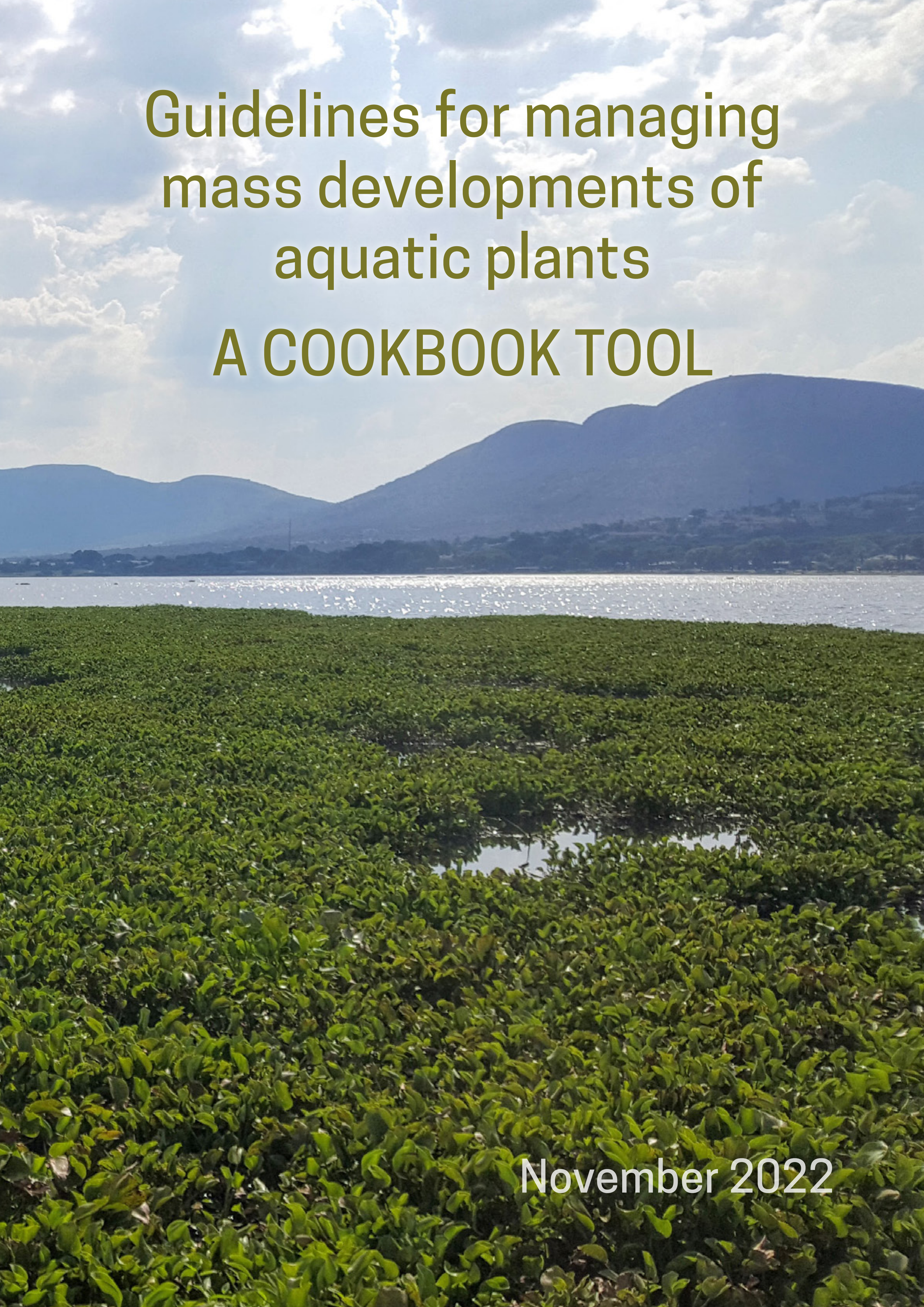
Guidelines for managing mass developments of aquatic plants

A COOKBOOK TOOL



November 2022

Contents

Contributors

Julie Coetzee[1]
Elena Galvanese[2]
Sarah Faye Harpenslager[3]
Sabine Hilt[3]
Jan Kohler[3]
Benjamin Misteli[4]
Samuel Motitsoe[5]
Andre Padial[2]
Antonella Petruzzella[5]
Susi Schneider[6,7]
Anne Schechner[3]
Keneilwe Sebola[5]
Gabrielle Thiebaut[4]
Kirstine Thiemer[6,7]
Jan Vermaat[7]

Contributors' affiliations

1. Centre for Biological Control, Botany Department, Rhodes University, Grahamstown, South Africa
2. Departamento de Botânica, Universidade Federal do Paraná, Curitiba, Paraná, Brazil
3. Dept. of Community and Ecosystem Ecology, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Müggelseedamm 301, 12587, Berlin, Germany.
4. UMR 6553 CNRS ECOBIO, Université de Rennes 1, 263 Avenue du Général, 35042 Rennes, France.
5. Centre for Biological Control, Dept of Zoology and Entomology, Rhodes University, Grahamstown, South Africa.
6. Norwegian Institute for Water Research, Økernveien 94, 0579 Oslo, Norway.
7. Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, P.O. Box 5003, 1430 Ås, Norway.

Cover photograph

Water hyacinth mass development at Hartbeespoort Dam, South Africa.

Photo: Julie Coetzee

Design and layout: Heath at ihwhiteDesign

A. INTRODUCTION AND PURPOSE OF THE GUIDELINES

Freshwater ecosystems make up only 0.01% of the world's water, but constitute highly valuable natural resources which provide important ecosystem services (human benefits obtained from nature). Aquatic ecosystems also provide habitats for many plants and a space for animals to feed, rest and reproduce. Rivers carry sediments that transform riverbeds and contribute to habitat creation. Humans, however, have modified the structure and function of many rivers in the world by constructing dams, weirs, and watermills in order to produce electricity, facilitate navigation, and irrigate.

Aquatic plants, termed macrophytes, are vital in freshwater ecosystems as their presence influences physical, chemical, and biological characteristics of aquatic ecosystems and consequently, ecosystem services. The benefits that aquatic plants provide may however be diminished when at high densities, termed *mass developments*, due to their ecological and socio-economic impacts.

Human societies historically prospered near freshwaters. Healthy freshwater systems are central to achieving the United Nations sustainable development goals (SDG), and mass development of macrophytes is a pivotal issue associated with many SDGs. Therefore, various control measures are employed by managers to reduce the impact of the mass developments, including: mechanical/manual removal, herbicide application, biological control, or a combination of these. However, some ecosystem services, such as good water quality, depend on the structure and functions provided by macrophytes. Freshwater managers should therefore aim to reach a macrophyte growth level that maximises the total ecosystem services value.

The purpose of these guidelines is to assist managers of invaded waterbodies with decision-making on control options to rehabilitate aquatic ecosystems, thereby increasing biodiversity and improving the ecosystem structure and functioning of these crucial systems. These guidelines outline appropriate methods to manage mass developments of macrophytes, while maximising ecosystem services based on the latest research of a multinational study across three continents.

1. What are macrophytes?

Larger aquatic plants growing in waterbodies are usually called macrophytes. The term includes aquatic flowering plants and ferns, aquatic mosses, and some larger algae that have tissues that are easily visible. Macrophytes, like all other plants, use the sun's energy to convert carbon dioxide into energy (carbohydrates), which provides the energy source for organisms reliant on plants for their food source (animals, bacteria, and fungi). Aquatic macrophytes come in a variety of forms and shapes and are generally categorized into five groups (Figure 1):

- **Rooted macrophytes**
  - Emergent macrophytes:

    Emergent plants pierce the surface. They therefore grow in and above the water, for example, reeds and sedges.
  - Floating-leaved macrophytes:

    Floating-leaved plants consist of floating leaves which are rooted in the sediment, for example, water lilies.
  - Submerged macrophytes:

    Submerged macrophytes grow entirely underwater with roots attached to the sediment, for example, milfoils and oxygen weeds.
- **Unrooted macrophytes**
  - Free-floating macrophytes:

    In contrast to the other plant groups, free-floating macrophytes are not rooted in the sediment and can move with water currents or wind, for example, water hyacinth.
  - Free submerged macrophytes:

    Submerged plants that grow without a rooting system, for example, hornworts and bladderworts.

2. Benefits of macrophytes

Aquatic macrophytes are important in freshwater ecosystems and are often called ecosystem engineers as their presence can influence physical, chemical, and biological ecosystem characteristics. Aquatic macrophytes have a variety of important functions in the ecosystem that may translate into several provisioning and supporting ecosystem services, illustrated in Figure 2 below.

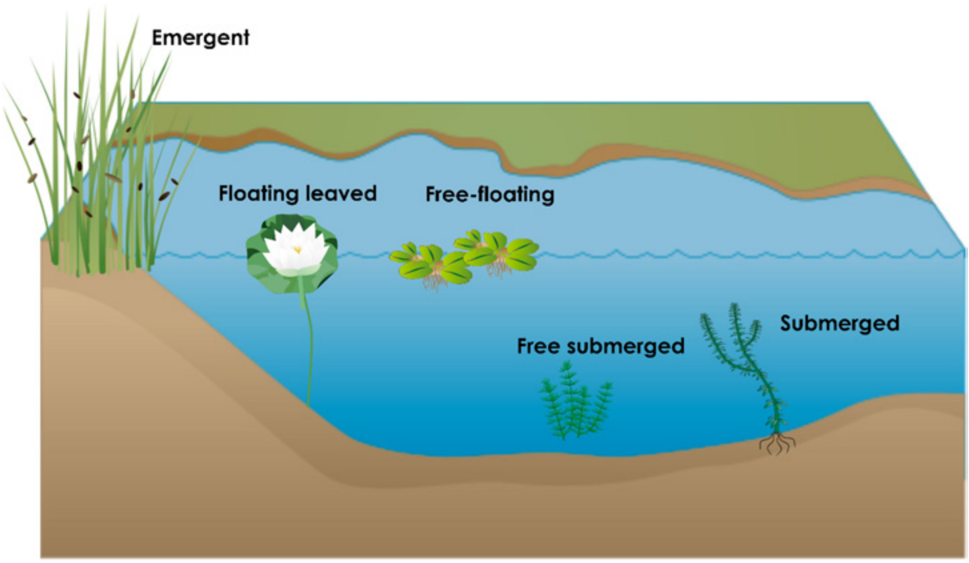


Figure 1. Scheme of aquatic macrophyte growth forms.

The presence of macrophytes provides habitat and food for other organisms such as fish, invertebrates, and waterfowl, and thereby provide food for human consumption and important cultural services, such as recreational angling and birdwatching. Rooted macrophytes enhance stream bed and lake sediment stability, reduce water velocity, and increase water residence time and water level. Macrophytes can thus promote sedimentation and reduce resuspension of sediment and nutrients, which is important in preventing harmful phytoplankton blooms.

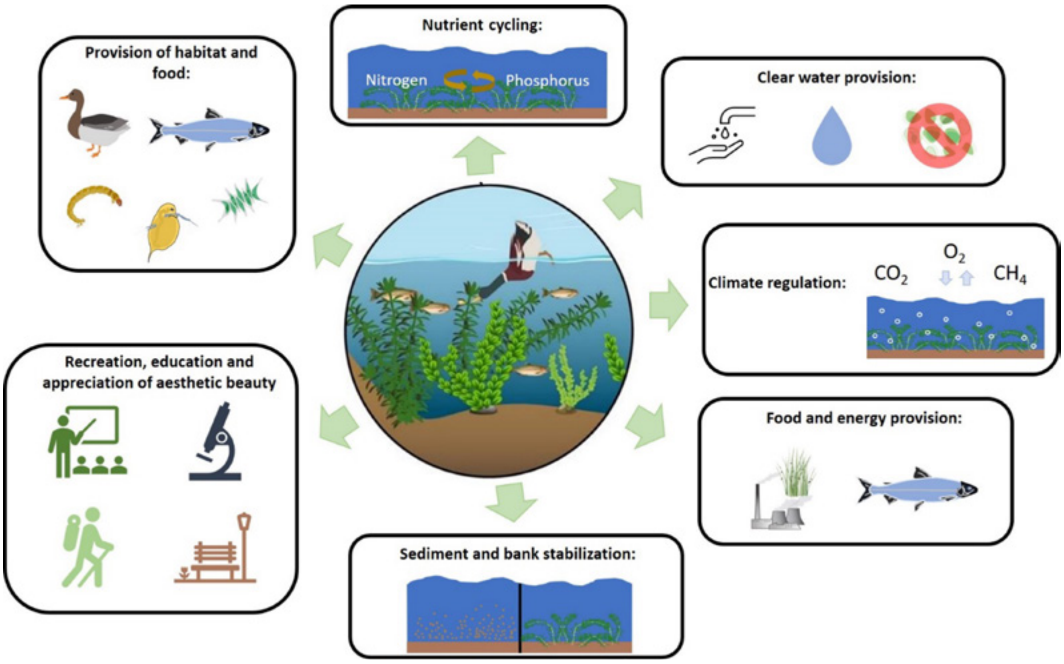


Figure 2. Examples of benefits that aquatic macrophytes provide and support

Macrophytes are therefore able to maintain clear water and provide ecosystem services such as drinking water and water for irrigation. Macrophytes can further promote clear water by taking up nutrients from the sediment and water column through their roots and leaves. Macrophytes can also regulate the emission of greenhouse gasses (carbon dioxide (CO_2) and methane (CH_4)), by taking up carbon dioxide through photosynthesis, increasing carbon burial by enhancing sedimentation, but also by altering methane production.

The role macrophytes play in freshwater ecosystems is complex and depends on several factors, such as macrophyte species (including different life-forms), the type of ecosystem (e.g. river, streams, or lakes), and on the distribution of the macrophytes within the system (density of macrophyte growth and size of macrophyte patches).

3. What are mass developments?

While macrophytes provide many benefits, under certain conditions, native and non-native species can proliferate and, within a short time, cover a large area with high density mass development that may have negative impacts. Only a few aquatic plant species, with different growth forms, can form dense mats. The most rapidly-spreading invasive species in their introduced ranges include floating species such as *Pontederia crassipes* (water hyacinth), *Salvinia molesta* (giant Salvinia) and *Pistia stratiotes* (water lettuce); submerged species such as *Elodea nuttallii* (Nuttall’s waterweed), and *Myriophyllum spicatum* (milfoil) in Europe; and emergent species such as *Ludwigia* spp. (water primroses) and *Alternanthera philoxeroides* (alligatorweed).

The mass development of macrophytes is usually dominated by one or two species. Mass developments are expected to increase in frequency due to global change, and as nutrient pollution of water bodies increases, and as such, the problems they create will get worse.

Where do they develop?

Mass developments occur in many different types of waterbodies: natural and manmade ponds and lakes, rivers, streams, and wetlands. Macrophytes need resources (nutrients, light) for growth, while disturbances (e.g. floods, grazing) limit macrophyte development. Nutrient enrichment generally enhances the growth of macrophytes, while reduced disturbance, e.g. reduced frequency and intensity of floods, minimises the loss of plant biomass, thereby enabling the build-up of large plant biomasses over time. Mass development of macrophytes therefore typically occurs in ecosystems that provide enough light for plant growth, that have enough nutrients in water and/or sediment, and that have little mechanical disturbance. In such ecosystems, both native and non-native aquatic plants can build mass developments. Eutrophication, i.e., the anthropogenic enrichment of nutrients is therefore a common cause of macrophyte mass development.

Risk for mass developments is highest in nutrient-rich shallow lakes, particularly during the growing season, as experienced in Lake Grand Lieu, France; the lowest risk of mass development is in nutrient-poor, temperate rivers, unless hydrological flows are altered, as is the case in the River Otra, Norway. In these types of ecosystems, reduced disturbance can cause macrophyte mass development even when nutrient concentrations are low. This is because perennial water plants can build up massive biomass over several years, provided disturbance is low. Many macrophyte species can stay winter-green and continue to grow the next spring and summer. In this way, much biomass can be built up over several years. *Juncus bulbosus*, for example, can grow perennially and accumulate massive biomass in regulated rivers in Norway, because river regulation greatly reduces the frequency and intensity of floods and droughts.

Why do they develop?

Different growth forms of macrophytes (Figure 2) are particularly well-adapted to different conditions, and therefore build nuisance stands in different types of water bodies. A mass development of floating plant species typically occurs in ecosystems with high nutrient supply and turbid water. Floating plant species can build mass developments in any water depth, because they float at the water surface. Emergent species need high

Box 1
A glossary of key definitions

Native plant species (synonyms: indigenous plant species): Plant species that have originated in a given area without human involvement, or that have arrived there without intentional or unintentional intervention by humans from an area in which they are native.

Non-native plant species (synonyms: non-indigenous, exotic, introduced, alien plant species): Plant species in a given area whose presence is due to intentional or accidental introduction as a result of human activity, or which have arrived without the help of people from an area in which they are non-native.

Naturalized plant species (synonyms: established): Non-native plant species that present self-sustained populations over many life cycles (at least 10 years) without direct human intervention by recruitment from fragments (seeds, ramets, tubers), capable of independent growth. Naturalized plant species include both invasive and non-invasive plant species.

Invasive plant species: A subset of naturalized plant species that have the ability to thrive and spread aggressively outside their natural range; and whose introduction causes, or is likely to cause, economic or environmental harm or harm to human health sediment nutrient supply, tolerate turbid water, and need shallow areas. Submerged species only grow in water that is sufficiently clear to enable photosynthesis under water. Via positive feedback, mass developments of submerged macrophytes enhance water clarity, thereby promoting further plant growth. Due to their need for light under water, mass development of submerged macrophyte species generally occurs in relatively shallow water (typically between 0.5 and 4 m water depth, but the exact depth may vary depending on species and water clarity). The mass development of annual submerged macrophyte species depends on sufficient nutrient supply and sufficient access to light in spring to enable the build-up of large biomasses within one vegetation period. In contrast, perennial species can grow slowly in nutrient-poor ecosystems and may build up massive biomasses over several years, provided disturbances are low and there is enough access to light.

4. Why should we manage mass developments?

The impacts of mass developments are dependent on the type of waterbody, and the species of aquatic plant, and management options must consider these on a case-by-case basis.

Impacts

Large mats of floating plants, whether rooted or free, may limit access to water for commercial, recreational, and subsistence purposes; can reduce water quality for human and animal use; and alters habitat quality for native flora and fauna, all with negative economic consequences. In addition, the presence of floating mats enhances habitat for vectors of disease, such as malaria, Dengue fever, West Nile virus, encephalitis, bilharzia, and swimmer's itch; as well as increasing the risk of property damage during floods as a result of plants building up against bridges, fences, walls, etc., which obstruct water flow and increase flood levels.

Ecologically, reductions in light and therefore oxygen depletion beneath floating macrophyte mats alter submerged plant, plankton, invertebrate, and vertebrate communities, resulting in food web changes. Competition from these plants alters native plant communities, often displacing wildlife forage and habitat.

In the case of non-native aquatic plant species, the negative impacts are often more severe. In their alien range, non-native species often manipulate and infiltrate aquatic ecosystem structure, and in so doing, compete for space and resources with native aquatic communities, negatively affecting the ecosystem functioning which destabilizes critical aquatic biodiversity and associated ecosystems services (see below).

5. What do we manage an invaded aquatic ecosystem to?

Rehabilitate to a functional ecosystem

Aquatic plants are important for maintaining aquatic ecosystem structure and functions, supporting critical ecosystems services provided by aquatic environments. Their presence in an ecosystem is therefore critical. However, once a mass development occurs, management is necessary to preserve desirable abiotic and biotic ecosystem characteristics. These in return will assist and maintain the ecosystems' structure and function and safe guard critical ecosystem services i.e. improving water quality (clarity or purification) and quantity (run-off retention), supporting aquatic biodiversity by providing suitable habitat structure for aquatic organisms, providing a food source for aquatic organisms and terrestrial animals and helping maintain ecosystem integrity (or ecosystem resilience).

6. Macrophyte management definitions

Manual and mechanical control

Manual and mechanical control entail the physical harvesting of the weed, by hand or using machines. Physical removal is aided using cables (booms) to accumulate or control the location of mats. These methods are used in many instances, always at great expense.

Mechanical removal is carried out with a wide range of techniques, including cutting, dredging, and harvesting of macrophytes (Figure 3). The equipment used for removal of macrophytes varies and depends on tradition, type of macrophyte, and environment. Removal equipment includes excavators, boats mounted with large automatic knives, and scythes. In smaller streams and rivers, as well as in drainage ditches and canals in agricultural catchments, excavators are used for dredging with the aim of total removal of macrophytes. Removal of macrophytes by boat is preferred in deeper, non-wadable streams and in lakes, where macrophyte biomass can either be cut and left in the system or harvested. A combination of removal techniques and equipment is often used to fit local conditions and goals of management. Effective macrophyte removal would lead to a substantial reduction in plant biomass.

Figure 3. Mechanical management methods of aquatic macrophyte mass developments. Mechanical cutting by boat (left) and scraping with a harrow to remove plant roots (right). Both examples from removal of Juncus bulbosus in the Rysstad Basin, River Otra, Norway. *Photos: Benoît Demars.*

Chemical control

Herbicide use has contributed to the control of aquatic plants in a number of countries across the world. Active ingredients can include glyphosate, diquat, paraquat, 2,4-dichlorophenoxyacetic acid (2,4-D), and fluridone, used in conjunction with various surfactants and detergents. Applications may be aerial, boat, or land-based depending on the extent of the invasion and accessibility (Figure 4). Chemical control is the method of choice in the USA, but is banned in waterways of Europe.

Figure 4: Helicopter application of glyphosate-based herbicide to *Pontederia crassipes* (water hyacinth) on the Roodeplaat Dam, South Africa. *Photo: Lukas Otto*

Biological control

Biological control relies on feeding damage by suitably host-specific natural enemies (biocontrol agents), mainly plant-feeding insects and mites, and pathogens that are sourced from the invasive species' countries of origin to suppress the invasiveness of the targeted weeds. It is an ecologically sound method that aims to maintain weed populations at acceptable management levels. Floating aquatic weeds are particularly susceptible to biological control with a number of successful cases throughout the world (Figure 5).

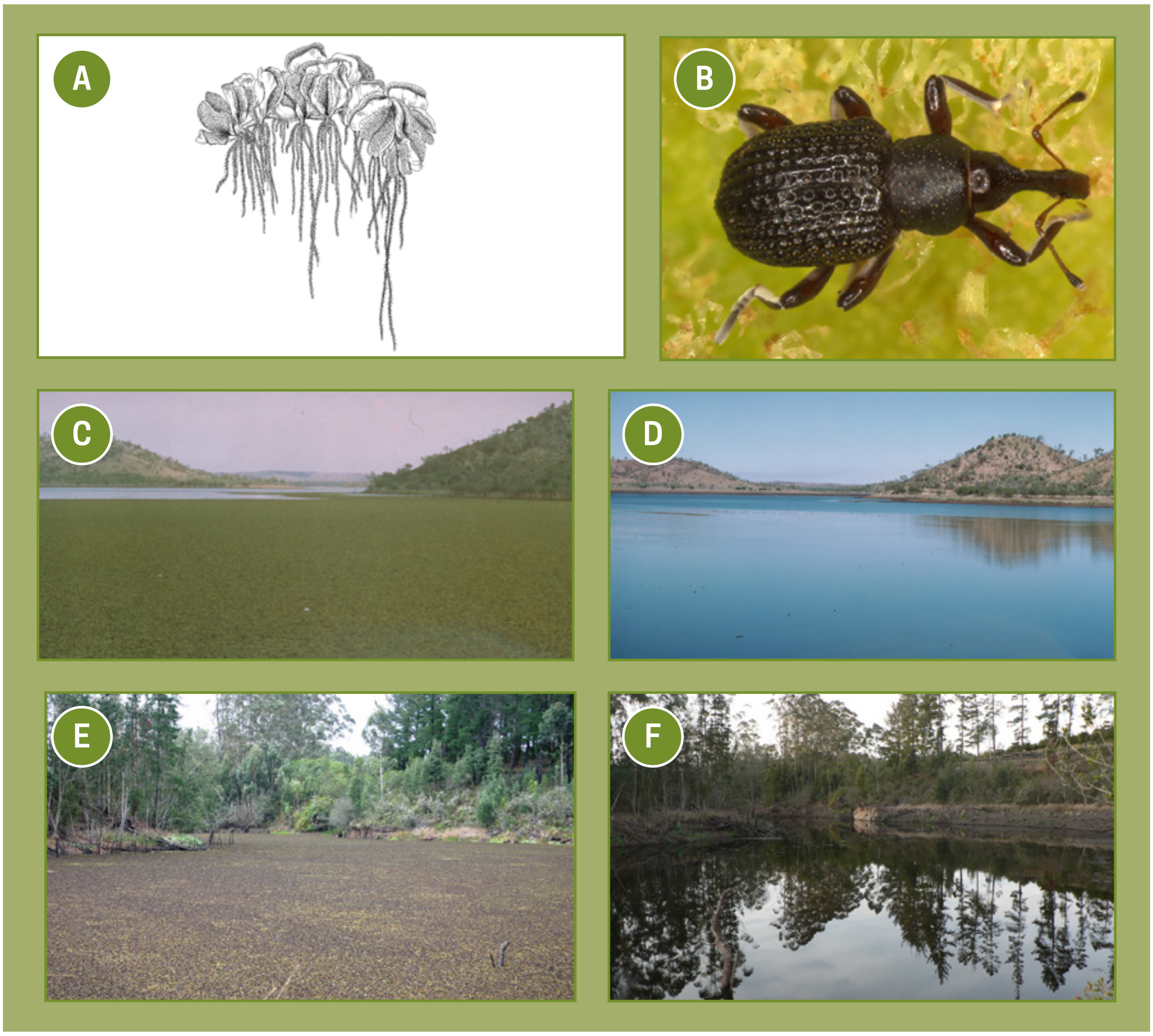


Figure 5. **A.** *Salvinia molesta* D.S. Mitchell (Salvinaceae). **B.** The biological control agent, *Cyrtobagous salviniae*.
C. Lake Moondarra, Mt Isa, Queensland, Australia in June 1980. Lake Moondarra had a 400 ha mat of salvinia, with a fresh weight > 50 000 t. *(Source: CSIRO, with permission)*. **D.** The first release of *C. salviniae* was made at Lake Moondarra. The damage caused by the huge population of weevils that developed following release resulted in spectacular destruction of the mat within 15 months, reducing it to less than 1 t. *(Source: CSIRO, with permission)*.
E. Farm Dam near Knysna, Western Cape Province, South Africa before introduction of *C. salvinae*, and **F.** 2 years later in 2009 following successful biological control.

Integrated control

The combination of various control methods for optimum aquatic plant removal is termed integrated control. Integrated control, particularly in the USA where biological control does not provide the rapid results required by water managers, could go a long way in reducing the need to broadcast spray herbicides across large invaded water bodies. Ultimately, aquatic plant management decisions are context driven; for example, a lake manager for a hydroelectric plant or a pond manager for duck hunting has more incentives and significant resources to control invasive aquatic plants.

Table 1. Overview of different aquatic macrophyte management methods, their benefits, disadvantages and potential applicability.

Management method	Benefits	Disadvantages	Plant life-form
Mechanical **(Cutting, dredging, harvesting)**	Easy to control effect size Rapid results Can remove plants from the system	Expensive (labour intensive) Short-term benefits May spread large amount of plant fragments Resuspension of sediment	Submerged, Emergent, Free-floating
Chemical **(Herbicides)**	Inexpensive, Large-scale application Rapid effect Limited drift	Can have unknown toxic effects on other organisms Short-term benefit Not targeting underground growth/ submerged growth Biomass stays in the system	Emergent, Free-floating
Biological **(Biological control agents, e.g. herbivorous fish and insects)**	Inexpensive Slow to rapid effect Species selective Long-term (decades)	Effect size difficult to control In many situations, not efficient in reducing areal coverage Need to be species specific – does not exist for many plant species yet Biomass stays in the system	Submerged, Emergent, Free-floating

B. MASS DEVELOPMENT MANAGEMENT GUIDELINES

1. Assess Mass Development State

What is the history of the water body and its alterations?

Identifying the historical use of and alteration to freshwaters, and further to the landscape around them to facilitate the water body, can inform understanding of the current and potential conditions and mass development scenarios.

What is the state of mass development?

Mass development can present variably depending on the growth form of present macrophytes (emergent vs submerged, rooted vs unrooted), density (higher densities can block light and navigation), community dynamics, and source.

What are the current and potential ecosystem services of the aquatic environment?

Water bodies and macrophytes therein provide different ecosystem services, including recreation, water supply, food provisioning, and hydropower. These may change or be variably desired over space and time, and internalizing stakeholders to inform assessment of the relative value of different management actions or inactions will improve outcomes. The Impact Evaluation approach encourages continual revisiting of aims and progress and adjustment to methods to better target aims.

What is the gap between optimal macrophyte management outcomes for ecosystem services and public perception?

Aesthetic or perceived macrophyte conditions don't always match ecological or public priorities; macrophyte stands can provide structure that improves ecosystem health, but limits recreational use. Improving stakeholder involvement, and thus understanding, can help unify aims.

2. Identify Partnerships/Stakeholders

Who are the relevant stakeholders and partners to seek out?

Stakeholders can variably constrain management options, and those most affected by environmental decision-making have often been those most historically excluded from management participation. At the broadest scale, regulatory and administrative requirements will limit management options, which will further be constrained financially. Traditional ecological knowledge (TEK) can offer broader solutions and ecological understanding through partnership with local and indigenous people in the context of a long historical relationship with, and guardianship of, the natural environment. Maximizing participation and contribution, while acknowledging economic and political realities, improve resultant buy-in and support. Involving the public in the form of education campaigns, community science data collection, and collaboration across sectors are investments in long-term social support.

It is important to identify relationships and conflict among stakeholders, and to assess which stakeholders will receive disproportionate burden or benefit of management decisions. The relative power, influence, and impact associated with each stakeholder should influence management, in that the loudest voice shouldn't necessarily have the greatest say.

3. Decide on Management

To control or not to control?

- **Is the species native or non-native to the waterbody?**

  Non-native species intrinsically differ from natives given they have no evolutionary history in the ecosystem, adding uncertainty to their impacts. For instance, non-natives can promote other invasions, including attached organisms, parasites, and disease vectors. If the mass-development is caused by a non-native, special attention should be taken. When the mass development is caused by a native species, the reasons for their new accelerated growth is likely related to a human-induced disturbance to the natural habitat.

- **What is the underlying cause of the mass development?**

  Mass-development occurs as a result of exponential species population growth. Reasons are varied, but are usually associated with human-related habitat changes. Identifying the changes is a key step for management decisions. For instance, damming a river may create suitable standing waters for macrophyte development; nutrient enrichment due to sewage disposal is an optimal fertilizer for macrophytes; and deteriorating margins of waterbodies can increase light input and promote macrophyte growth.

- **Can the underlying cause for the mass development be addressed?**

  The best control option is to address the causes. Dealing with point and non-point sources of nutrient pollution could result in a major decrease in macrophyte growth, requiring less control effort. Revegetating waterbody margins reduces light input, a requirement for submerged macrophyte growth. Maintaining the natural hydrology of the waterbody, for example, running waters instead of impoundments may have numerous benefits, but when lakes must be created (for hydropower or water supply), the shallower waterbodies are particularly prone to mass-developments.

- **Are there regulations for control?**

  Prior to management, legal authorization at different levels (municipal, state/province and/or national) must properly support actions. If necessary, proposals for legislations changes should consider scientific evidence and risk assessments.

- **Assess socio-economic impacts**

  Mass-development can jeopardize water uses such as hydropower generation, water supply, subsistence and commercial fishing, recreational uses (boating, sports fishing), etc. On the other hand, controlling mass-development can be too expensive, and may cause impacts such as promotion of algal blooms and decreased phytoremediation (improvement of water quality given the accumulation of pollutants in plants). Costs and benefits should be balanced (see box).

- **Assess ecological impacts**

  While macrophytes play an important role in aquatic ecosystems, their disproportionate growth resulting in mass developments has severe impacts on aquatic ecology. Water bodies with unique ecological features may be particularly sensitive to the simplification that mass-development represents. It is therefore crucial to evaluate if the mass-development has an effect on a particularly important species for conservation, or a particularly important ecological process, such as maintaining food webs. A thorough evaluation of the impacts should be done before control.

Benefits and disadvantages of controlling mass-development

Both are dependent on the history and use of the ecosystem, as well as on the identity of the species causing mass-development.

Possible benefits of control

- Restore the original uses of the water body
- Return desired ecological functioning
- Prevent undesired secondary invasions, including disease vectors
- Prevent the transition of deeper aquatic bodies to swamp
- Remove pollutants accumulated in the biomass of the plants

Possible disadvantages of control

- Costly and laborious
- Nutrient release and consequent promotion of undesired algal blooms
- Difficult to control effect on other aquatic organism groups
- Challenging disposal and/or re-use of the removed biomass
- Prevents the removal of undesired pollutants e.g. heavy metals, by the plants
- Change to the environment promoting undesirable consequences e.g. new invasions
- Loss of ecosystem services provided by macrophytes (if too much biomass is removed)

4. Decide on control method/s

What are the available management options?

Various control options are listed above, but it is important to take into account policies and integrated policies together with governance, norms, rules and agreements to facilitate the process of removal and disposal. The implementation of control options for a site will vary depending on the initial level of mass development, the acceptable level of control determined for that site, the role of the water resource and the financial resources available for control.

What is your management goal?

The level of control will depend on the water body, and its intended use. Once a mass development has established in a river, lake or dam, eradication is usually impossible, so an acceptable level of control has to be determined. This level will vary depending on the role of the water resource infested and the resources available to control the development. In South Africa the ‘rule of thumb’ has been that water hyacinth should be reduced from 100% and maintained at no more than 20% cover. This is a very important step in the management plan and one that invariably results in heated debate.

Assess consequences of removal method

e.g. algal blooms, the need for follow up control

Time frames and sustainability

Management of the mass development may be constrained by season, drought, or flood. Different control options offer different long-term results which must be considered when deciding on how to control the invasion. Macrophyte removal is usually not sustainable unless the underlying reasons for the mass development are addressed. Managers must acknowledge that removal will have to be done regularly, from several times a year to once every few years, if the underlying causes of the mass development remain.

Cost implications, including future costs

Costs are an important consideration when planning how to control a mass development. Small-scale, targeted interventions can be implemented in a relatively cost-effective way when the mass-development is limited in distribution, either within or between systems. As the scale of the project increases and the challenges to achieve control increases, the costs can also increase exponentially.

5. Monitoring

The completion of mass development management operations is often considered the final stage of a project, but in fact it is only the beginning of the next phase: Monitoring. The success of control measures should be monitored to learn by experience, to meet developing goals, and to assess sustainability of the achieved improvements. The monitoring program should meet the management goals and cover the main ecological and socio-economic impacts of aquatic plants. It should cover both short-term effects (within a few weeks) and long-term consequences of the management operations. The latter should ideally be performed until a new (or the old) steady state is reached. The results of this monitoring program should not only assure the success of the chosen measures but also contribute to better-informed management of similar cases. Monitoring data should be recorded and freely shared; they are very valuable for both research and future management decisions.

Even if the decision is taken to not control the mass development, the system should still be monitored to track the dynamics of the water body, and to evaluate consequences of the “do nothing” option.

6. Community engagement and public involvement in identifying potentially problematic mass developments, removal and monitoring

Accurate knowledge about the distribution of macrophyte invasions is essential to initiate management programmes. Community engagement and public involvement focusing on the involvement of volunteers as field assistants in scientific projects, can increase data collection on invasive species distributions through social media and online platforms. This becomes especially relevant in macrophyte mass-development projects, not only because it allows scientists to obtain spatial and temporal databases at low cost, but also because it contributes to increased environmental education and social awareness of the potential dangers of mass developments, and focuses managers on invasion hotspots for control.

Funding

The MadMacs project (Mass development of aquatic macrophytes - causes and consequences of macrophyte removal for ecosystem structure, function, and services) was funded by the Research Council of Norway (297202/E10), the German Federal Ministry of Education and Research (033WU005), the French Agence National de Recherche (N° ANR-18-IC4W-0004-06), the South African Water Research Commission (K5/2951), and the Fundação Araucária in Brazil (N° 186/2019) in the frame of the collaborative international consortium of the 2017 call of the Water Challenges for a Changing World Joint Programme Initiative (Water JPI).

Key references

MadMacs website:
https://www.niva.no/en/projectweb/madmacs

United Nations Sustainable Development Goals:
https://www.un.org/sustainabledevelopment/

NIVA
Norwegian Institute for Water Research

ECOBIO
Rennes

RHODES UNIVERSITY
Where leaders learn

NMBU
Norwegian University
of Life Sciences

IGB
Leibniz-Institut für
Gewässerökologie und Binnenfischerei

UFPR
UNIVERSIDADE FEDERAL DO PARANÁ

Water JPI