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Benefits of Controlling Nuisance Aquatic Plants and Algae in the United States

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Introduction

Freshwater provides the very basis of human health, ecological sustainability, and economic and homeland security.

Abundant water resources are essential to the well-being of the United States. Freshwater provides the very basis of human health, ecological sustainability, and economic and homeland security. Aquatic resources are necessary for drinking water, food, fiber, industry, energy production, navigation, recreation, fisheries, wildlife, and biodiversity. Many actions can negatively impact the quantity and quality of water resources, including human construction and development, excessive discharges of industrial and human waste products, and elevated nutrient runoff from cleared lands. There is another more subtle and growing challenge to maintaining sustainable water resources, however—nuisance aquatic vegetation, especially introduced invasive species.

Invasive plants and algae have become major threats to rivers, lakes, wetlands, and riparian ecosystems.

Invasive plants and *algae*[1] have become major threats to rivers, lakes, wetlands, and riparian ecosystems. Most of these species have invaded from other continents—particularly Eurasia and South America—either accidentally or by design. Once established in their new environment, they easily spread within and between water bodies, infest nearby watersheds, and disrupt the ecological status quo with few natural checks and balances to inhibit their growth and spread. For example, Eurasian watermilfoil was first reported in 1987 in Lake Minnetonka and has currently infested 280 Minnesota lakes (Invasive Species Program 2014). Thousands of acres across the country are being degraded at an annual cost of tens of millions of dollars. These invasions do not respect political boundaries. Every watershed in the United States is at some level of risk.

This paper will present an overview of aquatic weed problems and how water bodies are degraded by nuisance plant infestations—ranging from fish and wildlife habitat to drinking water supplies to crop irrigation and more. Unmanaged growth of invasive vegetation alters critical habitat

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[1] *Italicized terms (except genus/species names and published material titles) are defined in the Glossary.*

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for threatened and endangered species. Most importantly, the cost-effective benefits provided by proactive and environmentally sound management strategies will be reviewed. The clear linkage between advancements in control techniques and the application of those methods on an operational scale will be noted in reviewing some case histories.

We must recognize that managing nuisance aquatic vegetation is, in reality, managing water.

Resources are generally lacking to fully implement invasive species management programs. Focus is spent on prevention, but once a species gets introduced there is often a lack of support and resources to actually manage the problem species, with such delays allowing for quicker spread of a species. This is partly because management is often left to private funding with regulation by local agencies, and there is a multidimensional use of the resources that must be considered. The price for this discrepancy is yet to be determined. As this paper will highlight, successful management can have a positive influence on the many uses of our waters. We must recognize that managing nuisance aquatic vegetation is, in reality, managing water. The importance of clean and abundant water to the progress and survival of civilization must always be considered.

Human Health Impacts

Entanglement and Drowning

Aquatic plants can harbor disease-causing organisms that adversely affect human health or may affect people more directly.

Aquatic plants can harbor disease-causing organisms that adversely affect human health (Marsollier et al. 2004) or may affect people more directly. For example, aquatic plants have entangled swimmers and caused or contributed to drowning. Although scientific reports specifically enumerating these deaths are not available, a quick search on the Internet reveals just how prevalent drownings influenced by aquatic weeds have become. From 1990 through 2007, 12 drowning incidents have occurred in either Eurasian watermilfoil- or hydrilla-infested waters of California, Florida, Minnesota, Texas, and Washington. These tragedies might have been prevented if timely aquatic plant management actions had been conducted.

Toxins and Drinking Water

Algae-producing toxins in freshwater are prevalent and can cause restrictions in drinking water supplies and contact recreation such as swimming.

Algae-producing toxins in freshwater are prevalent and can cause restrictions in drinking water supplies and contact recreation such as swimming (Carmichael 2001; Ferguson 1968). Toxin-producing cyanobacteria (commonly referred to as blue-green algae) are a serious and emerging issue for freshwater resource managers throughout the world and an area where more science is needed to fully understand their impacts. These cyanotoxins have caused domestic and wild animal deaths and have been implicated in human illnesses and even death (Backer et al. 2013; Sivonen and Jones 1999; Stewart et al. 2011). An *epiphytic* cyanobacterial species has been linked to avian vacuolar myelinopathy and implicated in deaths of bald eagles and other water birds in the southeastern United States (Wilde et al. 2005). They also negatively impact fish and other aquatic biota. The golden alga, *Prymnesium,* has been implicated in numerous fish kills (Sallenave 2010).

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Approximately 50 species of cyanobacteria produce freshwater toxins that are harmful to vertebrates, including humans. Common bloom-forming species have exotic scientific names such as *Microcystis*, *Anabaena*, *Planktothrix* (*Oscillatoria*), *Cylindrospermopsis*, *Aphanizomenon*, *Plectonema* (*Lyngbya*), and *Nodularia*.

Cyanotoxins fall generally into three groups—neurotoxins, hepatotoxins, and dermatoxins.

Cyanotoxins fall generally into three groups—neurotoxins, hepatotoxins, and dermatoxins. Neurotoxins—which include anatoxin-a, anatoxin-a(s), saxitoxin, and neosaxitoxin—primarily cause neurological symptoms, including paralysis and respiratory failure. A unique amino acid, ß-N-methylamino-L-alanine (BMAA), is widely produced by cyanobacteria. This amino acid has been linked to neurological disorders in humans, but occurrence and risk data are limited. It has been associated with an increased incidence of amyotrophic lateral sclerosis (Lou Gehrig's disease) and Alzheimer's disease. Toxicological data are limited, and it initially seems that neurological impacts may largely result from exposure to BMAA through bioaccumulation (consumption of organisms that feed on cyanobacteria) and not through recreational or drinking water exposures.

The second group of cyanotoxins—hepatotoxins—acts primarily on the liver and kidneys (as well as other organs) and includes microcystin (>80 variants or forms), nodularin, and cylindrospermopsin. Some data suggest that microcystins and cylindrospermopsin can be carcinogenic (causing cancer), cancer promoting, and teratogenic (causing birth defects). In the third group, the most common dermatoxin is lyngbyatoxin produced by *Plectonema* (*Lyngbya*) *wollei*, primarily causing skin irritation, rashes, and gastrointestinal upset.

Although each of the toxins acts somewhat uniquely, initial, low-level exposure may include skin irritation and gastrointestinal upset, regardless of the specific toxin involved (Graham, Jacoby, and St. Amand 2009). A critical need for scientific information regarding harmful algal bloom occurrence and impacts exists; thereby, responsible agencies can establish guidelines and limits where necessary to protect humans, livestock, pets, and natural resources. More than 100 wild elk were killed in New

Mexico in 2013 after drinking water contaminated with anatoxin-a, a neurotoxin produced by blue-green algae (Radford 2013).

Rooted aquatic plants can cause freshwater resources to be unreliable by producing and exuding organic compounds that make water difficult to treat for human consumption. Decaying aquatic plants and algae produce taste-and-odor compounds such as 2-methyl isoborneol and geosmin and cause drinking water to taste like soil or impart an earthy flavor (Ferguson 1968). Cyanobacteria can also produce these taste-and-odor compounds. The excess organic load contributed by aquatic weeds is a health concern for public water supplies because chlorination of organic material can result in production of trihalomethanes and other disinfection by-products that may be carcinogens. As societal demands for potable water supplies increase in coming years, managing nuisance plants (particularly algae) in drinking water sources will become more critical and costly.

Food Production—Irrigation

Rooted aquatic plants clog canals, impeding water movement at critical times for crop needs (e.g., during periodic droughts). They decrease water supplies through *evapotranspiration* and *percolation*. Rooted aquatic plants, along with filamentous algae, can also clog irrigation equipment (such as drip systems and micro-emitter sprinklers, which are highly efficient for crop watering), thereby increasing food prices. In 1950 there were 25 million irrigated acres in the United States, and by 2005 that number had grown to more than 60 million acres. Nuisance aquatic vegetation poses a serious risk to the irrigation systems serving these croplands. Approximately 31% of the water withdrawn for human use in the United States is for irrigation, and about 80% of that water is spent (i.e., not available for further use) (Madel 2010). The efficiency of water conveyance structures can be severely impaired by aquatic weeds. Even a moderate amount of aquatic weed growth can restrict flows enough to prevent water managers from being able to deliver adequate water to downstream users. As water for irrigation becomes more limited and managing that water becomes more costly, people can expect to pay more for food.

Spread of Insect-borne Diseases

Numerous diseases are known to be exacerbated by excessive growths of aquatic weeds (Fritsch 2013). As a primary example, aquatic weeds can harbor active breeding mosquito populations that carry the virus causing West Nile disease in humans. According to the Centers for Disease Control and Prevention, there were nearly 40,000 reported cases of West Nile disease in the United States from 1999 to 2013, but infection rates may be much higher than reported. During that same period, mortality from the disease was reported as more than 1,500 deaths (CDCP n.d.). In 2012 the West Nile virus killed 286 people (with the state of Texas hit hard by the virus), making that year the deadliest on record. Some forms of encephalitis or swelling of the brain can also be transmitted by aquatic insects that are harbored by aquatic weeds. Aquatic plants can decrease the effectiveness of mosquito control programs designed to limit transmission of this disease, and some are important key components in life cycle events of the insect (Burton 1960; Ferguson 1968).

Additional mosquito-borne diseases include eastern equine encephalitis and malaria. Schistosomiasis and lymphatic filariasis are also important water-related vector-borne diseases that can be intensified by aquatic weeds and the linkage to parasitic hosts. Most cases occur in the Atlantic and Gulf Coast states. Malaria, which is a human illness, is caused by a protozoan parasite in the genus *Plasmodium* and is transmitted by the bite of some mosquitos. Schistosomiasis is a collective name of parasitic diseases caused by several trematode species belonging to the genus *Schistosoma*. Snails serve as the intermediary agent between mammalian hosts. In other countries, mosquito-borne filariasis includes a group of diseases that lead to inflammation and obstructive lesions of the human lymphatic system.

Aquatic weeds are often important for optimal breeding conditions for mosquitos and provide food and shelter from predators. Nuisance vegetation can also hinder attempts to directly control disease vectors and intermediate hosts, and it has been implicated in transmission of harmful bacteria and protozoans such as those causing dysentery in food crop irrigation waters. Because of this aquatic plant–mosquito association, many of the early aquatic plant control programs were initiated by mosquito control districts (Gallagher and Haller 1990).

Economic Impacts

In the United States, invading alien species (plants and animals) cause major ecological damages and economic losses estimated at almost $120 billion per year (Pimentel, Zuniga, and Morrison 2005). The estimated annual damages or control costs associated with these aquatic nonindigenous species is approximately $14 billion (Pimentel 2005). Federal expenditures on invasive

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species are estimated at greater than $1.3 billion per year (NISC 2009). For the three aquatic or semi-aquatic weeds for which there are data available (Eurasian watermilfoil [*Myriophyllum spicatum*], purple loosestrife [*Lythrum salicaria*], and water chestnut [*Trapa natans*]), the loss attributed to these species is more than $800 million per year (Pimentel 2005). Other aquatic weeds contribute approximately $155 million in damages each year (Pacific NorthWest 2012; Pimentel, Zuniga, and Morrison 2005; Rockwell 2003). In contrast, the estimated annual net benefit of invasive aquatic plant control in 13 public lakes in Florida is nearly $60 million (Adams and Lee 2007).

Nuisance plants can interfere with or prevent the use of critical water resources and may adversely impact one's health or economic situation.

Nuisance aquatic plant economic impacts are derived from human needs and perspectives. In other words, these weeds prevent water resource use for a desired purpose while the weeds are growing prolifically until they reach some limiting factor (e.g., run out of water). Essentially, humans and aquatic weeds compete for the same resource—freshwater (Lake Champlain Basin Program 2013). Less than 1% of the water on earth is fresh, and in sufficient quality and quantity it can provide great health, economic, and aesthetic benefits. Often people find themselves in situations where the quality of water is inadequate for a desired use. Nuisance plants (both rooted aquatic plants or *floating* weeds and noxious algae) can interfere with or prevent the use of critical water resources and may adversely impact one's health or economic situation (NOAA Fisheries Service 2012).

Commercial and Recreational Navigation

Commercial goods and freight transportation interruptions by aquatic weeds could be very costly.

A major portion of commercial freight (including coal, petroleum, and grain) moves by water, and nuisance aquatic plants can interfere with movement of those goods. Approximately 25,000 miles of inland waterways in the United States (exclusive of the Great Lakes) are used to move approximately 630 million tons of cargo valued at more than $73 billion annually. Conveyance of many types of commercial freight can be accomplished most efficiently on inland waterways. Towboats may push more than 40 barges totaling some 23,000 tons as a unit. If the cargo transported on inland waters had to be moved by other means, an additional 6.3 million railcars or 25 million trucks would be required. Efficient transport requires less fuel and releases less carbon dioxide and other emissions. Further, water transport results in less traffic on crowded highways and fewer accidents and disruptions. Clearly, commercial goods and freight transportation interruptions by aquatic weeds could be very costly (in millions of dollars per year) (USACE 2010).

Left unmanaged, nuisance aquatic vegetation can completely shut down boating activity.

Aquatic weeds can also prevent or limit subsistence fishing, water skiing, and other water-based recreation. According to a recent analysis by the National Marine Manufacturers Association, recreational boating contributes $121 billion to the United States economy each year (NMMA 2013). The boating industry supports 964,000 jobs and 34,833 businesses, generates $40 billion in labor income, and drives $83 billion in spending on an annual basis in the country. Access to waters that are unimpaired by aquatic weeds is crucial to sustain this billion-dollar industry. Left unmanaged, nuisance aquatic vegetation can completely shut down boating activity; many boats are unable to pass through surface mats of submersed weeds.

Hydropower and Flood Control

Direct impacts of nuisance aquatic plants to hydropower production include clogging turbines and penstocks.

Direct impacts of nuisance aquatic plants to hydropower production include clogging turbines and penstocks, which increases costs of electricity to consumers (both homeowners and industrial). For example, hydrilla clogged the hydroelectric generators at Tom Miller Dam on Lake Austin in Texas, and it cost approximately $300,000 to stop the generators and clean the filtering system in 2003 (Vertuno 2003). This plant was also responsible for a $4 million shutdown in 1991 when a large mass of hydrilla broke free and clogged the water intakes at St. Stephen hydroelectric facility on Lake Marion in South Carolina (NCAES 1992).

Indirect impacts also include increased evapotranspiration by emergent plants, decreasing the available water for hydropower production.

Indirect impacts also include increased evapotranspiration by *emergent* plants, decreasing the available water for hydropower production. In addition, riparian trees and shrubs, such as salt cedars, seriously lower underground water tables via evapotranspiration in the desert Southwest (DiTomaso and Healy 2003). Despite the best efforts of engineers to design, construct, and maintain water conveyance structures and drainage ditches, rooted aquatic weeds such as hydrilla (*Hydrilla verticillata*) and alligatorweed (*Alternanthera philoxeroides*) have exacerbated floods (both amplitude and duration) and intensified harmful impacts on residential properties.

A water conveyance canal that is 35% obstructed by aquatic plants may be only 65% efficient in moving water. The potential flood damage due to these inefficiencies of the impeded canal would be a function of the rainfall event magnitude, the degree of aquatic weed infestation, and the density of affected activity in the flooded area (housing or agriculture). In hurricane-prone Florida, a property-damages-avoided method was used to estimate flood control benefits for an aquatic plant control project (Thunberg, Pearson, and Milon 1992). In that study, the ratio of flood control benefits to plant control costs was 148:1 (mean benefit-cost ratio). For agricultural land in Florida, aquatic plant control benefits were >$4,800 per acre of harvestable land for flood control in citrus groves (Thunberg and Pearson 1993).

Recreation Impairment and Property Values

Lakes and reservoirs support a myriad of water-associated recreation.

Lakes and reservoirs support a myriad of water-associated recreation, including primary contact recreation (e.g., swimming, diving, skiing) as well as secondary contact recreation (e.g., fishing, boating, camping). In a special issue of *National Geographic*, *Water—Our Thirsty World*, it is reported that people rank going to the beach or lake as a favorite vacation activity (Kingsolver, Larmer, and Johns 2010). More Americans fish than golf or play tennis. The U.S. Army Corps of Engineers is the largest federal provider of water-based recreation in the nation (USACE n.d.), and Corps recreation projects host 370 million visits per year. These projects are significant economic drivers for many communities and the nation; recreators spend $16 billion to visit Corps lakes. To further illustrate the use of lakes, an economic study of the aquatic weed control value in Guntersville Reservoir in northern Alabama showed that the recreational value of aquatic weed control to the 11-county region surrounding the lake was $120 million to $160 million worth of total gross output per year (Bergstrom et al. 1996). Unfortunately, as is often the case, there are very few public funds available to manage this water resource with such a benefit to the local economy.

Fishing is a significant part of recreation expenditures, and anglers have a unique view of aquatic weeds.

Fishing is a significant part of recreation expenditures, and anglers have a unique view of aquatic weeds: when the fishing is good and the weeds serve as an attractant or structure, they are happy; when the fishing is bad and they have difficulty getting their boats around (and cannot get to the fish) or have to clear their propellers every few feet, they are very unhappy (Henderson et al. 2003). Uncontrolled hydrilla growth in Florida lakes can have a ten-fold reduction in economic activity in local communities (Colle et al. 1987). It is clear that anglers spend a considerable amount of money on food, lodging, and transportation while pursuing fish, and aquatic weeds can adversely impact them in their pursuit.

Aquatic invasive species can depress land values and decreased property values often leave families “under water” in their home mortgages.

Waterfront property usually commands a large financial premium in most regions of the United States. Aquatic invasive species can depress land values, however, and decreased property values often leave families “under water” in their home mortgages. In a Wisconsin lake study, Horsch and Lewis (2008) concluded that water bodies invaded by Eurasian watermilfoil experienced a 13% average decrease in property values. These findings were confirmed by Johnson and Meder (2013), who reported a statistically significant, negative association between home sales price and milfoil infestations. Similarly, in a study of ten New Hampshire lakes, Halstead and colleagues (2003) concluded watermilfoil presence had a substantial negative effect on lakefront housing prices (20–40% decline). Agricultural property values can also decrease severely as aquatic weeds become more prevalent; this includes rice production and aquaculture farms (Lovell and Stone 2005; Thunberg and Pearson 1993).

Industrial Intakes and Water Supplies

Aquatic weeds can cause shutdowns in industrial production and increase the cost of goods produced.

Aquatic weeds can cause shutdowns in industrial production and increase the cost of goods produced. Aquatic plants have clogged intake pipes for industries requiring water for production and processes, such as cooling. Critical industries that need a reliable cooling water supply, such as nuclear and coal-fired power plants, have to closely monitor aquatic weeds (see earlier Hydropower and Flood Control section). Industries that maintain water supply reservoirs, or ponds, and those that have wastewater lagoons are also impacted by aquatic weeds. For example, gasoline supply in several eastern states became limited when a wastewater lagoon developed an algal bloom and a massive refinery had to close until the algae could be treated and the effluent could comply with the total suspended solids limits. The price of gasoline temporarily increased by more than 30% until the shortage could be alleviated (USDOE 2006). The close connections between water and energy provide ample opportunities for aquatic weeds to worsen already-precarious shortages in water supplies.

Ecological Effects

Nuisance plants and algae have the ability to negatively impact aquatic communities and habitat in primarily four ways: (1) structurally changing habitat through fast growth rates, greatly increasing populations and biomass; (2) dominating the capture of energy from sunlight; (3) stabilizing and limiting water exchange processes; and (4) producing large amounts of dead plant material, or detrital matter. These factors work in concert, driven by abiotic and temporal events expressed in site-specific water bodies. Long-term impacts typically result in the suppression of native plants, a decrease in overall species diversity, potential effects on threatened and endangered species, a shift in animal communities, and an alteration of ecosystem services.

Structurally Changing Habitat—Fast Growth, High Populations, and Biomass

Nuisance aquatic plant habitats can become too dense for optimal growth and survival of many aquatic animals.

Nuisance vegetation grows quickly, and species such as hydrilla can achieve growth rates of up to one foot per day (Glomski and Netherland 2012). They can be primary colonizers, rapidly adapting to the surroundings and capitalizing on new real estate. New infestations can become established in areas of disturbance, such as shorelines or reservoirs in which wave action creates sites for growth, or newly inundated areas or wetlands. These plants, however, also can invade and out-compete established plant communities over time (Madsen et al. 1991). As an example, hydrilla has a unique physiological mechanism in plants that makes it more productive under limiting conditions (Langeland 1996). Fast growth increases plant density, as well as total plant volume and weight (biomass), in a given area. This ability to rapidly increase in density and biomass allows a competitive advantage over other species, and the same ability can displace and/or eradicate native plant competitors (Madsen, Eichler, and Boylen 1988).

Nuisance aquatic plant habitats can become too dense for optimal growth and survival of many aquatic animals. Invasive *macrophytes* can form dense monotypic stands, which can change *macroinvertebrate* and fish densities and community structure as well as interactions between macroinvertebrates and fish (Dibble, Killgore, and Harrel 1996). An increase in plant density within aquatic habitats due to an invasion may increase macroinvertebrate density, but it can decrease fish-foraging efficiency. This shift to high densities of invasive plants will influence overall community composition.

Surface mats of submersed species can greatly limit light penetration into the water column, shade out native plants, and change community composition.

Despite a potential increase in habitat complexity due to invasion of certain macrophytes, investigators have found that macroinvertebrate densities decreased (Cheruvelil et al. 2002; Hessen, Skurda, and Braathen 2004; Stiers et al. 2011) or were not different (Phillips 2008; Theel, Dibble, and Madsen 2008) compared with native vegetation. Macroinvertebrate densities were negatively related to percentage cover of three invasive macrophytes (*Hydrocotyle ranunculoides*, *Ludwigia grandiflora*, and *Myriophyllum aquaticum*), probably due to *anoxic* conditions caused by dense mats that limited diffusion of oxygen and excess detritus (Stiers et al. 2011), suffocating the invertebrates. It is well known that *allelopathic* compounds produced by some plants can help protect other plants from disease and predation. Certain invasive aquatic macrophytes exude allelopathic chemicals that negatively affect epiphytic, herbivore, and fish growth and survival (Schultz and Dibble 2012). Compounds from some species can be lethal, or sublethal, to fish larvae and have the potential to change fish distributions and occurrence of affected species in invaded habitats (Linden and Lehtiniemi 2005).

Limiting Light and Water Exchange Processes

Floating mat species intercept most of the light entering aquatic environments in a given area. Under decreased light conditions, submersed macrophyte and algae production is limited, thus changing the aquatic community composition and food web structure (Troutman, Rutherford, and Kelso 2007; Villamagna and Murphy 2010). Researchers estimated that floating water chestnut mats decreased light transmission in a lake by 93%, which resulted in up to eight times less algal biomass and up to ten times fewer macroinvertebrates than *submerged* species could provide (Cattaneo et al. 1998). As with floating species, surface mats of submersed species can greatly limit light penetration into the water column, shade out native plants, and change community composition (Boylen, Eichler, and Madsen 1999). Dense surface mats of vegetation can decrease atmospheric gas exchange with underlying water and significantly lessen water exchange processes or flow, especially in shallow areas of lakes and reservoirs.

Dense submersed vegetation stands can dramatically increase water column temperatures, which can be directly stressful or even lethal to fish populations.

These situations can decrease the amount of dissolved oxygen (DO) in the water available to fish and other aquatic animals (Frodge, Thomas, and Pauley 1990; Kornijow, Strayer, and Caraco 2010; Schultz and Dibble 2012). In addition, dense submersed vegetation stands can dramatically increase water column temperatures—on a *diurnal* basis—which can be directly stressful or even lethal to fish populations (Caraco and Cole 2002; Frodge et al. 1995). Water temperature increases can also be indirectly lethal to fish—as water temperatures increase, low DO levels result because water's ability to maintain adequate oxygen concentrations decreases in aquatic plant stands (Getsinger and Dillon 1984).

Plant Material and Decomposition

Increases of plant material decomposition can cause negative effects on fish and invertebrate populations by increasing internal nutrient loading into aquatic systems (James et al. 2007). Such in-loads can increase phytoplankton and/or algae populations, placing such a demand on DO that it can create a very low hypoxic or even anoxic condition. This condition is generated by excess nutrient release from dead plant material decomposition (Stiers et al. 2011). Such a condition can cause high fish mortality and severely decrease, or even totally destroy, a fish community. Areas especially susceptible to high plant material decomposition effects are warm, shallow water environments such as ponds, small lakes, reservoirs, and estuarine and coastal ecosystems (Diaz 2001).

The Effects of Management Techniques

The detrimental effects of weeds on human water uses can be ameliorated and in some instances eliminated through management. Although these strategies are time consuming and costly, the ecological and economic return on investment is considerable. Drinking water supplies, water-based recreational activities, agricultural irrigation systems (food and fiber production), and industrial water intakes depend on consistent and effective aquatic plant management programs. Moreover, these techniques are based on results of numerous scientific evaluations. The most widespread management technique involves the use of environmentally compatible chemical herbicides. Biocontrol agents (e.g., insects, grass carp), mechanical harvesters and other physical methods (e.g., dredges, dewatering), and integration of various techniques, however, are also utilized in selected locations. A thorough discussion of commonly used control techniques can be found in Gettys, Haller, and Petty (2014). It should also be noted that rapid-response approaches to eliminate pioneer infestations are becoming more accepted and that there are a few instances of active "eradication" programs—Washington State (spartina); Florida (giant salvinia); Indiana (hydrilla and egeria); and California, Maine, Ohio, Wisconsin, and New York (hydrilla). A few examples of more traditional operational programs from different regions of the United States are presented here.

The detrimental effects of weeds on human water uses can be ameliorated and in some instances eliminated through management.

Northeast–Southeast

The Vermont Department of Environmental Conservation administers a very successful program to control water chestnut in Lake Champlain and other Vermont water bodies (Hunt and Marangelo 2013). This program relies on an aggressive mechanical harvesting approach, augmented by hand pulling of water chestnut plants to decrease or eliminate pioneer infestations. Related efforts are being conducted in the Missisquoi National Wildlife Refuge and in nearby sites in New York. A recent invasion of hydrilla into Lake Cayuga, New York, has spawned an ongoing eradication project being administered by the New York State Department of Environmental Conservation in cooperation with other agencies. Initial efforts have focused on the use of herbicides, *benthic* barriers, and hand-removal techniques (Johnson 2014).

The Vermont Department of Environmental Conservation administers a very successful program to control water chestnut in Lake Champlain and other Vermont water bodies.

With more than 1.5 million acres of lakes and rivers and thousands of miles of canals, the state of Florida maintains arguably the most aggressive and highly successful nuisance plant management program in the nation, with an annual budget of more than $30 million. In addition to routine maintenance control activities—limiting the impacts of invasive vegetation on recreation, angling, property values, flood control, and natural habitat—the program coordinates management with agencies responsible for protection of numerous threatened and endangered species in the state. For example, management activities of the submersed invasive plant hydrilla are coordinated among stakeholders to protect foraging areas of the federally listed Everglades snail kite in the Kissimmee Chain of Lakes located in central Florida (Netherland and Jones 2012). This chain of lakes is also critical for flood control in the state, particularly in hurricane season. This strategy has been used to successfully control hydrilla and to maintain important habitat for the snail kite.

With more than 1.5 million acres of lakes and rivers and thousands of miles of canals, the state of Florida maintains arguably the most aggressive and highly successful nuisance plant management program in the nation.

Lake Seminole is a major recreational and economic resource in the panhandle area of Florida and Georgia. When the abundance of submersed plants (especially hydrilla) was decreased in portions of Lake Seminole, Georgia, via chemical management, there was an increase in the growth and number of largemouth bass (Sammons, Maceina, and Partridge 2005). Reservoirs of the Tennessee Valley Authority in Alabama and the Santee-Cooper System (Lakes Marion and Moultrie) in South Carolina have successfully been managed for many decades using herbicides and grass carp for invasive plant and algae problems, maintaining valuable water resources and fish and wildlife habitat.

Midwest–West

Houghton Lake, Michigan, is a 20,000-acre water body that serves as a major resource for a variety of recreational activities (e.g., angling, boating, hunting), drawing users from across the Midwest. When Eurasian watermilfoil covered more than 10,000 surface acres, local commerce was significantly impacted (Smith, Mongin, and Heilman 2003). In addition, the native plant community was greatly decreased. A lakewide integrated management plan using a species-selective herbicide was used based on results of extensive replicated small-scale evaluations (Netherland and Getsinger 1995a,b; Netherland and Getsinger 1997; Netherland, Getsinger, and Turner 1993; Netherland, Skogerboe, and Getsinger 1997). Herbicide treatments on the lake were supplemented by biocontrol weevil introductions to suppress Eurasian watermilfoil regrowth. This integrated management strategy decreased the invasive plant infestation by more than 90% and restored much of the native plant populations. Recreational and economic benefits recovered quickly after the Eurasian watermilfoil removal, and they continue to this day.

> Wisconsin has developed an adaptive monitoring framework to weigh costs of management actions against management benefits.

More than 600 Wisconsin lakes are infested with Eurasian watermilfoil, and recreational opportunities are impacted by the abundant plant growth (Nault et al. 2012). In addition, many native plant species are being displaced, degrading the ecological services provided by healthy aquatic plant communities. Wisconsin has developed an adaptive monitoring framework to weigh costs of management actions against management benefits. This approach uses long-term, ecosystem-wide strategic actions based on early-season herbicide applications to decrease Eurasian watermilfoil distribution and density as well as to restore native vegetation to the lakes. Again, these operational management actions are predicated on the results of extensive small-scale herbicide concentration and exposure time evaluations (Glomski and Netherland 2010; Poovey, Slade, and Netherland 2007; Skogerboe and Getsinger 2002; Sprecher, Getsinger, and Stewart 1998). This ongoing effort is used to define acceptable trade-offs between management costs and benefits. In a recent Indiana water supply reservoir study, algal treatments in the reservoir decreased taste-and-odor compounds and consumer complaints, resulting in a 21% decrease in treatment costs for acceptable potable water (Isaacs et al. 2013).

> When invasive species grow too abundantly, they displace the resident native plants, upsetting the balance of ecosystem services provided by healthy water bodies.

In the Sacramento–San Joaquin Delta in California, water resources are used for multiple purposes—crop irrigation, drinking water, recreation, flood control, etc. Invasive species have threatened the water resource there. For example, there is a pumping plant designed to extract freshwater from the delta into an aqueduct system in which it travels to southern California to provide drinking water, among other uses, for millions of people. The floating weed water hyacinth has clogged the intake pipes in the past. This problem has been solved by a state-run program that uses registered herbicides and manual removal to treat water hyacinth before the plants achieve nuisance levels. The submersed Brazilian elodea interferes with navigation, irrigation, and recreational water use in the delta and has also been managed using herbicides under a legislatively mandated program. Applied research in academia, government, and the private sector provided the basis for regulatory approval of these herbicides in this ecologically sensitive aquatic environment.

The northern Sacramento Valley is a rich rice-growing region. Each year approximately 580,000 acres are devoted to rice production in the valley, representing 20% of the U.S. total (Geisseler and Horwath 2013). Flooded rice fields provide critical habitat to more than 200 species of wildlife and are a major wintering resource for migratory waterfowl because much of the natural wetlands in this valley has been eliminated (California Rice Commission 2007). A number of weedy aquatic plants and algae interfere with rice production. The annual $500 million rice crop grown in this region is possible because of the successful efforts made to manage these aquatic weeds using a variety of cultural, mechanical, and herbicide methods.

> The increasing scarcity of clean freshwater—through population growth and development, droughts, contamination, and other factors—places greater demands on the very foundation of society.

When invasive species grow too abundantly, they displace the resident native plants, upsetting the balance of ecosystem services provided by healthy water bodies. In a study conducted in the Pend Oreille River in northeastern Washington, researchers used site-specific knowledge of water currents to carefully time the application of a herbicide (Getsinger et al. 1997). The result of this effort not only removed a large percentage of the invasive species biomass but caused an increase in the abundance and diversity of native species, restoring much of the ecosystem services provided by the native plant community.

Conclusion

How important is water? Life depends on it. Freshwater is arguably mankind's most precious commodity. The increasing scarcity of clean freshwater—through population growth and development, droughts, contamination, and other factors—places greater demands on the very foundation of society. Unfortunately, invasive plants and algae are progressively disrupting the ecological balance required for maintaining adequate freshwater resources—for flora, fauna, and humans. Once established and thriving, these plant infestations are threatening the long-term fitness and biodiversity of rivers, lakes, and wetlands. Their growth and spread do not respect "political" boundaries because watersheds can traverse many states, counties, and municipalities within broad regions of the United States. These plant populations generate negative impacts and stress on many modern society prerequisites, including agriculture, potable water supplies, human health and sanitation, energy production, recreation and property values, and fish and wildlife. In addition, after human expansion and development, invasive species pose the greatest threat to endangered or threatened species. This threat is primarily due to rapid and major transformation of critical habitats required by the listed species.

> On an annual basis, hundreds of millions of dollars in damages are caused by invasive aquatic vegetation.

On an annual basis, hundreds of millions of dollars in damages are caused by invasive aquatic vegetation, and many millions more are expended each year to mitigate the impacts and to implement control and management activities. With limited fiscal budgets (both public and private sector) and

> Clearly, a sustainable civilization is contingent on clean and abundant freshwater resources.

insufficient understanding of the crisis by many policymakers and the general public, the spread of invasive aquatic plant infestations is outpacing the ability to contain and decrease the problem populations. Likewise, the crucial ability to enhance management programs and continue to develop new control methods is steadily being eroded through lack of sufficient long-term funding commitments. If these operational and research/development trends are not reversed, a life-sustaining heritage—the nation's priceless water resources—will be severely and perhaps irreparably degraded or lost.

Clearly, a sustainable civilization is contingent on clean and abundant freshwater resources. People must make the protection and conservation of these resources a top priority for the future. Managing nuisance aquatic vegetation will be an increasingly important part of that priority.

Glossary

Algae. Distinguished from plants by the absence of true roots, stems, and leaves; examples are chara and nitella.

Allelopathic. Inhibition of growth in one species of plant by chemicals produced by another species.

Anoxic. Greatly deficient in oxygen.

Benthic. Occurring at the bottom of a body of water.

Diurnal. Happens daily.

Emergent. Rooted in the water bottom, but leaves and stems extend out of the water; examples are cattails, smartweed, and American lotus.

Epiphytic. Living on a plant surface.

Evapotranspiration. The loss of water to the atmosphere by evaporation and transpiration from the growing plants.

Floating. Not attached to the water bottom (roots may float extended from surface plant); examples are duckweed and water hyacinth.

Macroinvertebrate. Animal species that does not have a vertebral column and can be seen without a microscope.

Macrophyte. An aquatic plant growing in or near water that is either emergent, submergent, or floating.

Percolation. The loss of water into the soil substrate.

Submerged. Rooted plants with most of their vegetative mass below the water surface; examples are hydrilla and water milfoil.

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