, calcium and aluminum based products, and aeration have been extensively studied for decades. For these methods, careful discussions with impartial experts and current practitioners could significantly help managers determine whether application would be appropriate in a given management scenario. Other methods, such as terrestrial herbivores, acetic acid amendment, salt application, shading, and use of native plants for competition, have been explored on a much more limited basis. For these methods, careful documentation of effectiveness and environmental impacts could really benefit future practitioners. Many methods have currently only been evaluated in research experiments, and have not been refined, or in some cases permitted, for wide-scale management applications. In California, on the initiative of local Mosquito and Vector Control Districts, a variety of fishes and one invertebrate species are currently being evaluated as alternative mosquito predators. Nationwide, plant pathogens and cyanobacteria control agents are current research topics, where more funding is needed before they can be applied in the field. Peer reviewed research on commercially available biocontrol agents suggests that, despite their popularity in the field, they are not effective for aquatic algae control.

Like permitted chemical pesticides, alternative aquatic pest control methods, when used improperly, can present environmental risks to aquatic ecosystems. In some situations, mechanical methods such as harvesting and rotovation could actually increase an aquatic plant infestation over the long-term, or cause the infestation to spread more rapidly to new areas. Introduction of new plant or animal species for use in biocontrol can have unintended consequences on an aquatic ecosystem. Caution is particularly warranted with introduction of non-native biocontrol species, given the fact that unlike chemical and mechanical pest control methods, introduced plants or animals could reproduce and spread to new water bodies, causing permanent ecological changes in widespread areas. The sterile grass carp program in California is a good example of a program with regulatory mechanisms in place to reduce the likelihood of widespread adverse impacts.

Preventive measures are sometimes overlooked as methods to control future spread of aquatic infestations. Extensive resources and effort are spent to control non-native aquatic weeds, with the potential for adverse environmental impacts. It would be appropriate for decision-makers in California to consider whether sufficient organizational effort is currently being targeted to preventive measures such as early detection, quarantine, and regulation of aquatic plant transport.

For a successful and cost effective non-chemical weed control program, managers should assess the environmental conditions, physical characteristics, and use of the water body in detail. They should then make a decision regarding appropriate treatment methods based on this evaluation. To avoid budgetary constraints in the long run, all factors have to be taken into account, and the most effective and least disruptive control method should be determined. Appendix C of this report provides a summary framework for managers to decide whether some of the most commonly used plant control methods may be appropriate for a particular management circumstance in California.

In many weed management situations a mix of techniques, possibly including non-chemical and chemical methods, will be appropriate. Currently, research on integrated approaches involving multiple methods is limited (Van Vierssen et al. 2001). Novel application and evaluation of integrated approaches should hopefully control nuisance aquatic species, while minimizing potential negative environmental effects.

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APPENDIX A: CONTRACTORS/ RETAILERS THAT SPECIALIZE IN NON-CHEMICAL CONTROL METHODS

This listing includes contractors who regularly perform some of the aquatic pest control methods described in the literature reviews. All California-based contractors we are aware of have been listed.

Contractors who conduct Non-Pesticide Control Methods

American Civil Constructors
3701 Mallard Dr.
Benicia, CA 94510
Contact: Dan Palmer
707-746-8028 x28
http://www.acconstructors.com/index.html

Specialties include: mechanical harvesting; mechanical excavation

Aquatic Environments Inc.
P.O. Box 1406.
Alamo, CA 94507
Contact: George Forni
925 314-0831
email: gforni@covad.net
www.aquaticenvironmentsinc.com/

Specialties include: mechanical harvesting, cutting, and rotovation; mechanical excavation; shading; biocontrol (bacteria); aeration; habitat restoration

Clean Lakes, Inc.
P.O. Box 3186
Martinez CA 94553
Contact: Tom McNabb
925 - 957 1905
1-877-FIX-LAKE
Fax: 925 957-1906
email: info@cleanlake.com
www.cleanlake.com

Specialties include: mechanical harvesting and cutting; shading; biocontrol (bacteria); aeration

Environmental Water Works

Contact: Steve Walters
714 801-8546
email: stevenwalters@msn.com

Specialties include: mechanical cutting and harvesting on small ponds, biocontrol

PMC Production
10173 Croydon Way, Suite 3
Sacramento, CA 95827
916 638-8990
fax: 916 638-8991
email: info@pmcproduction.com
http://pmcproduction.com/

Specialties include: mechanical harvesting and cutting

Southwest Aquatics
P.O. Box 13212
Palm Desert, CA 92225
Contact: Paul Beaty
760 568-5499
Fax: 760 568-4019
email: SWAquatics@aol.com

Specialties include: small pond management; grass carp

United Storm Water, Inc.
14000 E. Valley Blvd., Suite B
City of Industry, CA 91746-2801
Contact: Paul Corn
1-877-71-STORM
Fax: 626-961-3166
email: pcorn@unitedstormwater.com

Specialties include: mechanical excavation and dredging

Companies that Manufacture and Sell Aquatic Plant Harvesters or Other Non-Chemical Devices

Aquamarine
1444 S. West Avenue, Waukesha
Wisconsin 53186, USA
Tel: (262)547-0211
Fax: (262)547-0718
E-Mail: weedharvesters@aol.com
http://www.aquamarine.ca/

Aquarius Systems
PO Box 215
North Prairie, Wisconsin 53153-0215
262-392-2162 (phone)
800-328-6555 (toll free)
262-392-2984 (fax)
email: info@aquarius-systems.com
http://www.aquarius-systems.com/

Lake Restoration, Inc.
12425 Ironwood Circle
Rogers, Minnesota 55374
Phone: (763) 428-9777
Toll free: (877) 428-8898
Fax: (763) 428-1543
E-mail: lrmail@lakerestoration.com
http://www.lakerestoration.com/

Miller Aquatic Technologies LLC
358 S Main Street, No 86
Orange, California 92868
1-714-667-5053
email: info@milleraquatics.com
http://www.milleraquatics.com/

PMC Production
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916 638-8990
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APPENDIX C: FEASIBILITY SCREENING FOR DIFFERENT WEED CONTROL METHODS

This Appendix develops practical recommendations, based on best available science, for what control methods may be appropriate in different plant management scenarios. The focus of the Appendix is on alternative methods used to control aquatic weeds. The end-users of this information will include the California State Water Quality Control Board, special interest groups, and the various state, local, and private agencies that control aquatic plants. This Appendix is not an evaluation of all potential aquatic pest control methods presented in the main body of the report. Rather, it provides a general starting point for practitioners having little experience with aquatic plant control methods, to decide if some of the most commonly used methods are appropriate for their management circumstances. This information may also be a useful reference in permit preparation, as it summarizes the recommendations of local experts regarding what methods may or may not be appropriate in various management scenarios.

This Appendix presents tables indicating what non-chemical control methods may work for plant management scenarios that are common in California. Once a manager has identified a water body type and plant problem to control, they may use these tables to quickly determine potential control methods. The tables provide information on feasibility of the methods, expected control costs, and permitting requirements. These tables were developed based on the recommendations of the aquatic plant scientists and managers from the Non-Chemical Alternatives Environmental Economic Workgroup, interviews with field practitioners in the state, and reviews of the scientific and management literature on these plant control methods.

Table 1 depicts an initial screening of plant control methods, to determine which ones are likely to be feasible for a given water body and plant type (the methods are described in much greater detail in the main body of the report). Numbered cells indicate significant limitations that may make a particular method unfeasible in a particular management scenario. **Table 2** presents narrative information about the limitations of the particular methods. As with Table 1, this information is organized according to water body type and plant type. Additionally, environmental hazards associated with the methods are presented, as well as other potential limitations. Both tables should be considered in creating an initial listing of potential methods.

Table 3 indicates the permitting requirements of the different control methods. Permits that may be required include **Section 404 permits, Section 401 permits, 1600 permits,** and **NPDES permits**. Several other types of permits are only required for one type of method, as presented in the table. Several permitting requirements may be addressed by filing a Joint Aquatic Resource Permit Application (JARPA).

The Army Corps of Engineers (USACE) requires a **Section 404** permit if large volumes of soil, sediment, or vegetation are discharged into "waters of the United States". Waters of the United States are defined as any water body connected to U.S. navigable waters. Whether the discharge is of sufficient scale to require a permit is somewhat subjective, but permits are typically required for operations that discharge more than 750 cubic yards of material. The California Regional Water Quality Control Boards (RWQCB) administers **Section 401** permits, which are required for certain activities that affect water quality (these are also referred to as CEQA permits). For practices possibly requiring **Section 401** permits, an inquiry should be made with the RWQCB office. California Department of Fish and Game require "**1600 Lake and Streambed Alteration Permits**" for practices that may damage benthic habitat. **NPDES permits** are required for all chemical control methods that result in discharge of chemicals into "waters of the United States".

Additionally, many control methods may require that a **Biological Assessment** be submitted to USFWS and/or NMFS, who will then prepare a formal **Biological Opinion**. A formal review by these agencies will be required if there is the possibility that federally endangered or threatened species will be harmed or killed, or their habitat degraded, by the control methods. This pertains to locations where USFWS or NOAA/NMFS has identified habitat for listed species. The USFWS/NMFS reviews can take upwards of a year or more, particularly for projects that are not conducted in collaboration with a federal organization.

Table 4 presents general cost information on the implementation of the methods. This table can be usable to generate some "back of the envelope" cost calculations for the methods. Managers wanting guidance on how to perform a more detailed cost effectiveness analysis for their particular management scenario should consult the report prepared by Mann (2003).

With many aquatic weed species, the risk of further spreading of the infestation should also be considered in control method selection. This is particularly important for species that readily spread by fragmentation. Although it is difficult to exactly quantify the risk that a particular control method will cause new infestations to develop, Table 5 qualitatively compares the relative risk among control methods and plant species. It should be noted that the risk of control methods spreading infestations within or among water bodies is an area where future scientific research is needed.

Several aspects of the water body are important in determining whether further spread is a concern. Spreading poses a much greater risk in water bodies with outlets flowing into other water bodies. Also, great caution should be exercised in controlling new infestations or infestations that have not taken over the entire water body. For example, CDFA's hydrilla eradication program on Clear Lake does not permit methods that spread fragments in areas adjacent to hydrilla infestations (CDFA 2003a). In contrast, closed systems that are completely taken over by an infestation do not pose a significant risk for further spread. In these systems, method selection may be more driven by other factors, such as the method that is likely to provide immediate relief from the infestation.

For methods listed as high risk in Table 5, specific management practices may be conducted to mitigate the risk of infestation spreading. For example, booms, curtains, nets, or other structures may be set up in the water bodies to keep fragments from spreading.

There is a trade-off in presenting these tables; by condensing a wide variety of management recommendations into a short space, many subtleties are overlooked. Please refer to the main body of the report to address these subtleties. Tables 1 and 2 should be viewed only as practical screening devices for identifying methods that may be effective for a given management problem. Table 3 should be used as an indicator of what agencies should be contacted to evaluate whether their permits will be required.

Table 1. Look-up table for feasibility of aquatic plant management practices by water body and plant type.

	Water Body Type							Common Weed Species							Plant Type		
Practice	**Delta**	**Small Lake**	**Large Reservoir**	**Irrigation Canal**	**Stormwater Canal**	**Wildlife Refuge**	**Estuarine Wetland**	**Eurasian watermilfoil**	**Hydrilla**	**Water hyacinth**	**Pondweed**	***Egeria densa***	***Spartina***	**Cattail/Tule**	**General Emergent**	**General Floating**	**General Submerged**
Harvesting								5	4,5			5					
Cutting								5	4,5			5					
Excavation	1		1							2							
Manual Removal*																	
Bottom Barriers*	6			6	6		6			2							
Rotovation								5	4,5	2		5			2		
Water Drawdown	1						6		5		5	5	3	3	2		
Sterile Grass Carp	4, 8				3,8	4	3,8	7		7			3, 6, 7	3,6,7	2,3,6,7		
Insect								3	7		7	7	7	7			
Chemical Controls																	6

Cells containing footnotes may not be feasible because of reasons listed below.
*Method works best on small infestations
1 – Likely to be very costly and logistically difficult
2 – Unlikely to be effective
3 – Feasibility unknown; never tried in CA waters
4 – Illegal or possibly illegal in CA
5 – May enhance species or spread infestation
6 – Rapid water flow or estuary conditions may interfere
7 – Not a preferred food item
8 – Fish escape or mortality likely
9 – Effective biological control agent not available

Table 2. List of Aquatic Plant Management Practices And Limitations

Practice	**Description**	**Restrictions by Type of Water Body**	**Restrictions by Type of Plant**	**Environmental Restrictions**	**Other Limitations**
No Practice	No intentional actions to reduce aquatic plants			Plant impacts on the ecosystem and the environment may be unacceptable	
Harvesting	Cut, harvest and disposal	Potential for fragment release is worse in flowing water	May spread infestation for milfoil, hydrilla, egeria, or other species that spread by fragmentation	Will remove aquatic animals (e.g., juvenile fish), particularly in dense vegetation	Must have acceptable disposal location
Cutting	Cut aquatic weeds	Potential for fragment release is worse in flowing water	Likely to spread infestation for milfoil, hydrilla, egeria, or other species that spread by fragmentation	May add excess nutrients to water column and cause dissolved oxygen reduction	Collection may include weed rakes, nets. Environmental impacts may dictate whether collection is needed.
Excavation	Remove sediments and overlying plants. Methods include rotovation, chaining, suction dredging, backhoe with rake	Generally require easy shoreline access for cost effectiveness; preferable in dewatered systems		Turbidity and contaminant flux. May spread infestation downstream	May require waste disposal. Wastes containing sediments very expensive to dispose
Manual Removal	Individuals "weed" bottoms, may require divers				Works best for small infestations or small areas
Bottom Barriers	Semi-permanent materials laid over plant beds	Difficult to maintain in flowing or tidally influenced waters	Not usually effective for floating or emergent plants	Could affect benthic habitat	Often used near docks and marinas. Barrier material must be gas permeable

Table 2. Continued. List of Aquatic Plant Management Practices and Limitations

Practice	**Description**	**Restrictions by Type of Water Body**	**Restrictions by Type of Plant**	**Environmental Restrictions**	**Other**
Rotovation	Submerged aquatic rototilling	Water must be at least 6" - 8" deep, but not too deep	Will not work for floating plants	May contribute to turbidity and contaminant flux	
Water Level Drawdown	Dewater system to kill plants	Must have water control structures	Some species enhanced by drawdown		Must be sufficiently long time to kill plants. Greater control achieved in freezing climates
Sterile Grass Carp	Stock juvenile carp		Eurasian watermilfoil, parrotfeather, and water hyacinth not preferred foods	Can switch lake from macrophyte dominated to algae dominated. Not permitted in waters that outflow to other natural waters	There is risk that all plants will be completely eliminated. Must determine appropriate stocking density
Insect	Introduce insects that specialize in consuming target plants	Population establishment more difficult in flowing waters	Currently available in CA for purple loosestrife and water hyacinth. Insects have substantially controlled alligatorweed in coastal states from Virginia to Texas.	Pathogens or predators in system may reduce biological control agent population	Generally long-term efforts; results may take 5-10 years.

Table 3. Permitting Requirements For Aquatic Plant Management Practices (not definitive)

Practice	Permits That May Be Required
General	USFWS or NMFS formal Biological Opinion may be required
Harvesting	RWQCB Section 401
Cutting	RWQCB Section 401
Sediment Excavation	CDFG 1600; RWQCB Section 401; USACE Section 404
Hand pull	Certification required if SCUBA used.
Bottom Barriers	CDFG 1600
Rotovation	CDFG 1600; USACE Section 404; RWQCB Section 401
Water Level Drawdown	RWQCB Section 401; CDFG Permit to kill fish, if drawdown will cause mortality in natural waters
Sterile Grass Carp	RWQCB Section 401; CDFG Stocking Permit; Method only permitted when not contiguous with other California waters or in FEMA defined 100 year floodplain; not permitted in water bodies containing endangered species.
Insect	
Chemical Control	NPDES permits; RWQCB Section 401; applicator must be licensed by DPR

Table 4. Estimated Costs for Various Aquatic Plant Control Methods.

Non-Chemical Control	**Cost Estimates per Acre in U.S. Dollars**	**Number of Treatments per Growing Season**	**References**
Grass Carp	45 - 125	1	Washington State Department of Ecology 2001
Mechanical Harvesting	500 - 900	2 – 6 (2 – 3 for submersed, 3 – 6 for floating plants)	Washington State Department of Ecology 2001
Rotovation	1,200 – 1,700	1 - 2	Taylor and Gately 1998
Diver Dredging	1,100 – 2,000	1 - 2	Taylor and Gately 1998
Bottom Barriers	14,000 – 26,200	0.5	Taylor and Gately 1998
Mechanical Cutting	100 – 11,000	10 - 12	Washington State Department of Ecology 2001
Weed Rollers	2,000	10 - 30	Washington State Department of Ecology 2001
Manual Pulling	500 – 2,400	1	Gibbons et al. 1994

Note: A range of different environmental conditions and different contract agreements apply for all of the above methods.

Table 5. Relative Risk That Aquatic Plant Management Practices Will Cause an Infestation to Spread to New Locations.

H = high risk of infestation spreading; M = medium risk; L = relatively low risk. N/A = Method not appropriate for that species for other reasons.

Practice	**Eurasian watermilfoil**	**Parrotfeather**	**Hydrilla**	**Egeria densa**	**Salvinia molesta**	**Water hyacinth**	**Cattail/Tule**	**Spartina**	**Pondweed**
Mechanical Cutting*	H	H	H	H	H	M	M	H	H
Mechanical Harvesting*	H	H	H	H	H	M	M	M	M
Rotovation *	H	H	H	H	N/A	N/A	H	H	H
Sediment Excavation	M	M	M	M	N/A	N/A	L1	L1	L1
Grass Carp**	L	L	L	L	N/A	L	N/A	N/A	L
Hand Pulling	L	L	L	L	L	L	L1	L2	L
Bottom Barrier	L	L	L	L	N/A	N/A	L	L	L
Insects	N/A	N/A	N/A	N/A	L	L	N/A	N/A	N/A
Chemical Treatment	L	L	L	L	L	L	L	L	L

*Specific management practices may reduce potential of spreading (e.g., booms, curtains)
**Grass carp is an introduced species that may not be used when spread between water bodies is likely.
L1Assumes complete removal of cut/harvested material.
L2 Only seedling, or very young Spartina is feasible to remove by hand.

APPENDIX D: PEER REVIEW

The following peer review of this report was provided by Dr. John Madsen, Faculty Member, Mississippi State University. Dr. Madson is the author of many aquatic plant management publications, including "Advantages and disadvantages of aquatic plant management techniques," LakeLine 20(1): 22-34. Available at http://www.aquatics.org/pubs/madsen2.htm. This document has been revised in April, 2004, in response to the comments of this peer review.

Review of Report:

"Review of Alternative Aquatic Pest Control Methods for California Waters"

Written by San Francisco Estuary Institute

Reviewed by John Madsen, 2 March 2004

General Comments:

1. The review of alternative management techniques was complete in both breadth and depth, without being encyclopedic. I think the discussion of each technique was objective and balanced. I have made numerous specific points below, but I think that these points are, on the whole, minor.

My main comment is a caution in terms of how this review is used. For managing invasive aquatic plants we need all the tools at our disposal, without unnecessarily restricting our selection. To eliminate one set of tools, herbicides, from our arsenal would be as foolhardy as to use this tool in a completely indiscriminate manner. The exact balance between chemical and nonchemical methods is one determined by the species managed, the ecological system, and other factors. The main problem is the invasive plant species, not the management. Invasive species are the second leading cause of species extinction and reduction of species diversity, as well as having other negative impacts on ecosystems.

In particular, herbicides are the single best tool for managing intermediate to large dense infestations. While significant progress can be made with a number of difference techniques on small infestations, the use of alternative techniques becomes progressively more difficult as the infestations grow in size.

Eliminating herbicides from management planning may only serve to unnecessarily increase the cost of managing invasive plants, or allow infestations to grow in size unchecked to the point where available tools or resources are not capable of managing the population. Often, these are resources that might be better placed in mitigating nontarget impacts of management.

If we sit back and reconsider how we are managing invasive species, without continuing our management activity, the invasive species will not observe our moratorium. They will continue to grow, developing a larger problem once we decide to address the issue once more.

2. I sensed a general willingness to introduce exotic animals (insects, snails, etc.) to control exotic plants, in lieu of using synthetic pesticides. I think that, while it is a value judgment whether the risk of new exotic infestations is more significant than the risk from synthetic pesticides in the environment, the potential for these exotic biocontrol agents to then become a problem has not been addressed. Aquatic pesticides, to be labeled for use in the US, must have no evidence of biomagnification, must break down and dissipate in the environment, and have a short half- life. A biocontrol agent, to be effective, must biomagnify (e.g., reproduce), ha ve a long and increasing half- life, and not dissipate in the environment but in fact persist. As an ecologist, this concerns me. John Magnuson aptly put it in 1976, that managing exotics with exotics is playing with fire.

Specific Comments:

1. Literature review, pg. 5. You did not specifically cite the Aquatic Plant Information Retrieval Service (APIRS) at the University of Florida. They are a particularly good source of information on gray literature regarding aquatic plant management, at http://plants.ifas.ufl.edu/search80/NetAns2/.

2. Practitioner Survey, page 5. I commend you for interviewing practitioners – they are an important source of information that is often overlooked.

3. Fish Biomanipulation, Page 10. Fish biomanipulation only works on planktonic algae, and has generally been most successful in small lakes when combined with nutrient input control. In addition, most lakes have only had successful water quality improvement (e.g., reduction in algal growth) for a few years after manipulation. Fish manipulation usually results in an increase in the growth of submersed plants. Fish biomanipulation works best in shallow lakes when top predator fish are increased AND omnivorous, benthivorous fish (e.g., carp) are controlled.

4. Insect biocontrol, pg. 12. It is highly debatable how effective insect biocontrol has been for waterhyacinth in Florida. Florida State DEP officials put so little stock in its effectiveness that they have continued their management program of maintenance management with herbicides on small populations of waterhyacinth. While some researchers contend that biocontrol on waterhyacinth reduces plant height and flowering, they concede it does little to prevent the expansion of the mat.

The hydrilla flies have shown even less propensity to control hydrilla in the field, though sporadic declines of hydrilla have been noted in the presence of the hydrilla flies. This contrasts with the hugely successful use of the alligatorweed flea beetle to control alligatorweed, which rapidly reduced the aquatic infestations of this pest throughout

much of its range (though not its terrestrial or wetland growth). Other biocontrol projects with purple loosestrife and melaleuca have likewise shown demonstrable results.
All of the projects above are examples of the classical approach to biocontrol, in which insects that feed on the target plant are found in the overseas native habitat and, after a long series of studies, released into the wild in the US. Eurasian watermilfoil biocontrol is completely different. The naturalized milfoil weevil was found to feed on Eurasian watermilfoil, but also feeds on the native northern watermilfoil, but with less damage. By serendipity, the milfoil weevil can cause declines of Eurasian watermilfoil under laboratory, experimental field, and natural field conditions. However, there is no guarantee that these high populations of weevils are sustainable. Simply put, there is no theoretical basis for believing that release of the milfoil weevil alone with suppress Eurasian watermilfoil populations, and no operational plan for their use has been implemented. The only way to make the weevils work predictably is to perform augmentive releases from reared populations, a prospect that is prohibitively expensive.

5. Organic Material Amendment, page 17. While some organic additions may reduce algal growth and some rooted plants, they may actually increase the growth of waterhyacinth and other free-floating plants, which prefer acidic water for nutrient uptake.

6. Acetic Acid, page 18. Acetic acid is effective on waterhyacinth, but has not been approved for use in aquatic environments by the US EPA as a pesticide, and is unlikely to receive this approval. Likewise, application of acetic acid to aquatic vegetation will increase acidity of surface waters and impact aquatic life. While it may be effective for floating vegetation, I predict that the impact on aquatic life will be far more than conventional herbicides.

7. Plant Competition, page 19. I have done a number of plant competition or native plant revegetation experiments. Invariably, the nuisance plant must first be controlled, and then the native plant added. Native plant revegetation is less a control technique itself than a remediation to prolong the effectiveness of control – and even at that, it does not always work as intended.

8. Mechanical Harvesting, page 22. The main problem with mechanical harvesting is that it is relatively slow; a single harvester may only be able to cut 1 to 4 acres per day. Mechanical harvesting of large infestations is therefore problematic, requiring a large number of harvesters.

The ability of harvesting to remove nutrients from lakes has been dramatically overstated. Carpenter's calculations, while correct, assume that one harvests all of the plants in the littoral zone – an unlikely scenario. The amount of nutrients removed by a typical management program is usually far less than internal loading rates, much less external inputs to the lake.

9. Mechanical Cutting, page 24. One overlooked aspect of cutting is that it is demonstrably faster than harvesting, thus allowing the same area to be treated by fewer machines than harvesting.

10. Rotovation, page 26. Rotovation creates a lot of turbidity, resuspends nutrients from the sediment, and produces large numbers of fragments that may spread target species, even if a harvester is attempting to collect fragments.

11. Weed Rollers, page 27. The State of Minnesota (DNR) requires permitting of weed rollers and limits their size and location to reduce impacts on littoral habitats. They are particularly concerned about the use of weed rollers on sediments high in organic matter.

12. Manual Removal, page 31. Manual removal seems to work best when occasional scattered plants are the target, rather than dense growths of plants. Particularly with submersed plants, once the first plant is pulled, visibility drops to almost nothing and companion plants are difficult to locate and remove.

13. Non-conventional Chemical Controls, page 38. One overlooked problem with nonconventional chemical controls is that US EPA has approved none of these chemicals for use in aquatic environments as pesticides, with the exception of Aquashade. The effects of many of these chemical treatments on aquatic life are virtually unknown. While many of these chemicals are widely used on pelagic algal growth, with generally predictable results, their use in the littoral zone for control of rooted or free- floating vascular plants are largely experimental or untested.

14. Relative Reliance, page 44. While I agree that some natural resource and regulatory agencies are attempting to manage invasive aquatic plants, notably Eurasian watermilfoil, using alternative methods exclusively, in Lake George they are losing that battle. Alternative methods work best if the infestation is managed as soon as possible, and on populations before they reach dense beds of greater than 1 acre. Once dense beds are formed, it is difficult if not impossible to control them with available appropriate alternative techniques.

Vermont recently approved the use of fluridone to control Eurasian watermilfoil, with considerable success. The number of applications and pressure to follow this up with additional treatments in other lakes was significant.

15. Preventive Measures, page 47. I heartily concur that any aquatic plant management program should include an element of prevention – both to prevent the spread of the target plant to other waters, and to prevent the introduction of new invaders to the waters being managed.

16. Mix of techniques, page 47. I would concur that any aquatic plant management program should have a mix of manage ment techniques, including both chemical and nonchemical techniques. Preferably, nonchemical techniques would predominate when target invasive plant populations would reach small numbers and density. Likewise, any

management effort focusing on reducing the growth of planktonic algae must include reducing the source of nutrients in the watershed. With nuisance rooted and floating plants the problem, however, is not the management technique itself, but all-too-often is the results of an introduction of no nnative aquatic vascular plants.

17. Page 49. Recheck the citation for Caffrey et al. 1996. I suspect that this is an article authored by either Boylen or Eichler, in a volume edited by Caffrey et al.

18. Page 55. Madsen 1997 was cited in the text, but is not listed in the literature cited section.

19. Appendix 3, Table 2, page 82, No practice. The "no management option" overlooks the impact of the nonnative aquatic plant invader on the ecosystem and environment that, in some cases, can be significant.

20. Appendix 3, Table 2, Page 83, Insect. Insects may be available for waterhyacinth in California, but they won't make much difference to the problem growth of waterhyacinth in the Delta. You could add insects have substantially controlled alligatorweed.

21. Appendix 3, Table 4, Page 85, Mechanical Cutting. I think 10-14 cuts per year are pretty excessive for mechanical cutting of submersed plants and, even, emergent plants. I don't see why cutting would be an order of magnitude higher than harvesting, which is essentially the same thing except that the cut material is collected. This might need clarification.

22. Appendix 3, Table 4, Page 85, Mechanical harvesting. I think 1-2 cuts per year is on the low side for submersed plants (in California), and well below what would be needed for emergent and floating plants – a better estimate would be 2 to 6 (2 to 3 for submersed, 3 to 6 for floating plants).

Completeness of Report:

The report on alternative pest control methods for California waters produced by the San Francisco Estuary Institute is thorough in both breadth (options discussed) and depth, without being unnecessarily verbose or encyclopedic. The most likely and applicable alternative technologies are discussed, a significant proportion of the scientific literature (both peer-reviewed and agency reports) is reviewed, and a relatively balanced view presented.