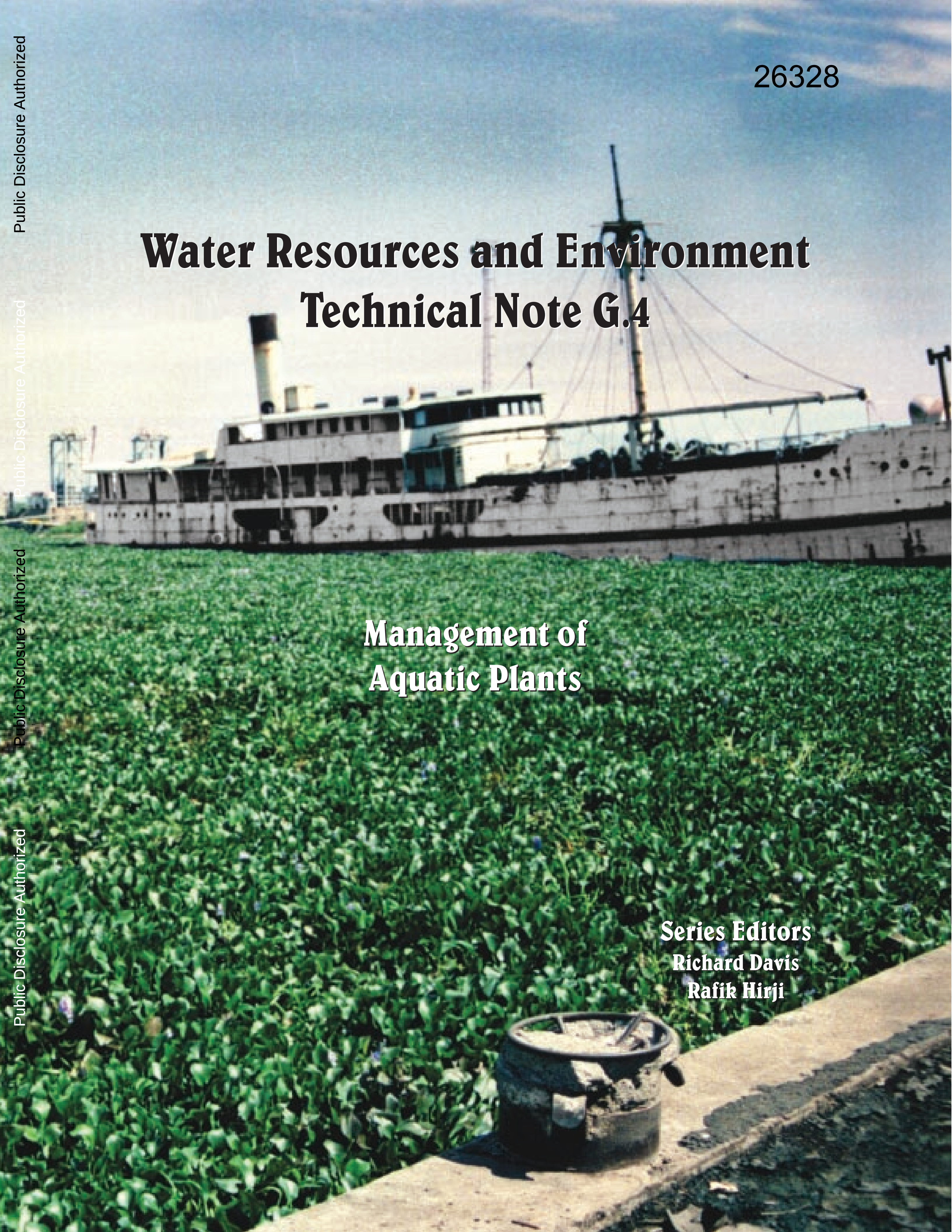

Water Resources and Environment
Technical Note G.4

Management of Aquatic Plants

Series Editors
Richard Davis
Rafik Hirji

WATER RESOURCES AND ENVIRONMENT

TECHNICAL NOTE G.4

Management of Aquatic Plants

SERIES EDITORS
RICHARD DAVIS, RAFIK HIRJI

The World Bank
Washington, D.C.

Water Resources and Environment Technical Notes

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FOREWORD

The environmentally sustainable development and management of water resources is a critical and complex issue for both rich and poor countries. It is technically challenging and often entails difficult trade-offs among social, economic, and political considerations. Typically, the environment is treated as a marginal issue when it is actually key to sustainable water management.

According to the World Bank's recently approved Water Resources Sector Strategy, "the environment is a special 'water-using sector' in that most environmental concerns are a central part of overall water resources management, and not just a part of a distinct water-using sector" (World Bank 2003: 28). Being integral to overall water resources management, the environment is "voiceless" when other water using sectors have distinct voices. As a consequence, representatives of these other water using sectors need to be fully aware of the importance of environmental aspects of water resources management for the development of their sectoral interests.

For us in the World Bank, water resources management–including the development of surface and groundwater resources for urban, rural, agriculture, energy, mining, and industrial uses, as well as the protection of surface and groundwater sources, pollution control, watershed management, control of water weeds, and restoration of degraded ecosystems such as lakes and wetlands–is an important element of our lending, supporting one of the essential building blocks for sustaining livelihoods and for social and economic development in general. Prior to 1993, environmental considerations of such investments were addressed reactively and primarily through the Bank's safeguard policies. The 1993 Water Resources Management Policy Paper broadened the development focus to include the protection and management of water resources in an environmentally sustainable, socially acceptable, and economically efficient manner as an emerging priority in Bank lending. Many lessons have been learned, and these have contributed to changing attitudes and practices in World Bank operations.

Water resources management is also a critical development issue because of its many links to poverty reduction, including health, agricultural productivity, industrial and energy development, and sustainable growth in downstream communities. But strategies to reduce poverty should not lead to further degradation of water resources or ecological services. Finding a balance between these objectives is an important aspect of the Bank's interest in sustainable development. The 2001 Environment Strategy underscores the linkages among water resources management, environmental sustainability, and poverty, and shows how the 2003 Water Resources Sector Strategy's call for using water as a vehicle for increasing growth and reducing poverty can be carried out in a socially and environmentally responsible manner.

Over the past few decades, many nations have been subjected to the ravages of either droughts or floods. Unsustainable land and water use practices have contributed to the degradation of the water resources base and are undermining the primary investments in water supply, energy and irrigation infrastructure, often also contributing to loss of biodiversity. In response, new policy and institutional reforms are being developed to ensure responsible and sustainable practices are put in place, and new predictive and forecasting techniques are being developed that can help to reduce the impacts and manage the consequences of such events. The Environment and Water Resources Sector Strategies make it clear that water must be treated as a resource that spans multiple uses in a river basin, particularly to maintain sufficient flows of sufficient quality at the appropriate times to offset upstream abstraction and pollution and sustain the downstream social, ecological, and hydrological functions of watersheds and wetlands.

With the support of the Government of the Netherlands, the Environment Department has prepared an initial series of Water Resources and Environment Technical Notes to improve the knowledge base about applying environmental management principles to water resources management. The Technical Note series supports the implementation of the World Bank 1993 Water Resources Management Policy, 2001 Environment Strategy, and 2003 Water Resources Sector Strategy, as well as the implementation of the Bank's safeguard policies. The Notes are also consistent with the Millennium Development Goal objectives related to environmental sustainability of water resources.

The Notes are intended for use by those without specific training in water resources management such as technical specialists, policymakers and managers working on water sector related investments within the Bank; practitioners from bilateral, multilateral, and nongovernmental organizations; and public and private sector specialists interested in environmentally sustainable water resources management. These people may have been trained as environmental, municipal, water resources, irrigation, power, or mining engineers; or as economists, lawyers, sociologists, natural resources specialists, urban planners, environmental planners, or ecologists.

The Notes are in eight categories: environmental issues and lessons; institutional and regulatory issues; environmental flow assessment; water quality management; irrigation and drainage; water conservation (demand management); waterbody management; and selected topics. The series may be expanded in the future to include other relevant categories or topics. Not all topics will be of interest to all specialists. Some will find the review of past environmental practices in the water sector useful for learning and improving their performance; others may find their suggestions for further, more detailed information to be valuable; while still others will find them useful as a reference on emerging topics such as environmental flow assessment, environmental regulations for private water utilities, inter-basin water transfers and climate variability and climate change. The latter topics are likely to be of increasing importance as the World Bank implements its environment and water resources sector strategies and supports the next generation of water resources and environmental policy and institutional reforms.

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INTRODUCTION

Nuisance aquatic plants come in both macroscopic and microscopic forms. Macroscopic forms include such common plants as water hyacinth (*Eichhornia crassipes*) and macroalgae such as *Cladophora sp.*, and are generally termed aquatic weeds. Microscopic forms include algae and cyanobacteria, commonly called algal blooms when their concentrations are great enough to be visible and discolor the water. Aquatic plants can seriously interfere with many water uses, including drinking water quality, accessibility, navigability, irrigation and hydropower production, water withdrawals, and ecological functioning. In addition, aquatic weeds can harbor vectors of disease and cyanobacteria can release potent toxins.

Water managers typically underestimate the economic loss from invasions of weeds and algae. Box 1, which is based on a 1997 study by the World Bank, provides examples of the severity of the problems caused by water hyacinth in many subsectors. Since that study was completed, the World Bank has supported a number of aquatic weed management programs, including GEF-funded projects to control water hyacinth and algal blooms in Lake Victoria and the control of a range of aquatic weeds in Southern Africa. The Bank has also been active in helping set up a secretariat for the Global Invasive Species Programme (GISP) in South Africa with Bank-Netherlands-Water-Partnership-Program funding support. The potential health consequences of nuisance aquatic plants can also be very significant. Weeds can harbor vectors for disease and provide habitat for snakes and other dangerous animals, and some species of algae can produce potent toxins that can enter drinking water supplies. Consequently, task managers at the World Bank confront problems arising from aquatic plants in a wide variety of contexts.

This Technical Note describes the occurrence and management of nuisance aquatic plants in freshwater. Though not discussed in this Note, estuarine/marine aquatic plants can cause considerable social and economic disruption, particularly in developing countries. The toxins released by some species of marine/estuarine cyanobacteria and dinoflagellates are extremely poisonous to humans and stock animals, causing "red tide" paralytic shellfish poisoning, ciguatera poisoning, and diarrhoeal shellfish poisoning. For example, blooms of the dinoflagellate *Pyrodinium bahamense* caused at least 34 deaths in the Philippines in 1983 and 1987, and 26 deaths in 1987 along the coastal areas of Costa Rica and Guatemala. The Further Information section includes some references on these estuarine/marine issues.

This Note is organized in six sections. A general description and typology of nuisance aquatic plants is followed by a description of the problems caused by these plants. The Note then discusses methods for controlling these plants, how to obtain benefits from them, and the advantages and disadvantages of the various control methods. It also provides cost estimates associated with different control options. The Note concludes with suggestions for obtaining further information from both websites and printed material.


Photo by Curt Carnemark, World Bank

Water weed, Senegal

BOX 1.
SOME PROBLEMS CAUSED BY AQUATIC WEEDS IN SOUTHERN AFRICA

Weeds that form dense mats, such as water hyacinth and Kariba weed (*Salvinia molesta*), can obstruct the flow of rivers, which in turn can obstruct floodwaters and increase the extent of flooding. For example, mats of water hyacinth caused extensive flood damage in the Swartkops River in South Africa in 1977. Aquatic weeds also cause direct loss of water via transpiration; for example, water hyacinth is reported to increase evapotranspiration by a factor of 3.5 over that from open water. This water loss represents a significant cost in water-scarce areas.

These mats also make fishing and water gathering difficult and impede navigation. The dense mats that choked Kisumu harbor during the 1996-8 outbreak of water hyacinth in Lake Victoria are estimated to have cost the Kenyan economy at least Ksh 2 million ($25,000) in extra fuel costs for ferries and Ksh 79 million ($1 million) in lost catches from artisinal fishing. Drifting mats of Kariba weed caused local fish catches to decline in the former Lake Liambezi on the border between Namibia and Botswana. It is believed that the mats reduced oxygen concentrations in the water sufficiently to affect zooplankton and fish numbers.

Mats of water weeds also block water intake points and canals. For example, dense mats blocked the intake screens and filters of the Owen Falls power station in Uganda; shutting down the turbines and removing the weeds cost the Ugandan Electricity Board $1 million per day. Rooted weeds, such as Parrot's Feather (*Myriophyllum aquaticum*), have caused problems in irrigation canals in South Africa by impeding flow and causing siltation.

Aquatic weeds also affect the quality of drinking and irrigation water. They cause odors and tastes and affect the pH. Thus, irrigators who draw water from the Mokolo River in South Africa have found that Parrot's Feather infestations discolor their tobacco crop, halving its market value.

Weed mats provide habitat for the vectors that spread tropical diseases. They provide shelter for mosquitoes that carry malaria as well as habitat for Bilharzia snails.

Finally, aquatic weeds affect native plants and animals by altering local ecosystems. The reduced sunlight penetration will suppress the growth of some plants and cause some animals to move to new locations; the reduced oxygen content of the water will favor some fish and zooplankton species over others; and the dense mats provide physical habitat that suits some species and not others.

Sources: Bethune S. and K. Roberts. (2002); Mogaka, H., S. Gichere, J.R. Davis, and R. Hirji. 2003. *Impacts and Costs of Climate Variability and Water Resources Degradation in Kenya.* Washington: World Bank.

TYPES OF NUISANCE AQUATIC PLANTS

DEFINITIONS AND CAUSES

Aquatic plants are considered nuisances when excessive growth interferes with desired water uses, including human health.

Aquatic plant problems have increased in the last two centuries, in line with increases in industrialization, travel and communications, agricultural productivity (including the agricultural "green" revolution), the growth of the human population, and changes in consumption patterns. Increased travel has expanded the opportunities for transmission of aquatic plants from their home ranges to new environments. Factors such as population growth and changing consumption have led to changes in land and water use, which have increased pressure on endemic aquatic plants and provided suitable habitats for introduced species. Aquatic plant problems are usually a symptom of broad land and water use changes and poor water management. Aquatic plant management should therefore be based on preventing or minimizing the side effects of developments that disturb aquatic environments. In practice, this means counteracting the causes of excessive plant growth, including vectors that spread weeds from their native habitat into new areas, and retaining ecological restraints such as herbivores, competitors, and nutrient scarcity (see Box 2).

Box 2.
Myriophyllum or Myriophyllum, which is the weed?

In North America, considerable effort has been spent to control the introduced Eurasian milfoil (*Myriophyllum spicatum*) as it is considered a weed, while the native *Myriophyllum* species are protected. However, "it requires expert knowledge to distinguish *M. spicatum* from a native species (*M. sibiricum*) and it is an absurd situation when the water management authorities have to call in a taxonomic botanist to know if they have a weed problem or not. I myself have seen *M. laxum* being sprayed in the southeast United States, where it is a rare and endangered species. The reason for the increased growth of *Myriophyllum,* native or introduced, in North America is usually the result of changes in land and water usage."

In short, caution is warranted, particularly when officials may have difficulty in properly identifying the species and confuse desired native species with the perceived weed.

Source: adapted from Cook, C.D.K. (1990).

PLANT FORMS

In freshwater, most aquatic weeds are either macroscopic angiosperms (flowering plants), also termed macrophytes, or microscopic algae. It is useful to categorize macrophytes by growth form, partly because particular growth forms are more common in particular types of water bodies, and partly because management options depend on the growth form (Table 1). The major aquatic weed species are found in the categories "submerged" and "free-floating."

Table 1.
Growth-form classification of freshwater angiosperm aquatic plants

Type	Description
Emergent	Roots occur from approximately 1.5 m underwater to waterlogged soils on land. Stems and leaves can be partially submerged, but some part emerges above the water surface. Most species have well-developed roots and long-lived rhizomes that anchor the plant in the sediment and may provide considerable aeration to the underlying sediment. Flowering occurs above water. Examples are cattail (*Typha*) and common reed (*Phragmites*).
Rooted with floating leaves	Similar to emergent plants in most characteristics, but the leaves rest on the water surface. The depth range is 0.5-3 m. In some species, submerged and aerial leaves also exist. Flowering is aerial. Examples are water lilies (*Nymphaea, Lotus, Nuphar*).
Submerged, rooted	These rooted plants are fully submerged, and flowering may occur underwater. They may occur at any depth, depending on light availability. Examples are pondweeds (*Potamogeton*) and hydrilla (*Hydrilla*). Roots are useful as anchorage, but also for nutrient acquisition, since nutrient availability in the sediment is often greater than in the overlying water.
Submerged, non-rooted	Several species are not firmly rooted in the sediment but float freely underwater. Examples are hornwort (*Ceratophyllum*) and bladderwort (*Utricularia*). Fragments and mats of rooted submerged plants may become detached and effectively act as if non-rooted.
Free-floating	These are freely floating on the water surface and suspend their roots into the water. Examples are duckweed (*Lemna*), water hyacinth, and water lettuce (*Pistia stratiotes*).

Source: Wetzel, R.G. 1983. *Limnology*. New York: CBS College Publishing.

Emergent plants are not often considered weeds, although in irrigation schemes emergents can be problematic when channel maintenance has been neglected. For example, *Glyceria maxima* is considered troublesome along the margins of eutrophic waters in New Zealand, typha is a nuisance plant in Senegal, and water lilies sometimes impede flow in drains, particularly in areas where it is not native.

Microscopic algae can be either attached (periphytic) or freely suspended in the water column (planktonic). Algal concentrations grow to bloom proportions as a consequence of excessive nutrient loading (eutrophication), particularly when physical water-body conditions such as temperature and flow are suitable and there are favorable ecological conditions, such as absence of grazers. Cyanobacteria (commonly called "blue-green algae," but taxonomically not algae at all) are a particular threat to freshwaters because some genera—for example, *Anabaena* and *Microcystis*—contain species that can release toxins that are highly poisonous to domestic animals and humans.

Freshwater macrophytes and algae are readily identified. National keys to the aquatic flora are available in many developing and all developed countries, and most botanically trained staff members in government agencies are familiar with the appropriate keys. Several aquatic plant species occur in many parts of the world. Among these cosmopolitan macrophytes are water hyacinth and hydrilla, which both cause serious problems. There are references to the identification of these widespread weeds in the Further Information section of this Note. Although it is usually sufficient to identify aquatic weeds to genus level, in some cases it can be critical to identify them to species level (Box 2). Similarly, some of the most common nuisance freshwater algae and cyanobacteria occur in many parts of the world—for example, *Microcystis*—and can be identified from readily available keys and identification guides.

FACTORS INFLUENCING GROWTH AND SPREAD OF AQUATIC PLANTS

Nuisance aquatic plants, both weeds and algae, can develop and spread with remarkable speed when the conditions favor them, often taking managers by surprise. There are a number of factors behind these outbreaks.

Both weeds and algae can grow quickly because of their rapid doubling times (the time taken to double its biomass) and (sometimes) lack of predators. Water hyacinth has a reported maximum doubling time of just 6–7 days, while Kariba weed and red water fern (*Azolla filiculoides*) have been reported to double in 3–5 days. Where the plants have been introduced from another environment, it is common to find that they have no local herbivores or parasites and so these rapid growth rates are unchecked. Thus, one method of controlling their growth is to introduce biological controls such as weevils for water hyacinth or invertebrates in the case of cyanobacteria (bio-manipulation).

Some nuisance plants have more than one reproductive strategy. For example, water hyacinth and red water fern can reproduce either vegetatively from small plant fragments or from spores that are resistant to desiccation. Similarly, some species of cyanobacteria, such as *Anabaena circinalis,* can form spores that can remain viable through drought periods.

The growth of most nuisance aquatic plants is nutrient limited; that is, they will respond to an increase in the availability of nutrients that are in short supply. Thus, waterbodies that have experienced increases in nutrient concentrations, often because of increased human activities, are susceptible to aquatic weeds and algae. Because of their rapid doubling and, often, freedom from grazing, they are better able to utilize these nutrients than other plants.

Physical conditions can also play an important role in the growth and spread of these plants. Floating forms, such as cyanobacterial scums and floating macrophytes, can be concentrated by wind conditions on a small length of shoreline, causing an immediate problem, sometimes even overnight. Impoundments (lakes and reservoirs) provide an ideal habitat for buoyant species of cyanobacteria. They can take advantage of the non-turbulent conditions and congregate near the surface, where they have maximum access to sunlight for growth. These problems are likely to increase as more waters are impounded for development.

Finally, aquatic weeds benefit from a lack of understanding by the general population about the problems that can be caused by their introductions to new waterbodies. Plants are transported in several ways: attached to boats and vehicles, introduced as ornamental garden plants, and for shelter purposes in hatcheries. The public needs to be educated about the economic and environmental losses that can occur because of these inadvertent introductions.

SCOPE OF THE PROBLEM

The major problems caused by nuisance aquatic plants are:

- Physical impediment to navigation, fisheries, and the intakes of water treatment plants, irrigation pumps, and hydroelectric turbines. These problems occur mainly in the tropics and subtropics, and are often caused by water hyacinth in larger lakes, reservoirs, and rivers. Only in the very shallowest waters do submerged species cause weed problems.
- Water quality problems (such as anoxia) occur most often as a consequence of either high respiration rates or the die-off and decomposition of plant biomass. This can arise from excessive growth of both macrophytes and algae.
- Health problems from harboring vectors of disease or the release of toxins from some species of cyanobacteria.
- In arid regions, the local water balance may be affected where emergent stands and dense beds of the larger floating species increase evapotranspiration.
- Ecological problems, such as threats to endangered species, can arise from changes in physical habitat, water chemistry, and light regime.
- Significant aesthetic or recreational problems can occur because of large mats of nuisance macrophytes or blooms of algae, although these are largely limited to the industrialized world or areas in the developing world that rely on tourism.

Table 2 provides a summary of the problems commonly caused by different aquatic weeds.

Algal blooms occur in both temperate and tropical conditions, although the biomass produced is often greater in tropical conditions because of the higher temperatures and greater light availability. Toxic cyanobacterial species are prevalent in both tropical and temperate conditions.

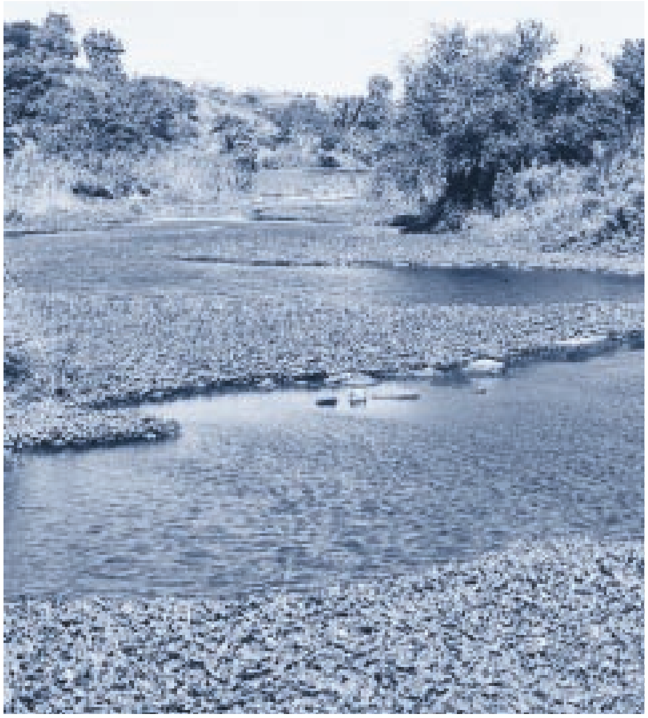
The same aquatic plant species may be considered desirable in some environments and weeds in others. Considerable sums have been spent to maintain or restore beds of water plants in lakes of Europe and North America because they are a desired and crucial component of a healthy littoral ecosystem, whereas the same species can be a serious problem in irrigation channels in other countries. Even when they are classified as weeds, aquatic plants can still provide some useful environmental services such as stripping nutrients from the water column in irrigation drains.

DIRECT PHYSICAL PROBLEMS

Impediments to flow. Emergent aquatic weeds can build up enough biomass to fill the entire water column and so cause serious resistance to water flow, particularly in comparatively small (<5 m width) and shallow (<1.5 m depth) channels, streams, and drains. As a result, flooding can increase, agricultural productivity can be reduced as

Table 2.
Major weed problems for different growth forms in different types of waterbodies.

Type of water body	Growth form: Emergent	Floating-leaved	Submerged, rooted	Submerged, non-rooted	Floating
Larger river	—	—	—	—	Only in (sub-) tropics, navigation may be impeded by large accumulations of *Eichhornia*
Medium-sized river or canal	—	—	Denser beds of e.g. *Hydrilla* and *Potamogeton* may impede flow and hamper navigation as well as swimming and fishing	—	As above, additional taxa: *Salvinia molesta, Trapa, Pistia*. The larger species significantly increase evapotranspiration
Smaller stream/ channel	Colonization from bank into margins (*Glyceria*) may impede flow	Denser beds of *Nuphar* may impede flow	As above	—	As above
Ditch/drain/dike	Full colonization of cross section (various species): impedes flow and thus hampers rapid drainage	As above; where introduced, the ornamental exotic *Aponogeton* may block drainage channels	As above, additional taxa: *Lagarosiphon, Elodea, Egeria, Callitriche*	Dense mats of *Ceratophyllum* may hamper recreation; water distribution works may be hampered	As above, here also duckweed and *Azolla* may form dense mats that seriously reduce light penetration to the water and re-aeration and thus can cause anoxia
(Shallow) pond	Full colonization of cross section (various species) may affect scenery, recreation value, water balance (increased evapotranspiration)	—	As above, additional taxa: *Myriophyllum*	As above	As above
Deeper lake/ reservoir	—	—	Dense beds along the shore of robust *Myriophyllum* and larger *Potamogeton* species may be considered an asset for recreation	As above, intake screens of hydropower reservoirs may become blocked	Dense mats may block intake pumps and screens as well as affect navigation and local fisheries



Water hyacinth

a result of poor water delivery, and environmental problems can arise from poor drainage of tailwaters. In larger water bodies, which are normally too deep for emergent plants, floating weed mats may become colonized by emergent species and consequently obstruct access to shore or open water.

Rooted species with floating leaves are rarely problematic, and emergent species generally only become so when littoral areas are poorly maintained. Submerged rooted plants are probably the most important nuisance group, but in the tropics and subtropics, the larger floating forms such as water hyacinth may also play a significant role.

Closed pipes rarely have weed problems, since plants need light for photosynthesis. Pipes, pumps, filters, and water intakes may become blocked, however, if upstream plant biomass becomes mobile, such as after mowing or manual uprooting without planned removal of the plant material. These problems are particularly acute with high-value water uses such as hydropower generation.

Algal blooms, too, can cause physical problems. Dense mats of algae and cyanobacteria can block intakes to water treatment plants and other relatively restricted areas. However, they are never dense enough to impede water flow significantly in channels and open water bodies.

Water losses. When emergent aquatic plants, whether rooted or not, form dense mats they can considerably increase the water lost through transpiration. A recent report[1] states that water hyacinth mats have increased evapotranspiration rates by a factor of 3.5 over those of free water surfaces. These losses can be very costly in water-scarce areas. Smaller floating plants like duckweed probably have less effect on evapotranspiration, simply because the water transport system within these small plants is of little importance to the physiological functioning of the plant. There are even reports, in an arid climate, of a reduction in total water loss by a duckweed mat because the extra transpiration is more than offset by the reduced evaporation from the water surface.

Impediments to navigation, fishing, or recreation. Very dense and extensive accumulations of aquatic weeds, especially water hyacinth, may smother mooring sites and harbors as well as restrict access to both traditional and commercial fishing areas (Box 3). In some cases, the density of the weed mats impedes navigation to the point where significant financial losses occur.

In North America and Europe, dense weed beds and algal blooms have impeded recreational boating, fishing, and swimming. They are also unattractive. However, recreational losses are of secondary importance in developing countries, except in areas where tourism provides a major source of income (Box 4).

CHEMICAL CONSEQUENCES

Daytime photosynthesis and nighttime respiration of dense submerged weed beds may strongly influence the chemistry of the surrounding waters. During daytime, oxygen concentrations will be elevated; at nighttime, the levels may be seriously reduced.

[1] Bethune, S. and J. Roberts (2002).

Box 3.
Water hyacinth buildup in the Sudd, Sudan

The Sudd is a large, highly productive papyrus wetland area (10,000 km^2 in the dry season and 92,000 km^2 in the wet season) in the south of Sudan. The Sudd also provides a good habitat for water hyacinth. Considerable quantities of floating vegetation are brought downstream from the Sudd to the Jebel Awila Dam above Khartoum. These floating rafts may build up to large concentrations in side arms and dead ends of the Sudd. Along the Sudanese White Nile, these accumulations seriously impede navigation, particularly when seasonal winds further pile up the plant mass. The Sudanese government declared water hyacinth control a national priority in the early 1970s. With technical support from Germany, a large-scale study was launched to investigate control of the weed, as well as to develop locally feasible and economically viable ways of using the large quantities of biomass.

The study concluded that:

- chemical control was feasible, though at considerable cost, particularly since the main source of drifting water hyacinth lies upstream in the inaccessible marshes of the Sudd
- mechanical control by locally available labor was not very effective without supervision
- biological control had not been very successful
- most of the alternative use options were not very promising.

Water hyacinth was tested for biogas generation, fodder for cattle and sheep, bricketing for fuel, as well as composting and mulching. Only the latter proved promising, but not on all crops. The high water content of the biomass always necessitated drying as a pre-treatment. Still, the report concluded that "it is necessary to stop regarding the water hyacinth as a weed and to regard it as a beneficial or economic plant."

The weevils that were released for biological control around 1978 continued to multiply. By 1982, in spite of the report's conclusion, no more problems were reported and all observed plants showed distinct scars of weevil feeding. The water hyacinth is no longer regarded as a national priority, but it is unclear whether navigation is still substantially hampered in the White Nile.

Box 4.
Water hyacinth in Ooty Lake, India

At Ooty Lake in Tamil Nadu province in India, tourism is being threatened by water hyacinth, which is slowly spreading along the surface of the lake and threatening to choke it.

The lake was artificially formed by John Sullivan in 1823–1825 by damming the mountain streams flowing down the Ooty valley. Over the decades, the lake's area has shrunk due to lack of management, and the lake has become seriously polluted from sewage. The recent infestation of water hyacinth is believed to have resulted from the high nutrient levels now present in the lake. In spite of the importance of the tourism industry to the local economy, little has been done to remove the causes of the weed problem.

Oxygen concentrations below about 4 mg l^{-1} may lead to fish kills; most fish are unable to live in concentrations below 2 mg l^{-1}. Active photosynthesis will cause the pH to rise rapidly to alkaline levels (around pH 10), particularly in poorly buffered waters, with a consequent increase in NH_3 concentrations. The combination of low oxygen and elevated ammonia concentrations may affect fisheries and aquaculture.

The die-off of nuisance aquatic plants, whether weed beds, floating plants, or algal blooms, will lead to high carbon loads being deposited onto the sediments. Benthic oxygen concentrations will be reduced significantly as the biomass decomposes. This is particularly noticeable when the aquatic plants die abruptly, such as after herbicide treatment. The low oxygen levels will, in turn, cause phosphorus to be released from sediments via a reducing reaction. If this phosphorus reaches surface waters where light levels are high, it can fuel an algal bloom. Thus the die-off of water hyacinth following treatment resulted in heavy cyanobacterial blooms in two of the bays on the Ugandan shoreline of Lake Victoria. Even if the nutrients are restricted to the bottom waters and algal blooms are avoided, the low oxygen levels can lead to mortality among aquatic invertebrates and vertebrates, such as fish.

HEALTH CONSEQUENCES

Several diseases can be promoted by beds of water weeds. The association of bilharzia-bearing snails with water plants is well known. Cholera may also be associated with weeds; cholera bacteria (*vibrio*) are reported to survive well in organisms attached to the weeds.

Serious health effects can also arise from toxins produced by some species of cyanobacteria.[2] The reasons why the cells produce toxins are not known. Different cyanobacteria produce different types of toxins:

- Hepatotoxins, which affect the liver and are produced by many common species of cyanobacteria, including *Microcystis* and *Anabaena*.
- Neurotoxins, which affect the nervous system, are produced by some strains of *Aphanizomenon* and *Oscillatoria*.
- Toxic alkaloids, which cause gastrointestinal problems and affect the kidneys.
- Dermatotoxins, which cause skin rashes.

Toxins from *Microcystis* are also reported to act as tumor promoters, even in low doses.

These toxins can be removed or inactivated by chlorination, filtration through activated carbon, and ozonation. These treatments may not be sufficient during bloom situations or when a high organic load is present in the water supply. Removing these toxins is difficult and costly in developed countries; in developing countries, the best solution is to avoid situations that promote cyanobacterial blooms.

[2] Bartram, J. and I. Chorus. (1999).

There have been few documented cases of human death from freshwater cyanobacteria (for an exception, see Box 5). However, there is believed to be a relationship between cyanobacterial contamination of surface water and cancer mortality, particularly gastric, esophageal, and liver cancers. There have been a number of studies in China using different techniques that show a link between algal toxins and liver cancer.

ECOLOGICAL CONSEQUENCES

Ecosystem changes. Water plants form a key component of littoral, shallow-water ecosystems, and most weed species also have important roles as food and as habitat. There are mixed opinions about the direct impact of aquatic weeds, but the indirect roles are highly significant: weed beds are refuge to many invertebrates and juvenile fish and are home to species-rich guilds of invertebrates that feed on attached or suspended algae and bacteria in a variety of ways.

Water plant beds generally harbor considerably more biodiversity than unvegetated sediments. Commercial fisheries may incur losses after the influx of aquatic plants, when they previously relied on specialized fish species that inhabit bare sediments. However, this is not always so; one study in Uganda found there was little change as a result of an increasing cover of water hyacinth on both benthic invertebrates and fish. In most instances, a scientific investigation will be needed to assess the ecological impacts.

In bloom concentrations, algae and cyanobacteria can also affect food chains. Larger species of invertebrates such as some *Daphnia* (water fleas) can graze on small-celled algae. Their numbers have been observed to increase with persistent algal blooms. Increases in such invertebrates will lead to changes in higher levels of the food chain, including fish. Dense algal blooms also reduce light levels within the water column, adversely affecting macrophytes. In fact, there is a direct competition between free-floating algae and rooted aquatic plants, such that there appear to be two stable states

Box 5:
Deaths from cyanobacterial toxins: Caruaru, Brazil

A dialysis center in the town of Caruaru, Brazil obtained its water supply by truck from a reservoir about 40km away. In mid-February 1996, patients began experiencing nausea, vomiting, and visual disturbances after dialysis. During the following two weeks, 12 patients died of seizures or acute liver failure. Eventually, 50 deaths were attributed to liver failure following dialysis. Experts from the U.S. Centers for Disease Control were asked to assist local authorities with their investigation.

The water was not chlorinated or filtered, although the center passed the water through its own treatment / filtration equipment before use in dialysis. Maintenance of the equipment was poor, and neither the sand filter nor the micropore filter had been changed for at least three months.

It became evident that during dialysis the patients had been exposed to microcystins—the group of toxins produced by the cyanobacterium *Microcystis aeruginosa*. Microcystins were found to be present in the reservoir water, the delivery truck, the water storage tank, and treatment equipment at the center. Microcystins were also found in liver samples from deceased patients.

It appears likely that an algal bloom in the reservoir led to small amounts of toxin passing through the municipal water treatment plant. When the decision was made to bypass part of the municipal treatment process and truck the water to the center, the patients were exposed to high levels of toxin. Some of the histological observations of liver tissue were not typical of microcystin, and it is believed that cylindrospermopsin was also present in the water. There were no algal counts performed at the time of the incident, but low numbers of *Microcystis* and *Cylindrospermopsis* were present in the reservoir during the investigation.

Source: Jochimsen, E.M. *et al*. "Liver Failure And Death after Exposure to Microcystins at a Hemodialysis Center in Brazil." *New England Journal of Medicine* 338 (13): 873–78.

for many water bodies–dominance by phytoplankton or dominance by macrophytes (Box 6). Cyanobacterial toxins can affect fish as well as mammals. Salmon, striped bass, and shrimp have been found to harbor toxins from *Microcystis*, with the fish usually dying from acute liver failure. It is not clear if the toxins affect the shrimp.

SPREAD OF WEEDS

Some species of aquatic weed can rapidly form large numbers of viable fragments that are easily dispersed over large distances. Nonnative species can spread extremely rapidly after inadvertent, careless, or even deliberate introduction. Examples are available from most continents: two *Elodea* species into Europe, hydrilla into North America, and water hyacinth into Africa and Asia. Means of dispersal are highly varied and include wildlife (migrant ducks), cattle transportation, ships' ballast water, small boats, and careless dumping of plants by horticulturists or salesmen.

Some control methods can actually promote dispersal. For example, several species have adaptive survival organs (tubers, turions, seeds) that remain in the sediment after the aboveground vegetation is removed. They can regenerate within the same or following season once the water body has been cleared. Also, fragments detached during mechanical removal will easily form adventive roots and successfully reestablish.

Rapid growth in transportation and tourism has increased the opportunities for weed dispersal. In response, several countries–including the United States, Australia, and New Zealand–have drawn up tight preventive regulations and border controls to limit these anthropogenic introductions. Natural dispersal is much more difficult to control, particularly when water bodies are connected in a riverine drainage network or through wildlife or cattle migration routes.

Box 6.
Water plants and lake management: alternative stable states

As a consequence of increased nutrient loading, many shallow lakes in industrialized Europe, North America, and Australia have undergone a transition from a period with clear water, when water plants were present but not in excessive numbers, to a phase with turbid water, no water plants, and cyanobacterial blooms. This transition process involves a complex interaction among aquatic plants, light penetration and turbidity, anoxia and nutrient release from sediments, and fish and invertebrates.

Both the macrophyte and phytoplankton states are stabilized by feedbacks. Stabilizing mechanisms for the clear-water, macrophyte-dominated phase are:

- The dense submerged foliage reduces flow, thereby enhancing sedimentation, leading to clearer water.
- Submerged leaf surface (often leaf area indices >2 m^2 m^{-2}) is colonized by attached algae and bacteria that reduce nutrient and BOD concentrations in the water.
- Photosynthesis by the plants affects inorganic carbon equilibria, pH, and oxygen concentrations in the water, which all retard planktonic growth potential.
- Sediment oxygenation by roots creates an oxidized upper sediment zone, which retains nutrients in the sediments.
- Weed beds provide refuges for juvenile zooplankton and habitat for adult zooplankton as well as fish.
- Several macrophyte species reportedly produce compounds that reduce algal growth.

The algae-dominated, turbid phase also has stabilizing mechanisms:

- The sediment is no longer protected by plants and therefore easily resuspended, creating a harsh environment for reestablishing seedlings of water plants, as well as low light levels.
- Increased turbidity enhances survival rates of fish that eat zooplankton, which in turn graze on phytoplankton and stir up the sediment. Top predator fish, in contrast, are severely hindered by increased turbidity.
- High turbidity causes heat absorption in the upper layers and stratification of the water body. The lower water layer is cut off from the atmosphere and will turn anoxic, leading to increased nutrient losses from the sediments. These nutrients can feed algal blooms in the surface water layers.

Both states are stable. The transition is normally triggered by increases in nutrient concentrations and the crucial stage before algal "takeover" is often the development of attached algae that bloom when the water is still clear. Reducing nutrient loads to these lakes once algal domination has been established has often had disappointingly little effect on algal blooms because of the stability afforded by the feedback mechanisms. The interactions are usually complex enough to require an integrated management effort that tackles foodwebs, water clarity, nutrient inputs, and sediment stabilization simultaneously. A scientifically based understanding is needed if management intervention is to be successful in these cases.

Sources: Blindow, I. 1992. "Long- and short-term dynamics of submerged macrophytes in two shallow lakes." *Freshwat Biol.* 28: 15–27; Van Vierssen, W., M.J.M. Hootsmans, and J.E. Vermaat. 1994. "Lake Veluwe, A macrophyte-dominated system under eutrophication stress." *Geobotany 21.* The Netherlands: Kluwer.

METHODS OF CONTROLLING AQUATIC PLANTS

MANUAL CONTROL

Nuisance macrophytes can be controlled with manual methods when cheap labor is available. Hand tools are used to cut plants and/or roots and to pull plant biomass out of the water. Manual methods are mainly applicable in small water bodies, such as irrigation and drainage canals or small rivers and lakes. Complete removal of weeds is usually not achieved, and in many cases a quick regrowth occurs. Consequently, more than one cut per season is usually necessary.

Manual control has advantages when access for equipment is difficult and certain plant species or plant parts need to be harvested selectively. An important drawback is the potential health hazard from waterborne diseases, for example bilharzia, that workers encounter when entering the water.

MECHANICAL CONTROL

A wide variety of harvesting machinery is available on the market. The equipment is usually mounted on a boat or on a tractor that operates from the bank or the shore. Some mechanical equipment has only cutting bars, whereas others also include means for harvesting the plant material.

Dredging is a mechanical method that not only harvests the plant material but also removes the underground material of rooted plants and seeds. This provides an important advantage over other mechanical methods, because removal of roots, rhizomes, and other plant propagules causes a delay in regrowth of the weed. Unfortunately, even dredging can leave enough plant propagules behind for fairly quick regrowth. More critically, it is devastating to benthic organisms, as well as affecting suspended organisms through increased turbidity. Physical damage to the habitats of macro-invertebrates will affect fish feeding and growth. Fisheries may therefore encounter reduced fish yields after dredging or even other physical methods of weed control. Consequently, dredging is not a recommended management technique except in extreme cases.

CHEMICAL CONTROL

Herbicides are powerful tools in aquatic plant management. Herbicides are potentially more thorough and sometimes longer lasting than mechanical control methods. However, they can only be applied effectively and safely with a solid understanding of the chemistry and biology of the ecosystem.

Broad-spectrum herbicides affect all aquatic plants, while selective types only damage particular species. Application of herbicides should not surpass the recommended dose, in order to minimize the chance of side effects on other organisms. The effectiveness of herbicides can be improved by controlled dose applications using granular pellets or polymer carriers that slowly release the herbicide close to the plant or its roots. Given the potentially toxic nature of many agrochemicals, it is also important that personnel are trained in the safe storage, handling, and application of herbicides.

Special herbicides are available to control algal growth (algicides), although they are expensive. Copper sulfate is commonly used as a cheap, highly effective algicide. In developed countries, it is subject to stringent controls because of residual effects on fish and other aquatic life.

In general, herbicides and algicides are expensive, so chemical control is usually confined to relatively small bodies of higher-value water such as irrigation canals. It can be applied by hand, by helicopter, or plane. However, the latter two methods, while efficient, will often result in dispersal of the herbicide outside the target area.

Both physical and chemical control methods usually need to be repeated at least every growing season. Physical and chemical methods rarely provide a permanent solution to weed problems; as a result, a long-term management program will need to be implemented.

Photo by David Eastburn (MDBC)

Algal bloom, Darling River, Burke, Australia

It is important that aquatic plants are removed from the water body if they have been killed in large numbers by either physical or chemical methods. Unfortunately, this is usually difficult with algae because of their small size. If the dead biomass falls to the bottom of the water body, it can often result in anoxic conditions, and the release of nutrients and hydrogen sulfide from the sediments. These conditions are conducive to cyanobacterial or algal growth and even fish kills.

BIOLOGICAL CONTROL

Biological control methods potentially provide better long-term success than mechanical or chemical methods. To be effective, biological methods require more insight into ecosystem functioning than is required for chemical or physical methods. For aquatic weeds, biological control methods are based on the introduction of a herbivorous organism, fungus, or virus into the affected ecosystem (Box 7).

Biological control of aquatic weeds is regarded as successful if the control agent multiplies, spreads over the infected area, and reduces the weed population to acceptable levels. These agents may be selective, only affecting the weed, or nonselective, affecting all vegetation. Several reports exist of the successful introduction of arthropods and fungi for selective control. For example, the weevil *Neochetina eichhorniae* has brought infestations of water hyacinth in Lake Victoria under control (a fortuitous *El Nino*-induced drought probably also contributed). There have been no side effects reported from using arthropods for biological control, probably because these organisms are highly selective. Microbial herbicides (pathogenic fungi) that can be sprayed on emergent or floating plants offer potential for short-term management following sudden growth spurts of these weeds. However, pathogenic fungi need to be screened for their effect on other plants and fish before application.

The introduction of herbivorous fish such as grass carp into the affected water body provides an example of nonselective control of weeds. Not only do the fish reduce weed densities, but they may also provide additional food production.

An interesting biological approach to the control of flow resistance is the planting or stimulation of particular species of *Nymphaeids* that have limited submerged biomass, hence a low resistance to flow, and that shade out fully submerged, nuisance water plants.

Biological control can also be used with nuisance algae. Biomanipulation through the introduction of

Box 7.
Biological control of weeds in Southern Africa

In the 1970s, biological control still met with substantial skepticism in Southern Africa. For instance, the National Institute for Water Research of South Africa and the Science Council of Zimbabwe advised against using biological methods to control water hyacinth. However, the use of biological control methods was stimulated by the concern of both the public and scientists about other control methods. Although the first biological control method was initiated in South Africa in 1962, biological methods became accepted only in the 1980s.

A good example is the biological control of Kariba weed in the rivers and floodplains of the Easter Caprivi in Namibia. Initially, research was conducted into the causes of the weed problem in order to evaluate the effectiveness of several control strategies. It was found that biological control was both the most promising method and the most ecologically sound option. Today, Kariba weed is kept under control by *C. salviniae* weevils.

International cooperation between organizations such as the *Plant Protection Research Institutes* in South Africa and Zimbabwe, the *International Institute of Biological Control* in Kenya, the *Entomology Division of the CSIRO* in Australia, and the *Aquatic Plant Control Research Laboratory* in Florida played a key role in the development of biological control programs in Southern Africa. Most biological control programs started with the import of a biological agent from the Australian or American partner institute. After quarantine, careful screening, and breeding, the agent was released in the affected area, generally with success.

top-level predatory fish, such as bass, has been used to successfully reduce algal biomass in a number of shallow European and North American lakes. These large fish are often palatable and, in some cases, provide good recreational opportunities. Thus they can have economic side benefits, as well as providing algal control. Other biomanipulations, such as removal of all fish species, have been used with mixed success.

In a number of cases, the decline in algal biomass after biomanipulation was followed a few years later by a resurgence of algal numbers. Food-chain interactions are complex, and it is essential that attempts at biomanipulation are preceded by thorough ecological studies of the lakes, so that the likely effects of the interventions can be understood. Given the cost and expertise required for these studies, biomanipulation is more likely to be used in developed rather than developing countries.

HABITAT ALTERATIONS

The physical habitat of weeds and algae can be modified by, for example, lowering the water level in smaller, well-controlled water bodies such as irrigation channels and reservoirs. This method will expose weeds and algae to dehydration and direct sunlight. Weeds were managed successfully in an irrigation network in India at very low costs by implementing an annual five-day draw-down period. While this method can remove nuisance macrophytes, it can also promote phytoplankton such as cyanobacteria, which are quicker to colonize nutrient-rich waters if competition from macrophytes has been removed.

Reducing the penetration of light into the water body is another way of changing the habitat of submerged plants. This can be achieved by increasing the water turbidity with nonharmful dyes, by regulating flows, or by introducing an appropriate density of bottom feeding fish that stir up sediment. For smaller drains and streams, trees planted on the banks will shade the water and significantly reduce weed development.

Freshwater cyanobacteria are buoyant and are particularly favored by stratified water bodies where they can move to the surface layer to obtain light for photosynthesis. Destratification of these waterbodies removes this habitat advantage and allows other less harmful phytoplankton to dominate (see Note G.2). However, it takes considerable energy to destratify a mass of water, and this technique is only feasible for high-value water bodies such as drinking water supplies for major cities.

ENVIRONMENTAL CONTROL

Environmental control methods are aimed at restoring the key environmental conditions of the ecosystem. These prior conditions have often been disturbed by anthropogenic sources, such as wastewater discharge or runoff of fertilizers from agricultural land. Introducing proper wastewater treatment and limiting runoff prevents an increase in nutrient availability and hence will reduce the chances of excessive growth of weeds or algae.

INTEGRATED CONTROL

Integrated control refers to the application of a range of physical, chemical, biological, and environmental control methods when single methods are unlikely to succeed or when longer-lasting control of weeds or algae is required at reduced costs and with fewer undesired side effects (Box 8). However, it must be based on an ecological analysis of the aquatic ecosystem, including interactions with the surrounding terrestrial or aquatic ecosystems and socioeconomic considerations. Consequently, integrated control takes longer to implement and calls for a major investment in scientific investigation and monitoring. The example also shows the importance of involving stakeholders when several methods are being applied and long-term monitoring is required.

For example, the herbicide 2,4-D can be applied at a lower-than-normal dose if it is combined with introduction of the water hyacinth weevil *Neochetina eichhorniae*. In other cases, mechanical control of aquatic weeds can be combined with the introduc-

Box 8.
Selection and application of weed control methods in Mexico

Starting in 1993, an Aquatic Weed Control Program was implemented in three phases for three man-made lakes—Tacotán, Trigomil, and Miraplanes—in the Ayutla River watershed of Mexico. The first two of these lakes were heavily infested with water hyacinth, while the third lake was infested by both water hyacinth and cattail. The control program occurred in a number of phases.

Phase 1: Initial evaluation, participation, and communications
During this phase, water uses, agricultural activities, and weather conditions were inventoried and the extent of weed coverage was estimated from satellite images. Possible control methods were identified. Simultaneously, water users that were willing to work with government authorities were identified and informed about various aspects of the proposed control program.

Phase 2: Selection and application of control methods
The following methods were considered: chemical treatment, trituration (a mechanical method using large harvesting machines), biological treatment, water-level management, and manual removal. Control methods were selected for each lake based mainly on the characteristics of the lake, available budget, and domestic availability of the control method. In Tacotán Lake, water-level reduction resulted in the dessication of about 100 hectares of water hyacinth. These plants were burned. The remaining area of water hyacinth was sprayed with 3.3 kg ha^{-1} of 2,4-D, followed by an application of 1.7 kg ha^{-1} of diquat. For Trigomil Dam, a combined chemical-mechanical method was selected. Spraying with 3.35 kg ha^{-1} of glyphosate weakened the plants, and mechanical control with triturators resulted in 100 percent clearance. In Lake Miraplanes, 3.3 kg ha^{-1} of glyphosate was selected as the preferred treatment, because this chemical is reported to be very effective at killing cattail (*Typha sp.*). Two applications of this chemical (with a 200 day interval) resulted in 100 percent clearance.

Phase 3: Environmental monitoring and maintenance
An ongoing water quality monitoring program was established. Coverage due to regrowth was monitored and compared to established criteria for initiating new control actions. A users' committee was involved in the monitoring and preventive maintenance.

Source: Gutierrez, E., R. Huerto, P. Saldana, and F. Arreguin. 1996. "Strategies for water hyacinth (*Eichhornia crassipes*) control in Mexico." *Hydrobiologia* 340: 181–185.

tion of grass carp, or catchment management that reduces nutrient inflows can be combined with destratification of lakes to disrupt the habitat that is conducive to cyanobacteria. When the integrated approach includes a biological control measure, it naturally combines a short- and long-term perspective. For the long-term control of weeds to be effective, the ecological interventions need to be analyzed from an overall catchment perspective, rather than at the scale of the infected aquatic ecosystem. This approach will prevent quick reinfection of a cleared area with plants from remaining populations in the same catchment area.

Integrated approaches should also consider the timing of the control action in relation to the life-cycle stages of aquatic plants. For instance, the development of emergent as well as submerged weeds during one season depends on the number of propagules that were produced in the previous season. The number of propagules may be influenced by manipulating certain environmental factors. For example, reducing light availability by raising the water level or increasing turbidity causes one species of pondweed (*P. pectinatus*) to form relatively small tubers. This effectively hampers sprouting in the next season. Harvesting aquatic plants just before the formation of tubers and turions, or reducing light availability for young seedlings, are similar examples of approaches that make prudent use of bottlenecks in the weed's annual life cycle and interactions in the ecosystem.

Management of integrated control methods. Aquatic weed control programs are preferably executed as part of an integrated water management program. Integrated water management *per se* is not discussed here, but some specific requirements that are related to integrated control of weeds are presented. Design and implementation of integrated control methods require a multidisciplinary management staff that includes specialists in the various methods, as well as ecologists to provide the ecological analysis on which the integrated weed management is based.

Sustainable solutions require a long-term perspective with an ongoing commitment of funds and skilled personnel. This can be difficult to sustain when there is a strong urge for broad-scale application of herbicides, so that immediate results are observable. However, long-term integrated control methods do not necessarily exclude quick solutions to urgent weed problems. Thus, the temporary application of an effective chemical method may constitute an early stage of an integrated approach.

A catchment perspective is usually necessary for integrated control. A waterbody that spans administrative or national boundaries cannot be effectively dealt with by an institution with jurisdiction over only part of the waterbody. Without coordination, upstream pollution in another administrative area prohibits an integrated approach downstream. This problem occurs, not only with transboundary water bodies, but also if the administrative body responsible for aquatic plant control cannot influence activities in other sectors. Thus, manual and chemical control of algal blooms may be futile in the long run, if high loads of nutrients continue to enter the water body from other jurisdictions.

BENEFICIAL USES OR DISPOSAL OF WEEDS

Harvesting aquatic weeds can sometimes provide a product for sale. Many people in low-income countries harvest aquatic plants on a small scale and use the material as a resource, without being interested in weed control. Also, algae are sold as a health food in many developed countries. However, this is not a recommended practice because of its potential contamination with toxins. The following uses of harvested biomass refer to aquatic weeds only. There are few cases of large-scale weed control programs that include economically viable use of the harvested biomass. The financial return is usually not sufficient to contribute significantly to weed control costs.

FOOD FOR HERBIVORES

A number of aquatic plants, such as duckweed, have high protein content, favorable amino acid composition, low fiber content, and good digestibility. This makes them desirable for animal feed. Others–for example, emergent plants–have a high fiber content. The high moisture content of aquatic plant biomass usually necessitates extensive pre-processing, such as by mechanical pressing or solar drying. This adds to the cost of this food source. However, this pre-processing cost can be avoided by feeding aquatic plant material to herbivorous fish (Box 9).

SOIL AMENDMENTS

Aquatic plant material may be used to increase the organic and nutrient content, the microbial activity, and the texture of soils. The plant material can be applied after composting, directly spread on the surface, or mulched into the top layer of the soil. Mulching results in reduced evaporation, weed suppression, increased soil moisture and organic content, and reduced erosion. These applications may be helpful where economic conditions do not permit the purchase of artificial fertilizers.

FIBER AND PULP PRODUCTS

Several fiber products may be produced from aquatic plants. Paper, for instance, has been produced from papyrus plants for millennia. In Romania, a program has been developed in which common reed (*Phragmites australis*) is harvested from a 434,000-hectare delta for fiber board, alcohol, insulation material, roof cover, and fertilizer. Handicraft prod-

Box 9.
Integrated weed production and fish farming, Bangladesh

The 10-hectare Mirzapur Farm Complex in Bangladesh contains about 7 hectares of fish ponds. In part of this complex, the fish are fed on duckweed, which receives its nutrients from sewage. Between 125 and 270 m^3 of sewage is received per day from 2,000–3,000 persons. The sewage is passed through a sedimentation pond before entering a plug-flow lagoon where the duckweed is grown. Duckweed production averages 17 tons dry weight per year, and fish production averages about 11 tons/ha/yr. The fish are ultimately used as fertilizer in banana production. More than 100 tons of bananas are produced per year with the aid of this fertilizer.

BOD_5 of the influent sewage is 125 mg/l, while the effluent at the end of the plug-flow lagoon is 5 mg/l. Fecal coliforms in influent average 45,700 cfu/ml, while in the effluent it is <100 cfu/ml. Since the WHO standard for discharge of effluent water into a natural body is <100 cfu faecal coliform per ml, the effluent is considered safe. The levels of heavy metals and pesticides are monitored and are acceptable under international standards.

ucts such as woven mats, baskets, fish traps, handbags, and hats are also produced from numerous fibrous emergent species, as well as submerged ones.

ENERGY PRODUCTION

Chopped plant material can be fermented to produce methane or ethanol. These fermentation technologies are widespread in many countries. These processes are practiced in several places in Bangladesh, Brazil, India, and the United States. However, the economic feasibility of fermentation is very sensitive to international energy prices.

SANITARY LANDFILL

Disposal of aquatic plant material to sanitary landfills is subject to environmental concerns, as is true with any other waste. However, the leachate from landfills containing plant material should contain only natural organic compounds and nutrients, and should not be contaminated with hazardous compounds. Odors from decomposing biomass, insect breeding, and nutrient pollution of shallow aquifers are potential problems that need to be prevented. Biogas production in the landfill offers the possibility for energy generation and partial cost recovery.

ADVANTAGES AND DISADVANTAGES OF CONTROL METHODS

As the preceding discussion makes clear, there are a large number of options for managing nuisance aquatic plants. The selection of a suitable method will depend on costs, the skills needed, and institutional needs, as well as health, safety, and cultural aspects (Table 3).

COSTS

The costs of aquatic plant management quoted in the literature are often qualitative or poorly defined. This, along with the site-specific nature of many of the costs, makes a cost comparison difficult. Nevertheless, an attempt is made here to give a rule-of-thumb estimate of costs for managing macrophytes (Table 4) and algae (Table 5). Note G.2 provides further information, including costs, on the management of aquatic weeds and algae in lakes.

Although the reported costs vary widely, they clearly suggest that the use of heavy equipment increases both capital investment costs and running cost. Thus, the "mechanical removal" category in Table 4 is notably expensive. This is partly because different techniques are grouped together, including

[3] Microbial contamination is measured in 'colony-forming units (cfu)' per ml where a cfu is a bacterial cell or clump of cells capable of developing into a colony when grown in laboratory conditions.

TABLE 3.
COMPARISON OF FEASIBILITY, COMPLEXITY, AND POTENTIAL SIDE-EFFECTS OF DIFFERENT WEED CONTROL METHODS.

Control method	Feasibility /Applicability		Complexity		Side Effects
	Small systems (drains, streams)	Large systems (lakes, reservoirs, rivers)	Technological	Institutional	
Manual removal	++	–	o	o	o
Mechanical removal	++	+	ooo	oo	o/oo
Chemical control	++	++	oo	ooo	ooo
Biological control	++	++	oo	ooo	o
Habitat alterations (shading, draw-down)	++	–	oo	ooo	oo

Notes: A qualitative scale of judgment is used to measure feasibility (– = unfeasible, + = reasonable, ++ = good option) and complexity and side effects (o = low, ooo=high). Since the integrated approach involves combinations of these methods, it is not evaluated separately.

TABLE 4.
INDICATIVE COSTS OF DIFFERENT MACROPHYTE CONTROL MEASURES.*

Method	Mean ($ $ha^{-1}yr^{-1}$)	Range ($ $ha^{-1}yr^{-1}$)	Number of reports
Manual cutting	54	3-150	4
Mechanical removal	189	20-530	7
Herbicide application	110	46-145	3
Combinations	45	23-82	3

* Based on published literature from irrigation canals and lakes from various parts of the world. Data were converted to $/ ha^{-1}/ yr^{-1}, assuming a typical mean width of 5 m for irrigation canals and neglecting fluctuations in US dollar rates between 1980 and 1999.

dredging, which is particularly expensive. The few reports available on the costs of integrated control methods suggest that they are cost-effective. However, biological treatment costs were not assessed because of the difficulty of converting them to an areal basis.

FEASIBILITY

The feasibility of a control method is highly dependent on the spatial scale. In smaller drains or streams, most methods would be fairly easy to apply. In large lakes, reservoirs, and rivers, chemical control is usually more feasible than mechanical

TABLE 5.
INDICATIVE COSTS FOR DIFFERENT NUISANCE ALGAE CONTROL METHODS

Technique	Costs
Phosphorus inactivation	$640–$3,900 per ha
Algicides (Note these chemicals can have detrimental environmental effects and should be used only for crises)	$30 to $700 per ha per application.
Biomanipulation	Typically $300-600 per ha capital cost
Aeration of bottom waters.	Highly variable; Tegeler See, Germany installation cost was $2.7 million with $6,500/ha/yr operational cost.
Artificial destratification	Typical installation costs are $720/ha; corresponding operating costs are $320/ha/yr
Sediment removal	Lake Trummen, Sweden restoration cost about $5,700/ha (1970 costs)

control because the dredging and cutting machinery is slow compared to aerial applications. Furthermore, biological control may not be feasible in very large systems when the biological agent is to be strictly confined to the waterbody under treatment. The spatial scale thus places serious constraints on the methods that are applicable.

Shading using trees or fences may be feasible only in smaller systems, such as along secondary and tertiary irrigation channels. Draw-down of the water level is also only a feasible alternative in systems where the water level can be manipulated, such as irrigation systems that have a fallow period.

COMPLEXITY

The feasibility of a method is directly linked to its complexity. It has to be capable of being managed by locally relevant institutions and stakeholders. Mechanical and chemical controls require skilled labor before, during, and after treatment. Equipment needs to be maintained and used properly, and proper chemical dosing requires training. Conversely, field application of biological control methods is comparatively simple, although high quality scientific expertise will be needed during the planning phase. With all methods, the health of field workers must be protected, which may add a degree of complexity.

The design and conduct of eradication campaigns requires a level of institutional sophistication. Authorities responsible for the design of complex treatment programs should include proper training for their field staff, particularly for chemical and biological control. Managers also need to make sure there is a good understanding of the ecology of the weed as part of the control program. These management requirements demand skilled people and facilities, either in regional water management authorities or in irrigation departments.

SIDE EFFECTS VERSUS SPECIFICITY

In general, the more specific a method is, the fewer the unwanted side effects.

Potentially hazardous side effects are well-known with chemical control. Herbicides may be toxic to humans, fish, and other organisms, and so herbicide treatment will often make water unsafe for drinking by humans and animals. Furthermore, vegetation die-off after herbicide application is often rapid and depletes the dissolved oxygen, leading to fish kills. Most herbicides undergo a rigorous screening program before being allowed on the market, but legal restrictions and administrative oversight vary substantially among countries. Even when there are legal restrictions, banned or restricted herbicides continue to be available in many developing countries.

Mechanical removal has comparatively few side effects. However, plant material should be removed to minimize the effects of oxygen depletion on fish and other organisms. Cutting without removal of debris may also cause reestablishment of the weeds at other undesired locations, since many aquatic weed species are efficient at vegetative propagation. Dredging sediments, as already discussed, has severe side effects and should be avoided if possible.

Draw-down of water in channels and reservoirs may have serious side effects on desirable biota. When no refuges are present in the system, major losses are observed. Also, some aquatic plant species produce organs (tubers, rhizomes, turions, seeds) that remain in the deeper layers of the sediment. This control method, therefore, will select for particular weed species. Finally, during the period of draw-down, emergent weeds may encroach onto the dried sediments from the banks and can be difficult to remove later.

The possible dispersal of an introduced bio-control agent or an unexpected change in its diet are the major inherent risks with biological control. Although herbivorous insects are often very host-specific, a new race that attacks a local food crop may evolve. Consequently, biological introductions must be screened extensively for their possible side-effects before the decision is taken to introduce them.

IMPEDIMENTS

Some of the more common impediments to the success of a weed management program are:

- Strong political pressure for immediate action when a weed problem emerges at a late stage. Funding for these programs tends to come from nonsustainable budget sources and may favor quick and sometimes environmentally harmful solutions.
- Lack of an integrated ecological and catchment perspective.
- Lack of confidence in the effectiveness of biological methods.
- Impossibility of full control over the problem or problem area.
- Lack of consultation with and support from local stakeholders.
- Lack of sufficient skilled personnel and a strong institutional framework with political and legal status.

MONITORING AND PREVENTION

Early warning requires the identification of an aquatic plant at an early stage of its development. This is generally long before problems become apparent to the general public or immediate stakeholders (Box 10). Since the life cycles of most species have a clear seasonality, the timing of such a monitoring program should be linked to seasonal growth periods. Long-term monitoring schemes generally involve the selection of a few representative plots or stations, which are subsequently monitored after a broad system-wide survey has been conducted. The program should also include water quality monitoring (see Note D.1), as well as algal species and cell concentrations. The collection of water samples is important for algal monitoring; results can be skewed by the collection of wind-borne blooms or surface scums. Since plant growth and seasonality are governed by physical factors–light, water stratification, and temperature–as well as nutrient availability, the long-term data collection from such a monitoring program can be used to check for correlations

BOX 10.
HISTORICAL DEVELOPMENT OF AQUATIC WEED CONTROL STRATEGIES IN SOUTHERN AFRICA

The introduction of water hyacinth occurred at the end of the 19th century in South Africa. Other weeds appeared in the first half of the 20th century. Parrot's feather was introduced from South America around 1918. Water lettuce first occurred in African waters in 1937. Kariba weed was first reported in southern Africa from the Zambezi River in 1948, and red water fern was first reported from South Africa in the same year.

For most of these species it took decades before serious problems were reported. These weeds have now spread throughout the southern Africa region, especially since the 1970s, and have caused many problems. Water hyacinth caused problems on Lake Chivero in Zimbabwe in the 1950s. The control method applied at that time was a combination of manual control and spraying with the herbicide 2,4 D. Initially this operation was successful, and the lake remained clear until 1967. However, a drop in water level at that time caused germination of seeds in the lake sediments. After this reinfestation, large-scale manual control was initiated. This was unsuccessful, so the problem was solved by herbicides. A more recent example of the shortcomings of manual control occurred in Zambia in 1994. The Zambian Army attempted to remove water hyacinth from the Kafue Gorge Water Reservoir manually. Initially the reservoir was cleared, but after some months the weeds recolonized the waterbody.

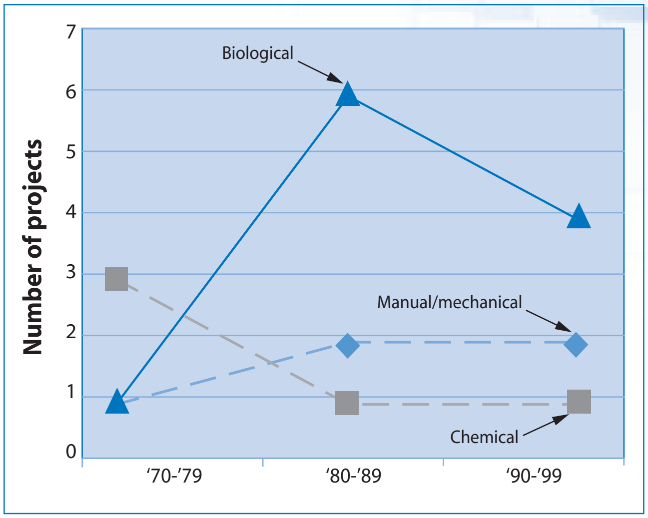
Because of the shortcomings of manual and mechanical methods, herbicide spraying became the most popular control method in the 1970s (Figure 1). Effective control was achieved in many cases with chemicals—for example, using the Terbutryn herbicide "Clorosan 500" for water hyacinth in 1978 on the Hartbeespoort Dam in South Africa. This project included a study on the health effects of the herbicides; local health authorities could not detect any danger. However, over the years public resistance toward herbicides increased. For this reason, herbicide control of aquatic weeds has now declined in favor of biological control.

Source: Bethune, S., and K. Roberts (2002).

between plant development and these environmental factors.

There are a number of early warning indicators that a weed problem may be developing. The presence of the plants themselves offers the most reliable predictor. Even the past occurrence of submerged vegetation is an indicator, since the sediment often still harbors seeds or other propagules. Sediment cores (with processing and enumeration) are a feasible means to assess propagule presence. Algal and cyanobacterial cells are almost always present in the waterbody and can multiply extremely rapidly when the physical and chemical conditions are right. Some species of algae can deposit seeds in sediments. Unfortunately, there is little information on the conditions that cause germination to provide managers with early warning indicators of this source of algal growth.

FIGURE 1.
MAJOR AQUATIC WEED MANAGEMENT PROJECTS IN SOUTHERN AFRICA, GROUPED BY CONTROL METHOD.



Source: adapted from Bethune & Roberts, 2002.

Environmental parameters such as high nutrient concentrations and high light availability (low turbidity), as well as moderate flow velocities, allow the rapid growth of submerged and/or floating species of weeds as well as algae and cyanobacteria. Buoyant species of cyanobacteria, such as *Anabaena* and *Microcystis*, are also strongly favored in stratified water bodies because they can float to the surface to make use of the good light conditions there. Together these factors create a "habitat probability window" of nuisance aquatic plants. Some of these environmental conditions, such as nutrient concentrations and stratification, can be manipulated by managers.

CONCLUSION

Nuisance aquatic plants can lead to serious economic losses in most water-using sectors. They can block water off-takes for hydropower production, irrigation, and drinking water supply; interfere with transportation; affect fisheries by blocking landing sites, alter habitat and lower oxygen levels; increase health problems by providing habitat for vectors such as mosquitoes; reduce water quality by changing water chemistry and releasing toxins; and reduce the overall availability of water for consumptive uses through enhanced transpiration. They also lead to ecological losses by smothering other plants, competing for nutrients and altering habitat and, in the case of phytoplankton, modifying foodchains.

Once established, these plants are very difficult to control and usually impossible to eliminate. Chemical control methods are not recommended except in emergencies because of their side effects. However, physical methods and biological methods have proven successful in a proportion of cases with minimal side effects when undertaken carefully. In the long term, the conditions that provide these plants with relative advantages need to be controlled. In combination with physical/biological control techniques, successful strategies may include integrated control methods that combine long-term nutrient reduction activities; education for the community; and consistent legislation and policies, especially in transboundary waterbodies.

FURTHER INFORMATION

General references for occurrence and management of freshwater weeds include:

Cook, C. D. K. 1990. *Aquatic Plant Book*. The Hague: SPB Publishing.

Joffe, S. and S. Cooke. 1997. *Management of the water hyacinth and other invasive aquatic weeds: issues for the World Bank*. Report for the World Bank Rural Development Department. Washington: World Bank.

Pieterse, A. H. and K. J. Murphy, eds.1990. *Aquatic weeds, the ecology and management of nuisance aquatic vegetation*. Oxford: Oxford University Press.

Scheffer, M. 1997. *Ecology of Shallow Lakes*. Population and Community Biology Series 22. London: Chapman & Hall.

Bethune, S. and K. Roberts, 2002. Aquatic weeds and their control. Chapter 8 in *Defining and Mainstreaming Environmental Sustainability in Water Resources Management in Southern Africa*. R. Hirji, P. Johnson, P. Maro and T. Matiza Chiuta, eds. Maseru/Harare/Washington: SADC, IUCN, SARDC, World Bank.

Two scientific journals are dedicated to aquatic weed management:

Aquatic Botany. Elsevier Science BV, Amsterdam, The Netherlands (http://www.elsevier.com/locate/aquabot)

Journal of Aquatic Plant Management. University of Florida, Fort Lauderdale, FL 33314 (http://www.apms.org/japm.htm)

Information on weed identification is provided by the Centre for Aquatic and Invasive Plants of the University of Florida (http://aquat1.ifas.ufl.edu/), which also has a large on-line data base available on aquatic weeds.

The following document provides definitive advice on management of cyanobacteria in freshwaters:

Bartram, J. and I. Chorus, eds. 1999. *Toxic Cyanobacteria in Water: A Guide to their Public Health Consequences, Monitoring and Management*. Geneva: World Health Organization.

The following website provides reliable information on cyanobacterial toxins:

http://www.worldwaterday.org/2001/disease/cyano.html

Information on marine and estuarine algal blooms can be obtained from:

http://state-of-coast.noaa.gov/bulletins/html/hab_14/references.html