NATIONAL PARKS
NANYANG TECHNOLOGICAL UNIVERSITY
PUB Water for All: Conserve, Value, Enjoy

A SELECTION OF PLANTS
for Greening of Waterways and Waterbodies in the Tropics

CUGE
CENTRE FOR URBAN GREENERY AND ECOLOGY

NIE
NATIONAL INSTITUTE OF EDUCATION SINGAPORE

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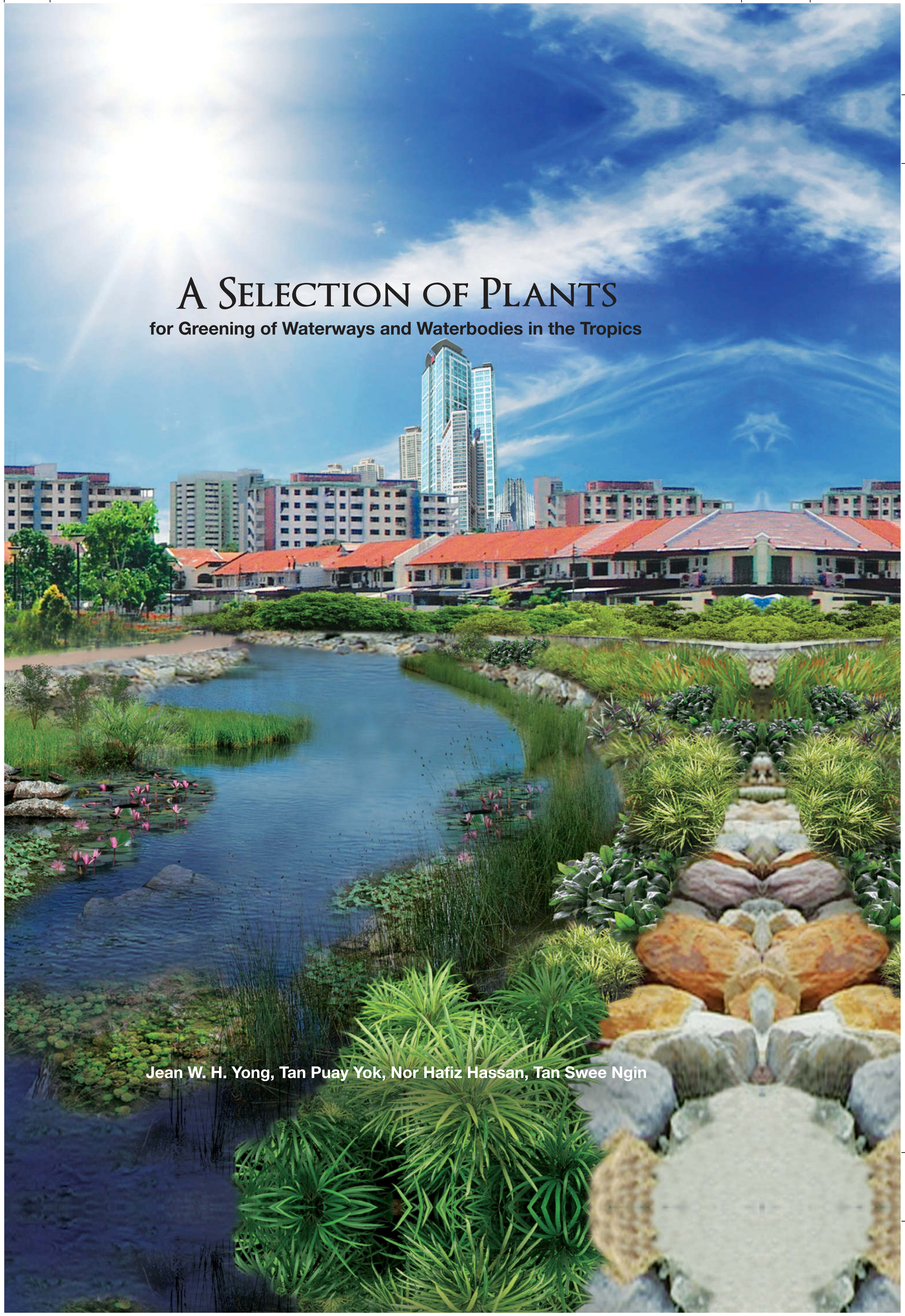

Jean W. H. Yong, Tan Puay Yok, Nor Hafiz Hassan, Tan Swee Ngin

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Editors
Jean W. H. Yong, Tan Puay Yok, Nor Hafiz Hassan, Tan Swee Ngin

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Front cover
An artist's impression of a conceptual planting design of a waterway in the tropics
Photo by Jean W. H. Yong; Designed by Ingrid Design Pte. Ltd.

Back cover
An artist's impression of Toa Payoh Town Park, Singapore
Photo by Elmich (Far East) Pte. Ltd.; Designed by Ingrid Design Pte. Ltd.

CUGE CENTRE FOR URBAN GREENERY AND ECOLOGY

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PUB Water for All: Conserve, Value, Enjoy

National Parks Board (NParks) is responsible for providing and enhancing the greenery of the Garden City of Singapore. Beyond managing public parks, the park connector network, lush roadside greenery, nature areas and nature reserves, NParks is committed to enhance the quality of life through creating memorable recreational experiences and lifestyles.

Centre for Urban Greenery and Ecology (CUGE) is an initiative of NParks. Through its research and training programs, NParks advances knowledge and expertise in urban greenery and ecology in the landscape and horticulture Industry in Singapore. It works closely with industry partners to promote good work practices and create a thriving, creative, innovative and professional industry that will support Singapore's aspirations to be a City in the Garden.

Nanyang Technological University (NTU) is a research-intensive university with globally acknowledged strengths in science and engineering. Ranked in the top 1% of the world's universities, NTU has four colleges with 12 schools, and three autonomous entities, the National Institute of Education, the S. Rajaratnam School of International Studies, and the Earth Observatory of Singapore. The university provides a high-quality global education to more than 23,000 undergraduates and 10,000 graduate students. Hailing from 67 countries, its 3,100-strong teaching and research staff bring dynamic international perspectives and years of solid industry experience.

National Institute of Education (NIE), Singapore, is an institute of the Nanyang Technological University (NTU). NIE provides all levels of teacher education, from initial teacher education programmes to professional development programmes for in-service teachers and executive leadership programmes for school leaders. NIE also administers postgraduate programmes and part-time programmes. NIE is also one of the leading teacher preparation institutions in the world. The institute is a founding member and inaugural chair of the International Alliance (IA) of Leading Education Institutes, which was established with several other world-leading education institutions.

Public Utilities Board (PUB) is a statutory board under the Ministry of the Environment and Water Resources. It is the national water agency, managing Singapore's water supply, water catchment and used water in an integrated way. PUB won the 2007 Stockholm Industry Water Award and was named Water Agency of the Year at the Global Water Awards 2006.

PUB's tagline: Water for All: Conserve, Value, Enjoy
PUB has ensured a diversified and sustainable supply of water for Singapore with the Four National Taps (local catchment water, imported water, NEWater, desalinated water).

To provide water for all, PUB calls on all Singaporeans to play our part to conserve water, keep our water catchments and waterways clean and build a relationship with water so we can enjoy our water resources. We can then have enough water for all uses – for industry, for living, for life.

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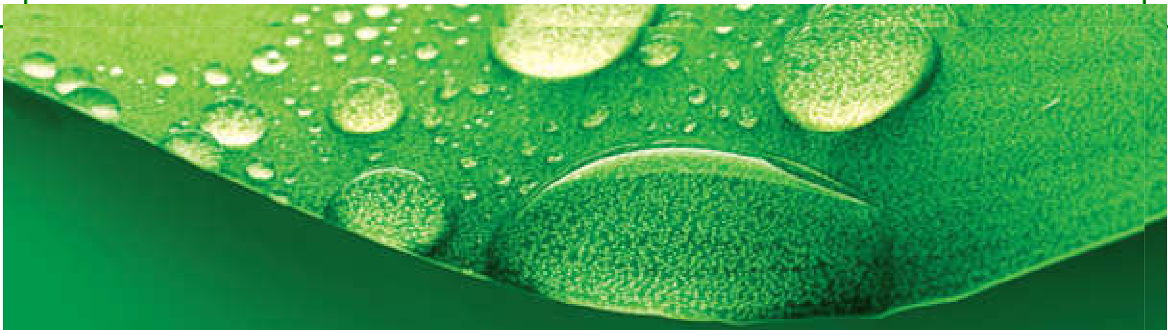
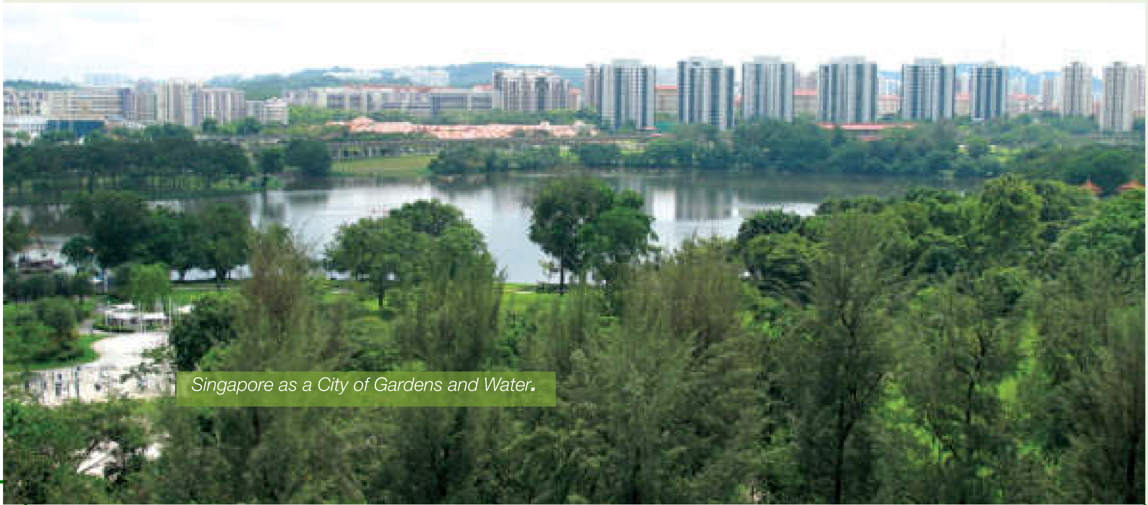


Preface

As Singapore moves towards its vision of becoming a “City of Gardens and Water”, one key element in this journey is the appropriate use of plants that are able to support various greening initiatives, such as the greening of the high-rise environment, naturalisation of canals and rivers, and creation of aquatic landscapes in ponds and lakes. As we embark on this ambitious journey to green up Singapore’s waterways and waterbodies, there is immense potential to tap on a large diversity of plants found in the tropics in various habitats. Despite this potential, very little has been written on this topic. This book was therefore written in response to the need to fill this information gap, and develop a suitable palette of plants for use by the relevant professionals in the industry. We have referred to such plants loosely as “water plants”.

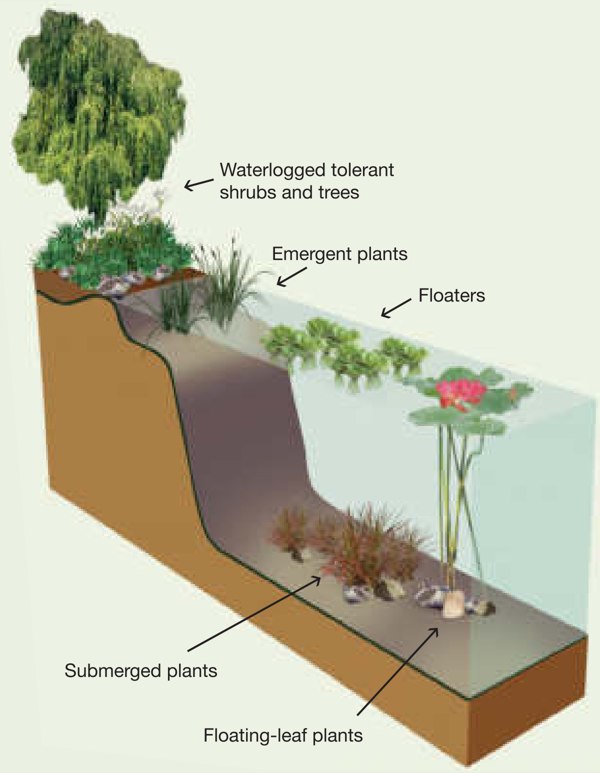
What are “water plants”? In many ways, water plants are just like any other kind of plants. They have roots, leaves, stems, and usually flowers. Like all plants, water plants require sunlight for photosynthesis, and absorb nutrients in order to grow. They also need air for respiration, and water to “drink”. What makes water plants different from their terrestrial counterparts is their ability to grow in a wet environment. Most terrestrial plants cannot tolerate having their roots submerged in wet soil or water. They are even less tolerant of having their leaves submerged. For most water plants, these conditions are beneficial, and perhaps even vital, to their survival. Their roots, stems, and leaves have adapted well in a wet environment, such that they require increased water levels in order to survive and grow. Water plants are most commonly classified by their zonal position in the natural habitat (e.g. submerged, floating, emergent), and this is how we have chosen to group the plants in this book. In addition, we have adopted a broader definition of water plants to include both the aquatic and waterlogged tolerant plants. With this broader definition, we have put together a broad diversity of plant species to include plants from mangrove and coastal forests.



Singapore as a City of Gardens and Water.

In addition, we recognise that plants have varying levels of capacity to absorb pollutants from the waterways and waterbodies. This book is thus, part of a larger effort to develop a "Periodic Table of Plants", that will serve as a reference to select plants that are best suited to absorb specific chemical elements or compounds from the environment. The plants in this book form the basis for the identification of potential candidates, which will be screened through scientific evaluation to identify the capacity of these plants to uptake specific pollutants. Where the pollutant uptake capacity for specific plants is already known, the relevant information has also been included in the description of the plants in this book. It is noteworthy that some of the floaters and submerged plants are known to be invasive under high nutrient conditions, and proper care should be taken to prevent these from proliferating in waterways and waterbodies

We have endeavored to present a reader-friendly book. The text is accompanied by photographs, common name(s), and how the plants can be used in typical landscaping applications, or used for water cleansing purposes. We hope that this will be a useful resource and photographic reference to introduce readers to a wide range of plants suitable for our waterways and waterbodies. However, we also recognise that the plants included in this book are by no means exhaustive. As we continually expand our knowledge in finding suitable plants for such applications in Singapore, we envisage a continual expansion of the plant list in subsequent editions of the book.



The natural zonation of aquatic and waterlogged tolerant plants.

The Water Lily is one of the most popular water plants for ponds and lakes.

ACKNOWLEDGEMENTS

This book is an important milestone in our ongoing efforts since 2003 to promote the wider use of plant-based remediation (or phytoremediation) techniques to improve water quality in our urbanised city-state. Many individuals and organisations have contributed to the work in this journey. We are very grateful to the following organisations for their funding, assistance and support in many ways: National Parks Board (NParks), Public Utilities Board (PUB), Nanyang Technological University (NTU SEP project grant RP21/06 YWH), and the National Institute of Education (research grants: RI13/06 YWH and RI11/03 TSN). Further research support from the Research School of Biology (Australian National University, Canberra), Nanyang Environment and Water Research Institute (NEWRI, NTU), and the Institute of Advanced Studies (IAS, NTU), is much appreciated. We are also grateful to the various organisations, individuals, publishers and journals for allowing us to reproduce their illustrations and photographs; acknowledgements are given beside the illustrations or photos in the book. In addition to the authors, many others have helped with comments, identifications and help across many fronts.

Last but not least, we are grateful to the staff and students (NParks and National Institute of Education, NTU) who have worked with us throughout our "phytoremediation-research" journey to build up a "Periodic Table of Plants": Ali Ibrahim, Chan Yi, Chen Siya, Chong Siew Chuen, Chua Hock Chye Lloyd, Fan Ying Hui, Heng Ming Yuan, Ho Qian Hui Audrey, Ho Kok Soon, Khoo Kai Ling Karen, Lao Yann Choo Cheryl, Lim Kai Hui, Low Kok Kiong Kevin, Ng Zi Qiang Arthur, Ong Zhongren Konrad, Peh Su Fang, Sai Tu Jian, Sanju Borana, Su Weizhi, Tan Hui Min, Tay Goon Guek, Teo Chin Chye, Toh Chong Kai, Yang Shufen and Yen Tsuan Hsiu Roger. We would like to express our sincere thanks to Angela Lim and Anna Yee who have provided the technical support for our students.

A team effort by staff and students in the periodic harvesting of aquatic plants and maintenance of a waterbody.

Damselflies are useful indicators of the biological health of freshwater bodies in our Garden City

CHAPTER
1

INTRODUCTION

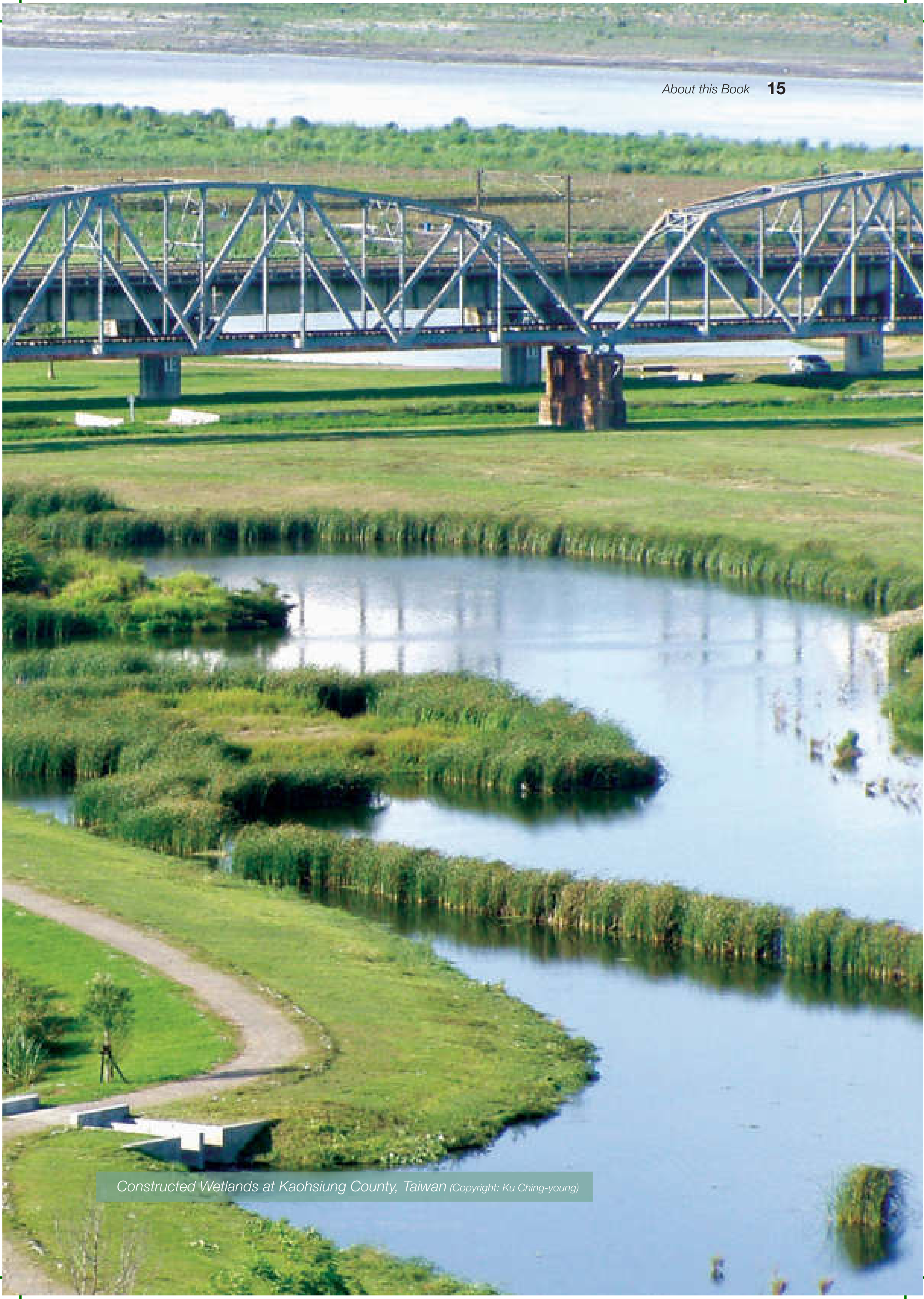
Chapter 1 | Introduction

About This Book

"A Selection of Plants for Greening of Waterways and Waterbodies in the Tropics" is a practical guide to using plants that are adapted to wet environments in urban settings. Wet environments include landscapes that are already commonplace, such as landscaped ponds and planted edges of stormwater sedimentation basins, as well as applications that are still new and being piloted in Singapore. The latter includes naturalisation of canals and river banks, constructed wetlands, cleansing biotopes, and floating vegetated islands in reservoirs or waterways.

A landscaped retention pond at MacRitchie Reservoir, Singapore.

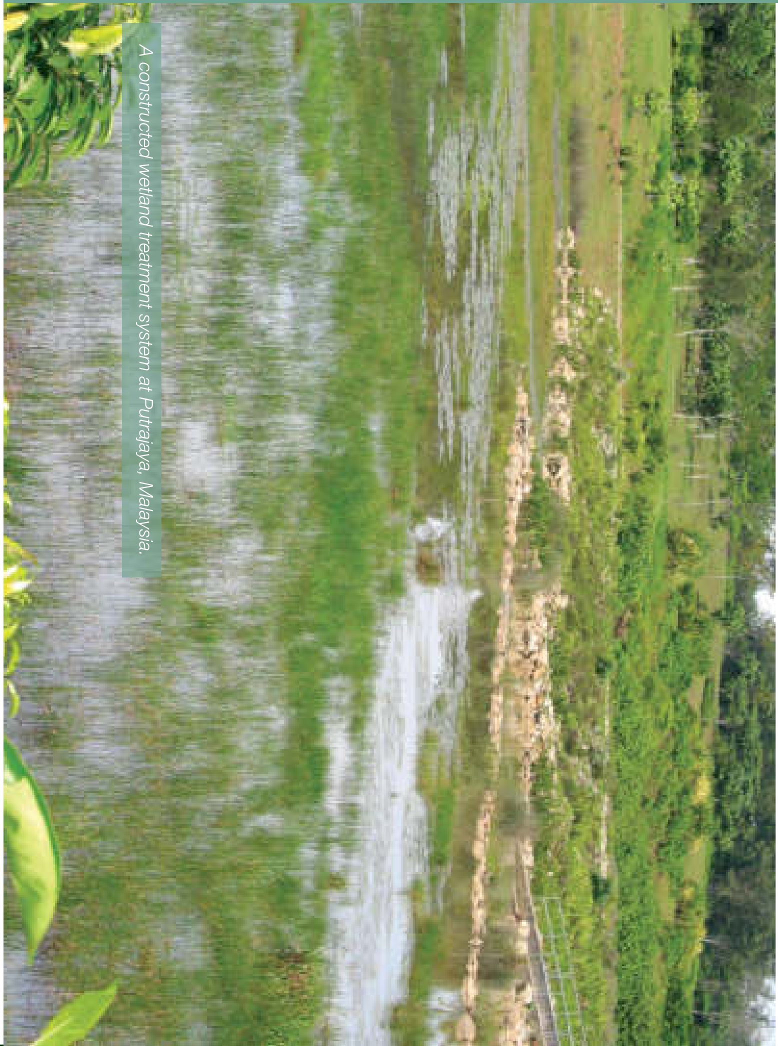
Toa Payoh Town Park is an example of an urban green oasis, filled with a variety of aquatic and waterlogged tolerant plants, in the heartlands of Singapore



Constructed Wetlands at Kaohsiung County, Taiwan (Copyright: Ku Ching-young)

The use of appropriate aquatic and waterlogged tolerant plants at Sengkang Riverside Park (Singapore) will help to create a wetland ecosystem within this urban neighbourhood park

A wetland park in Xian, China.



A constructed wetland treatment system at Putrajaya, Malaysia.

Plants help to soften the embankment surrounding Bedok Reservoir.

Aesthetically pleasing plants on the banks of a waterbody at Woodlands Town Garden.

A diversity of plants can be used to maintain good water quality and create aesthetically pleasing waterscapes

In the journey to transform Singapore into a 'City in a Garden', green habitats will be woven seamlessly into the urban fabric to ensure that Singapore is not only green, but is also ecologically rich despite its highly built-up nature. While the focus of our efforts has been on the roadside green verges, parks, precinct gardens, other green open spaces, and increasingly, the high-rise environment, the waterbodies and waterways of Singapore also present immense opportunities for green habitats to be introduced because of the extensive network of drains and canals that reaches to all parts of the island. Creating such green habitats that are integrated with our waterways will not only require innovative engineering solutions to be introduced so that the original functions of drains and canals are not compromised, but also emphasise on the use of plants that are ecologically appropriate to ensure the performance, long-term sustainability, and the aesthetic quality of habitats created. In fact, plants could be viewed as the most important foundation element of such habitats, and accordingly, should receive adequate attention in the conceptualisation and design process.

The plants selected in this book serve to fulfill such a need. The book aims to reach out to a diverse audience, including urban planners, hydrological engineers, architects, landscape designers, and horticulturists. The selection of plants is based on the accumulated knowledge of the various contributors, other publications, as well as observations of different plants in the urban and natural environment. A small group of plants that may not yet be available in large quantities in commercial nurseries has nevertheless been included primarily to highlight the horticulture potential of such plants and introduce them to the nursery trade.

Chapter 2 "Considerations on Plant Selection" introduces the key factors that explain the natural zonation of plants in an aquatic environment. Notwithstanding the fact that most plants exhibit a certain degree of resilience for tolerating deviations in environmental conditions from which they have evolved, it highlights the principle that selecting plants for landscape uses requires a good understanding of the conditions in which they have evolved and adapted to, so that subsequent maintenance can be minimised.

Chapter 3 "Types of Water Plants" describes the habitats, morphological and physiological features of the different groups of water plants. It is interesting to note that Mr Henry Nicholas Ridley, the first Director of the Singapore Botanic Gardens, was possibly the first person who noticed a very special group of plants featured in this chapter, called "rheophytes", more than 110 years ago!

Chapter 4 "A Selection of Water Plants for Waterways and Waterbodies" describes the 114 plants that have been included in this book according to the classification described in Chapter 3. Botanical, horticultural, and possible applications in waterbodies have been provided to increase the understanding of the functions of these plants. Where relevant, the ability of some plants to uptake specific pollutants from the environment, as well as their ethnobotanical uses, have been highlighted. The inclusion of such information helps to raise the awareness of the phytoremediation capacity of plants to rehabilitate polluted waters and soils, and encourage the development of applications that help to fulfill this potential.

Hydrocleys nymphoides *is one plant that can be considered for selection.*

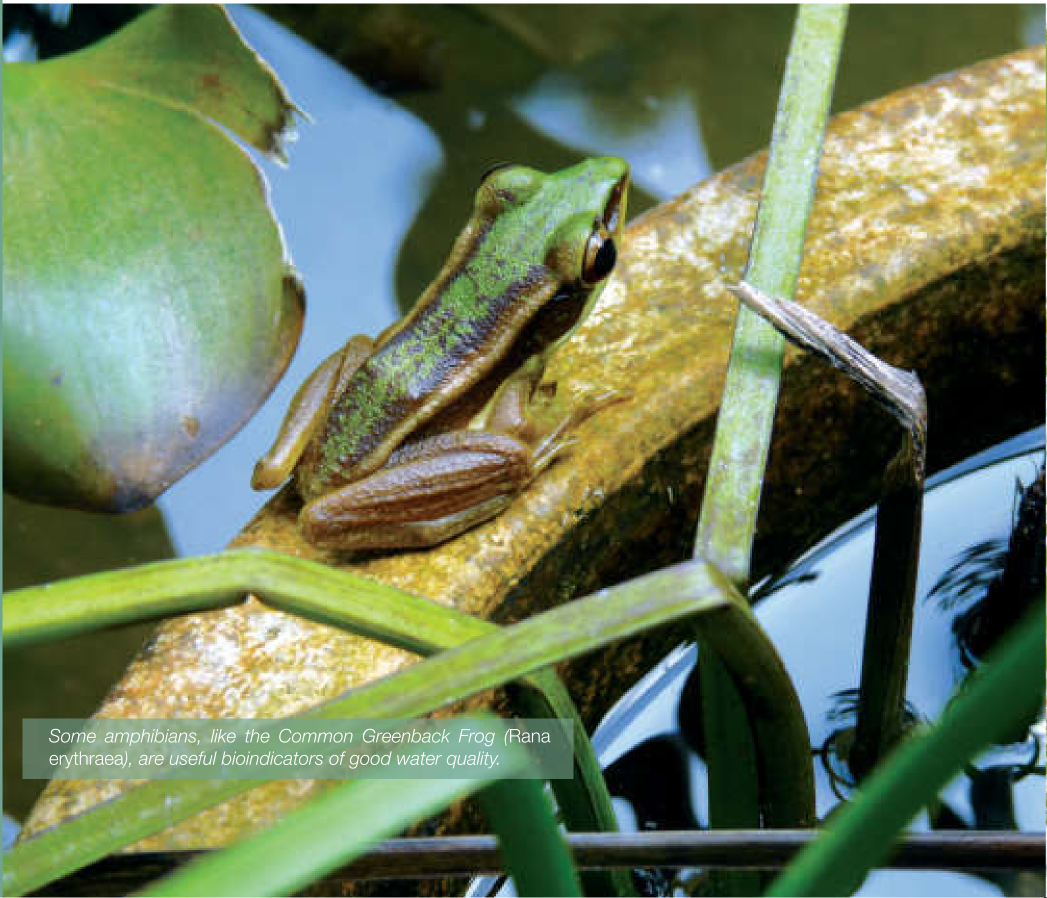
The Benefits of Greening Our Waterways and Waterbodies

The greening of waterbodies in the urban environment can bring about three key groups of benefits. The first relates to optimisation of space. Singapore's population will eventually grow to 6.5 million people in order to be economically viable. One important consideration for Singapore is to continue creating green space as the population grows. A logical approach is to integrate land uses that are currently segregated, so that the sum of the whole is greater than sum of its parts. The Public Utilities Board's Active, Beautiful and Clean (ABC) Waters programme will help to see the harsh concrete walls of water canals broken down and landscaped for better integration with the surrounding space, thus improving the aesthetic quality of the landscape and allowing better access for recreational uses. The first pilot project has been successfully implemented at Kolam Ayer along Kallang River, and more of such projects will be implemented islandwide.

The green banks along Kolam Ayer provide important habitats for the aquatic fauna within an urban setting. The landscaped banks are also designed to blend in with the recreational amenities provided for the residents of this neighbourhood.

A concrete canal in Singapore (top left) can be "greened-up" to emulate a naturalised stream (top right). A wide selection of plants from different zonations can be selected to naturalise our existing concrete canals and also to lower the nutrient loads of the water in our waterways and waterbodies (bottom, Copyright: Touche Designs).

The second benefit is the enhancement of biodiversity in urban settings. As water is the source of life, flora and fauna will gravitate naturally to sources of water in the landscape. Hence, the integration of green habitats with our water drainage infrastructure brings about immense potential to enhance the ecology of Singapore. This applies not just to flora and fauna along the banks of rivers and ponds, but also to aquatic life. For instance, one could look forward to recreating natural streams that previously existed in Singapore's undisturbed landscapes, including their complement of fishes, shrimps and other aquatic life, right in the midst of built-up areas. This is, in fact, a strategy to extend the habitats of important flora and fauna groups beyond their natural areas and into the urban environment.



*Some amphibians, like the Common Greenback Frog (*Rana erythraea*), are useful bioindicators of good water quality.*

Striated Herons

Yellow Bitterns

Lesser Whistling Ducks

A wide diversity of plants can be planted to green up the waterways. An example can be seen along the banks of Kallang River, Singapore

An example of a natural waterbody in Singapore: A freshwater swamp forest at Nee Soon. Only certain plants have adapted to growing in this waterlogged environment (top). The submerged plants in the water are Cryptocoryne griffithii *(bottom left) and* Blyxa *sp. (bottom right).*

The plants growing on the banks of the Nee Soon freshwater swamp forests include Magnolia candolii*, an endangered tree native to Singapore (top). Also found growing on the waterlogged soils of the Nee Soon freshwater swamp forest is the native aroid,* Crytosperma merkusii *(left).*

A natural river in a tropical rainforest in Malaysia *(Copyright: Lo Shiang Huei)*

The third benefit is that the use of plants can help to reduce the occurrence of eutrophication in our waterbodies. This is triggered by the accumulation of excessive amounts of nitrogen and phosphorus, leading to the proliferation of algae and other cellular organisms like protists. Eutrophication affects the water quality and other aquatic life by covering the surface of waterbodies and making them unsightly and unsuitable for recreational activities. In addition, such algal blooms may produce toxins that are released into the waters (Heisler *et al*., 2008). Scientific studies, including studies conducted locally, have shown that plants play an important role in the uptake of excess nitrogen and phosphorus from waterbodies.

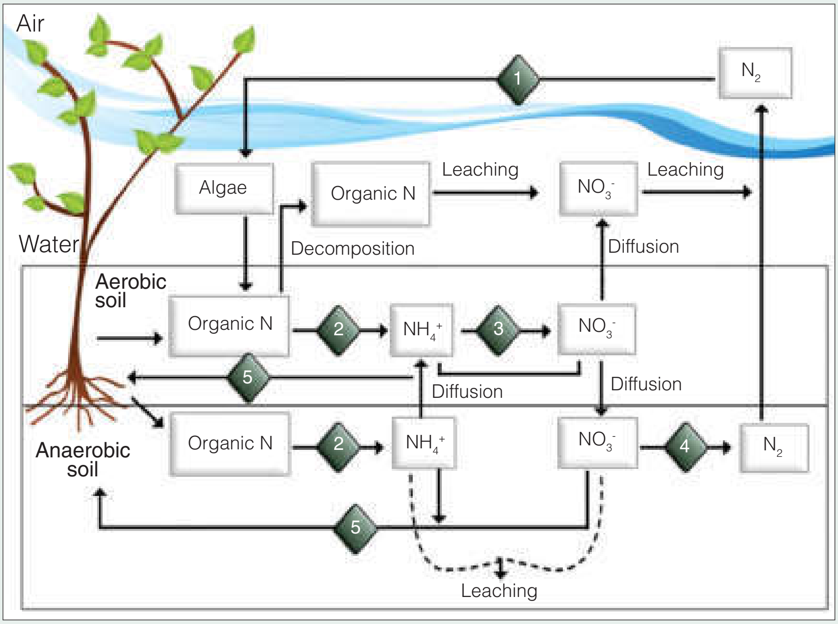
An example of a eutrophic (high nutrient) canal in Singapore. Algae and the other protists growing on the water surface of a canal (stagnant corner) with nutrient-rich waters (inset).

A eutrophic (high nutrient) waterbody in North Vietnam.

An oligotrophic (low nutrient) pond in Xian, China.

USING PLANTS TO REMOVE NITROGEN AND PHOSPHORUS

Nitrogen (N) can exist in various forms, namely ammoniacal nitrogen (NH_3 and NH_4^+), organic nitrogen and oxidised nitrogen (NO_2^- and NO_3^-). The removal of nitrogen from water is achieved through the processes of nitrification/denitrification, volatilisation of ammonia (NH_3), storage in detritus and sediment, and the uptake by plants for metabolism and storage in plant biomass (Brix, 1994). The mentioned processes are shown below.

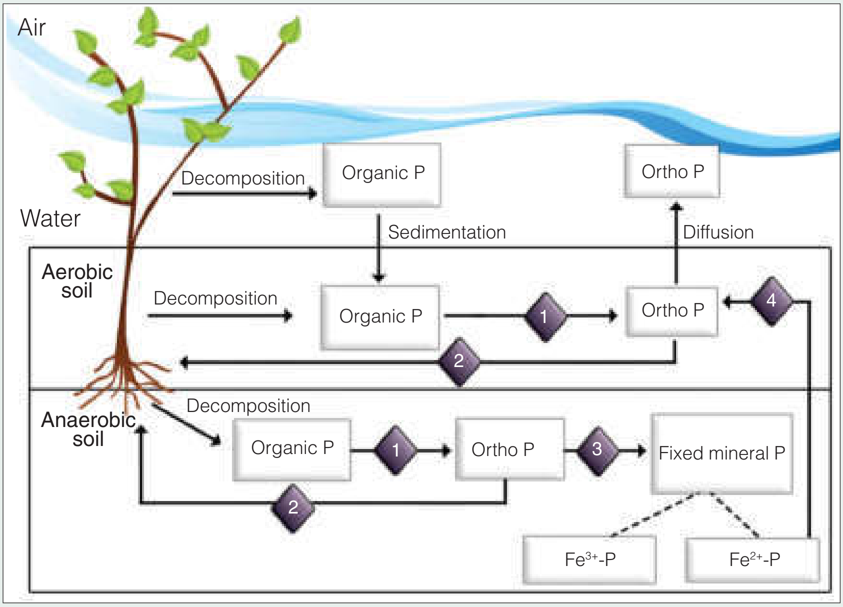


Nitrogen removal cycle and the different transformation processes involved: (1) N-Fixation; (2) Ammonification; (3) Nitrification; (4) Denitrification and (5) Immobilisation.

Although denitrification is the permanent removal of nitrogen from the system, the process is limited by numerous factors, such as temperature, pH, redox potential, carbon availability and nitrate availability (Poach *et al.*, 2003). Furthermore, the extent of nitrogen removal also depends on the design of the system, as well as the form and amount of nitrogen present in the water.

Based on the studies of Schnoor *et al*.,1995; Meagher, 2000; and Fraser *et al*. 2004, the majority of nitrogen removal essentially occurs through plant uptake.

Apart from nitrogen, phosphorus is also present in eutrophic waterbodies. Phosphorus normally occurs as orthophosphate, dehydrated orthophosphate (Polyphosphate) and organic phosphorus. The conversion of a majority of phosphorus to the orthophosphate forms ($H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}) is mediated by biological oxidation. Most of the phosphorus component may also be fixed within the soil matrix. Phosphate removal is achieved by physico-chemical processes, e.g. adsorption, complexation and precipitation reactions involving calcium (Ca), iron (Fe) and aluminium (Al). Similar to nitrogen, the removal of phosphorus can also be carried out by phytoremediation.



The phosphorus cycle through the various processes of (1) Mineralisation; (2) Immobilisation; (3) Fixation and (4) Reduction-Release.

An example of how plants can be used for this purpose is demonstrated in a trial conducted in Nanyang Technological University (see the following section).

Greening of a Sedimentation Pond at Nanyang Technological University

The main function of this pond is to retain the sediments present in the adjacent drains and to regulate water-flow especially during a heavy downpour. This pond was designed to capture 70% to 90% of the coarse to medium-sized sediments from the water draining into it. The addition of aesthetically-pleasing aquatic and waterlogged tolerant plants not only creates a more natural and pleasant living environment for the residents, but also improves the quality of drain water passing through the pond using the process of phytoremediation.

A sedimentation pond located at NTU Hall 6 in 2007, and before the addition of plants (top left). In 2009, some aquatic plants were added gradually to "green-up" the pond and its surrounding areas (top right). The additional greenery in the pond improves the water quality and also enhances the surrounding living environment for the residents (bottom).

Some of the selected plants are *Typha angustifolia*, *Thalia dealbata*, *Cyperus haspan* var. *vivipurus* and *Lepironia articulata*. The plants chosen were planted in rows to help filter out the finer sediments and also to absorb any pollutants that may be present in the water.

*Three types of plants were planted in the pond: Water Lily (*Nymphaea *sp.) (top), Water Banana (*Typhonodorum lindleyanum*) (bottom left) and Dwarf Papyrus (*Cyperus haspan *var.* vivipurus*) (bottom right).*

In addition, one would observe the return of insects such as pondskaters, damselflies, dragonflies, frogs, toads, waterfowls and Yellow Bitterns to the pond ever since the introduction of plants to the sedimentation pond.

Yellow Bittern is a common resident in freshwater habitats. Secretive in nature, it stays hidden inside emergents like Thalia *and* Typha *where it hunts aquatic prey.*

The diverse aquatic fauna found at the sedimentation pond: Dragonflies (top left); Pondskaters (top right); Damselflies (middle left); Toads (middle right) and White-Breasted Waterhens (bottom).

Here, nutrient-rich muddy waters entered the pond and were contained by a barrier of Lepironia articulata *(Blue Rush) (top left); The waters appeared less muddy after passing through the* Lepirona *barrier (top right) and into the area with* Salvinia molesta *(Giant Salvinia) (middle left); The population of the Giant Salvinia floaters increased rapidly over the next seven days (middle right); A second row of emergents plants function to support the nutrient absorption process (bottom left): Clearer waters at the end of the pond were observed from the second day onwards (bottom right).*

The aesthetically pleasing NTU Hall 6 pond

Plants selected for landscaping can also be used to remove pollutants from the water

CHAPTER
2

CONSIDERATIONS ON PLANT SELECTION

Chapter 2 | Considerations on Plant Selection

In selecting plants for use in urban landscapes, a logical strategy to adopt is to use plants that are naturally adapted to the conditions in the urban landscape. Such conditions, for instance, relate to soil moisture, light quality and quantity, wind exposure, air humidity, soil pH, etc. The process of selecting plants appropriate for the site calls for an understanding of the natural habitats of these plants. Plants have been evolutionary adapted to their natural habitat over thousands of years. Therefore, plants used for greening Singapore's waterways should ideally be able to survive in a natural habitat which is similar to Singapore's.This is arguably the most important step in a landscape design as the appropriate use of plants minimises subsequent intervention, maintenance, ensures the longevity and sustainability of the landscape, fulfils the design intent, and could also influence the ecological value of the landscape created.

The beautifully landscaped water feature at Victoria, Australia.

In the efforts to green up the waterbodies and waterways, the use of appropriate plants is therefore an important consideration in the design process. Much can be inferred by how plants are naturally distributed, and brief descriptions on the key factors affecting the distribution, or zonation of plants are highlighted. In addition, given that plants are recognised for their ability to remove pollutants from both the terrestrial and aquatic environment, the choices of plants can also be based on the known phytoremediation capabilities of plants. A partial listing of plants is also provided in the section to highlight the possibilities.

In addition to selecting plants naturally suited to the landscape conditions in which they will be growing, it is also useful to establish a diversity of plant types in waterbodies or waterways. Such diversity not only creates aesthetically interesting landscapes, attracts greater biodiversity to take root, but could also be important in maintaining good water quality in a waterbody. For instance, floating plants are known for their relatively high nitrogen and phosphorus uptake rates and could be used as the main plant group for nutrient uptake processes though periodic harvesting; woody emergents could be used to anchor the plant and fauna communities, and provide lower but steady levels of nutrient uptake. A diversity of plant types will also provide greater resilience to the landscape.

The proper selection of plant species will create a greener environment and provide a conducive aquatic water habitat for a variety of fauna, such as dragonflies and damselflies.

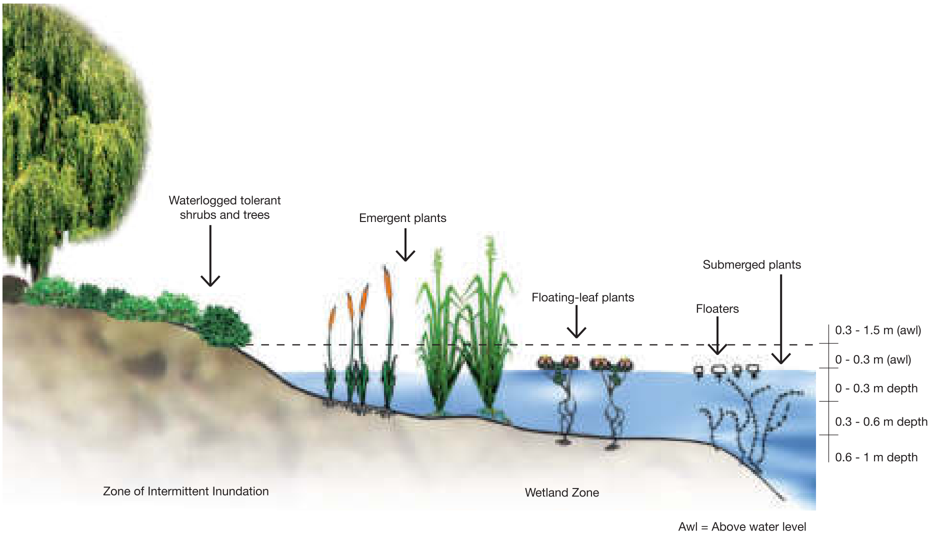
The green banks along Kolam Ayer will provide important habitats for the aquatic fauna within an urban setting

Emergents, such as Cyperus haspan *var.* vivipurus*, assist in the removal of nutrients and maintain the quality of water of the adjacent fish pond (Manado, Indonesia)*

The Natural Zonation of Plants

There is a natural gradient in soil wetness from from a terrestrial to an aquatic environment, that defines a zonation of plant habits and forms best adapted to the growing environment. In natural ecosystems, distinctive groups of plants are adapted to varying degrees of soil wetness.

For instance, in a wetland environment, the adaptation of different plants to different depths of water usually results in a clearly marked zonation or distribution of aquatic vegetation from the shoreline to the deep water. The shallow zone near the water edge is typically occupied by a zone of emergent plants. In the deeper zone, the emergent plants are replaced by rooted plants with floating leaves, which in turn is fringed by a zone of submerged plants often with free-floating species. The zonation of plants provides the basis for selecting plants for use in different parts of a landscaped waterbody.



A schematic view of the natural freshwater distribution/zonation of aquatic and waterlogged tolerant plants.

The deeper zone of the pond is often occupied by rooted plants with floating leaves as well as the submerged plants, such as Rotala *sp.*

A natural aquatic landscape with four types of plants from the different water zonations: a floater (Hygroryza aristata); *a floating-leaf plant* (Nymphaea *sp.*); *a submerged plant* (Hydrilla verticillata) *and an emergent* (Ruellia brittoniana) *along the bank*

FACTORS AFFECTING ZONATION OF PLANTS

The distinct zonation of aquatic and waterlogged tolerant plants can be explained by a set of factors that affect plant growth and development.

Temperature: Temperature affects normal plant growth and development because of its effects on enzyme-mediated chemical processes and intrinsic morpho-developmental events, e.g. flowering, stem elongation. Depending on their inherent adaptabilities, different water plants have their own optimal temperature ranges. Temperature is not a significant limiting factor for plant selection in the tropics, as there is no unusually low temperature episode like frost.

The minimum temperature is a significant factor in determining survival for certain water plants in the subtropical and temperate areas. For example, in north Vietnam, a recent cold spell caused the sudden death of many Lotus plants, while the Water Lilies (known to be more cold-tolerant) in the same lake survived! A close-up view of the dead Water Lotus (inset).

Light: Light affects plant growth through the direct effects on leaf photosynthesis. Different aquatic and waterlogged tolerant plants have adapted to varying light levels in the natural environment. It is useful to understand the light requirements of the specific plants before deciding on their use in any constructed wetland systems. Submerged plants only require low light levels: however, if turbidity in the waterbodies becomes too high, they may not survive. Emergents, floating leaf plants and mangroves require relatively higher light intensity, including full sunlight conditions for some species. Their leaves will turn turn chlorotic under low light conditions and the plants may eventually die if kept under prolonged shading.

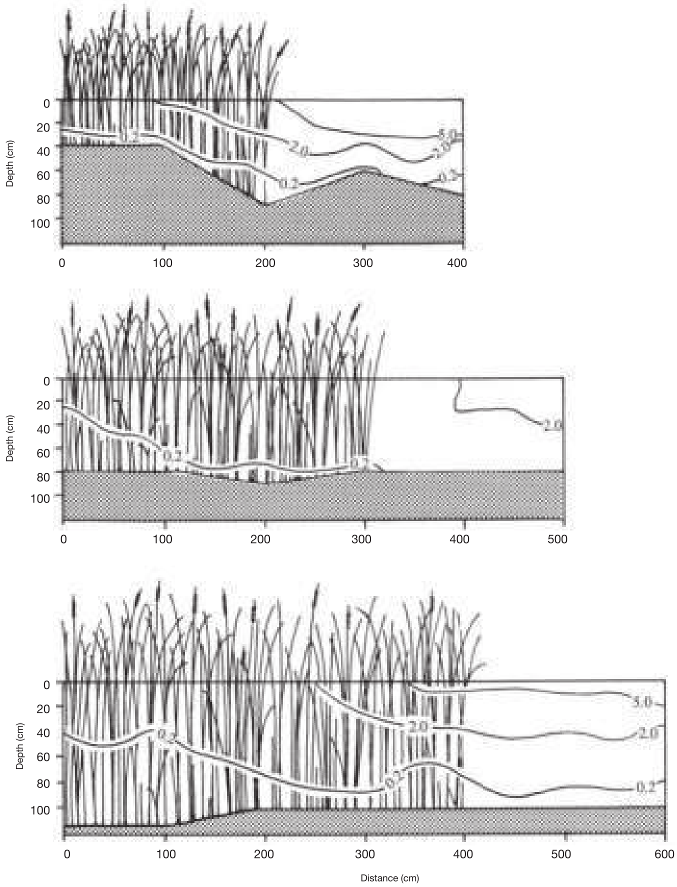
Cryptocoryne griffithii *in a stream at Nee Soon freshwater swamp forest, Singapore. A layer of fine forest debris covers the leaves of this submerged plant species, and thus leaf photosynthesis is limited by the availability of light.*

pH: Some plants are sensitive to water and soil pH fluctuations. Generally, the acceptable pH range for water plant growth ranges from acidic to slightly alkaline i.e. pH 5 to 7.5. However, there are some hardy species which can tolerate extreme pH ranges. For example, *Limnocharis flava* can grow in acidic environment of pH less than five and saltwater plants can tolerate high pH or alkaline environment. These plants make good candidates to be selected as the pioneering plant species for the initial stages of treating contaminated waterbodies where the pH is either very acidic or alkaline.

Limnocharis flava *can tolerate and grow in an acidic environment. Healthy growth is observed under optimal conditions.*

The growth of Limnocharis flava *is curtailed under sub-optimal conditions.*

Water depth: Water depth is also another point of consideration when selecting plants, for inclusion into urban waterbodies. The amount of oxygen available to the plants varies at different depth within a waterbody. For instance, at a 2 m depth, the oxygen content is lower than the oxygen content at the surface. Emergent plants such as Lotus and Phragmites are generally sensitive to water depth and do not grow well in water deeper than 1.2 m.



Plant zonation is affected by a variety of environmental factors, such as water depth and oxygen availability to the plants. The lines denote the approximate concentration of dissolved oxygen within the water matrix
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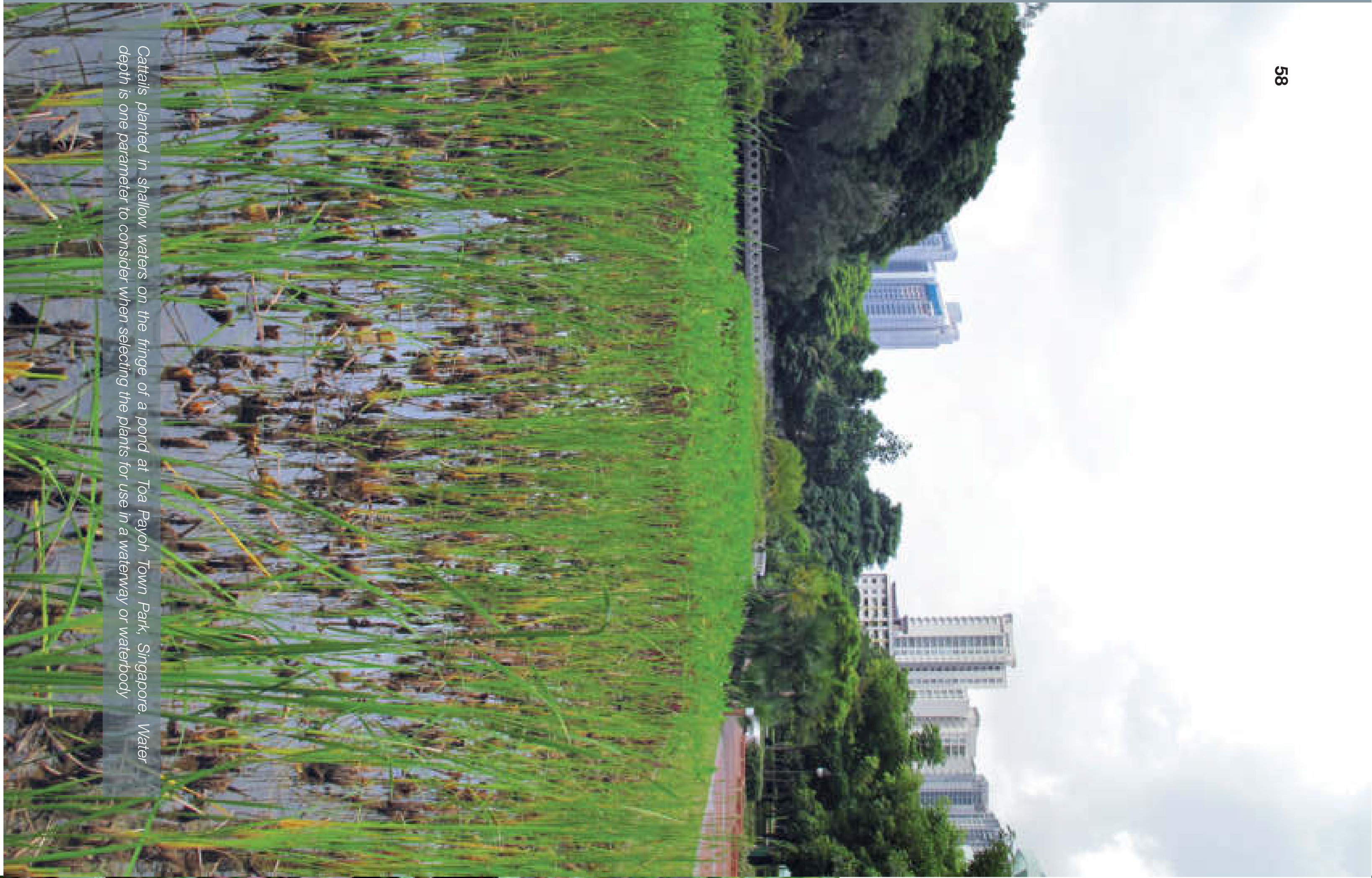


Cattails planted in shallow waters on the fringe of a pond at Toa Payoh Town Park, Singapore. Water depth is one parameter to consider when selecting the plants for use in a waterway or waterbody

Selecting Plants with Specific Phytoremediation Abilities

In addition to removing nutrients such as nitrate and phosphate from the waters, aquatic and waterlogged tolerant plants have also been shown to remove other pollutants such as heavy metals, metalloids, pesticides, hydrocarbon, organics and endocrine disruptors. The process of removing pollutants by plants is termed phytoremediation, and many plants have been used to treat contaminated soils.

Portulaca oleracea *was found to be able to phytoremediate bisphenol A from water (*Imai et al.*, 2007). Bisphenol A is a phenolic endocrine disruptor which affects the body's normal hormonal functions.*

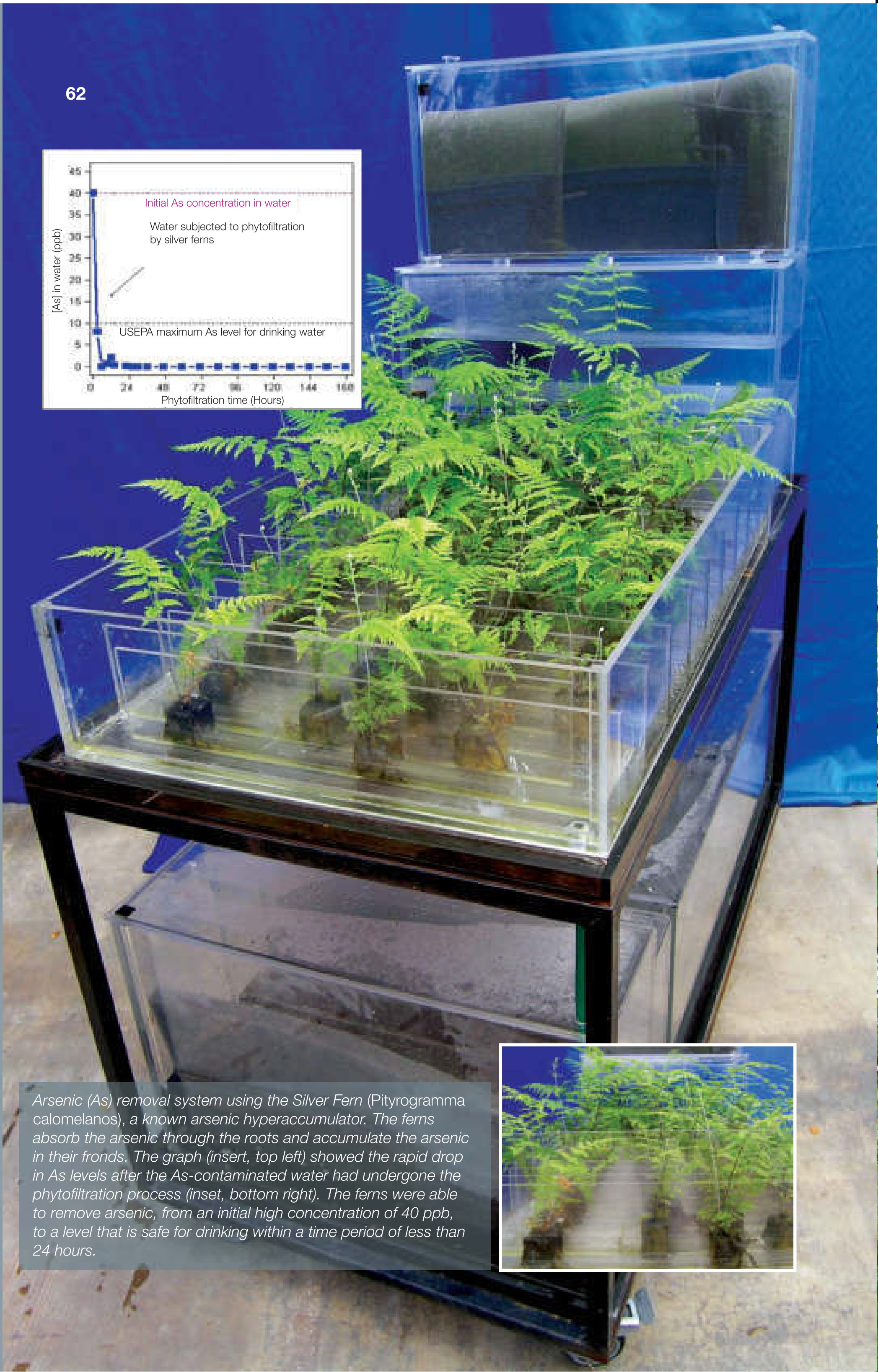
Interestingly, during the process of phytoremediation, these plants have the ability to accumulate such pollutants, but yet they do not suffer from phytotoxicity. Thus, they can serve as pioneering species to treat contaminated waterbodies in which most other plants cannot establish themselves. To qualify as a plant hyperaccumulator, the metals or metalloids concentrated by the plants in their tissues should be at least 1000 ppm, with both translocation factor (the ratio of contaminant concentration in leaves in relation to those present in roots/rhizoids) and bioaccumulation factor (the ratio of the contaminant concentration in above ground biomass in relation to that of the soil) exceeding 1 (Abhilash *et al.*, 2009; Liu *et al*., 2007). However, special care and effort must be taken to dispose of the plants containing high levels of pollutants/contaminants, as improper management will cause the pollutants/contaminants to leach back to the environment. A list of common plants with the ability to accumulate different types of heavy metals and metalloids is shown in Table 4.1.

Table 4.1 Some common aquatic and waterlogged tolerant plants with specific phytoremediation potential for heavy metals and metalloids.

Plant name		Heavy metal/ Metalloids
Scientific name	**Common name**	
Salvinia molesta	Giant Salvinia	Cr, Ni, Pb, Zn
Eichhornia crassipes	Water Hyacinth	Cd, Cr, Cu, Hg, Pb, Zn
Hydrilla verticillata	Hydrilla	Cd, Cr, Cu, Pb
Ipomoea aquatica	Kangkong	Cd, Hg, Pb
Lemna minor	Lesser Duckweed	Cd, Hg, Pb
Melastoma malabathricum	Sendudok	Al
Typha angustifolia	Cattail	Cd, Cu, Pb
Pistia stratiotes	Water Lettuce	Cr, Cu, Hg, Pb
Chrysopogon zizanioides	Vertiver Grass	Pb, Zn
Pityrogramma calomelanos	Silver Fern	As, Cu, Hg, Pb
Cyperus alternifolius	Umbrella Plant	Cd, Cu, Pb, Zn

Cr: Chromium; **Ni:** Nickel; **Pb:** Lead; **Zn:** Zinc; **Cd:** Cadmium; **Cu:** Copper;
Hg: Mercury; **Al:** Aluminium; **As:** Arsenic.

An example of a pond with a high concentration of iron oxide, which can affect plants and aquatic life (top). Numerous studies were conducted using plant hyperaccumulators of arsenic, e.g. Brake Ferns (Pteris vittata) *and Silver Ferns* (Pityrogramma calomelanos)*, using a system that was designed for rapid arsenic removal from water (bottom left). Boron uptake kinetics by* Xylocarpus *was analysed using a simulated tidal tank system (bottom right).*



Arsenic (As) removal system using the Silver Fern (Pityrogramma calomelanos)*, a known arsenic hyperaccumulator. The ferns absorb the arsenic through the roots and accumulate the arsenic in their fronds. The graph (insert, top left) showed the rapid drop in As levels after the As-contaminated water had undergone the phytofiltration process (inset, bottom right). The ferns were able to remove arsenic, from an initial high concentration of 40 ppb, to a level that is safe for drinking within a time period of less than 24 hours.*

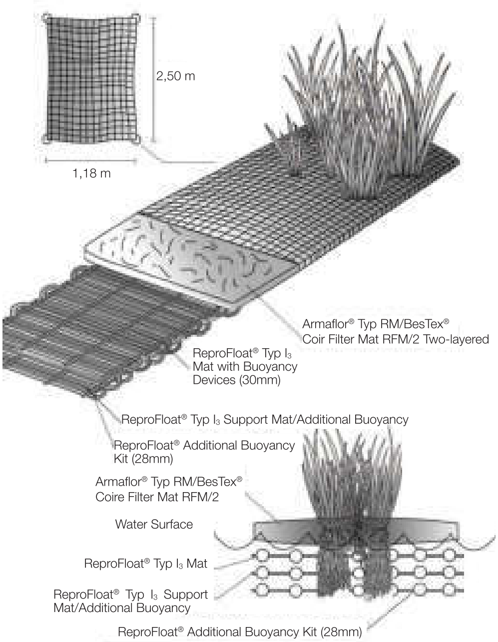
Helping Terrestrial Plants to "Float"

It is postulated that all plants have varying capacities to remove different classes of pollutants/contaminants. Woody plants, in particular, have high potential to be deployed as pollutant removers because their larger biomass can physically contain more of the removed pollutants (Pulford & Watson, 2003), and achieve higher rates of sequestration, compared to the herbaceous water plants (Tan and Yeo, 2009).

Certain species of fig are waterlogged tolerant and can be used for carrying out phytoremediation related functions in waterbodies (Hanoi, Vietnam).

The use of floating mats from BioHaven® with a variety of wetlands and terrestrial plants, both woody and non-woody, can help to remove pollutants from the water

To broaden the choices of plant species available for targeted/selective phytoremediation (e.g. Brake Fern for arsenic) in our canals and waterbodies, assistance must be given to these land-dwelling plants to operate in an aquatic environment. This can be achieved through the use of interlocking floating mats. Examples are shown below.



The application of BioHaven® floating islands at Lower Seletar Reservoir, Singapore (top left). Different types of plants, grown on the floating mats, were also evaluated in a pond (top right). An illustration of a floating mat, ReproFloat® I2/I3 Floating Blanket from Bestmann Green System™ with planted vegetation (bottom, Copyright: Bestmann Green Systems – BGS Ingenieurbiologie und -ökologie GmbH, Germany (manufacturer) and Enviro Pro Green Innovations (S) Pte Ltd, Singapore (supplier)).

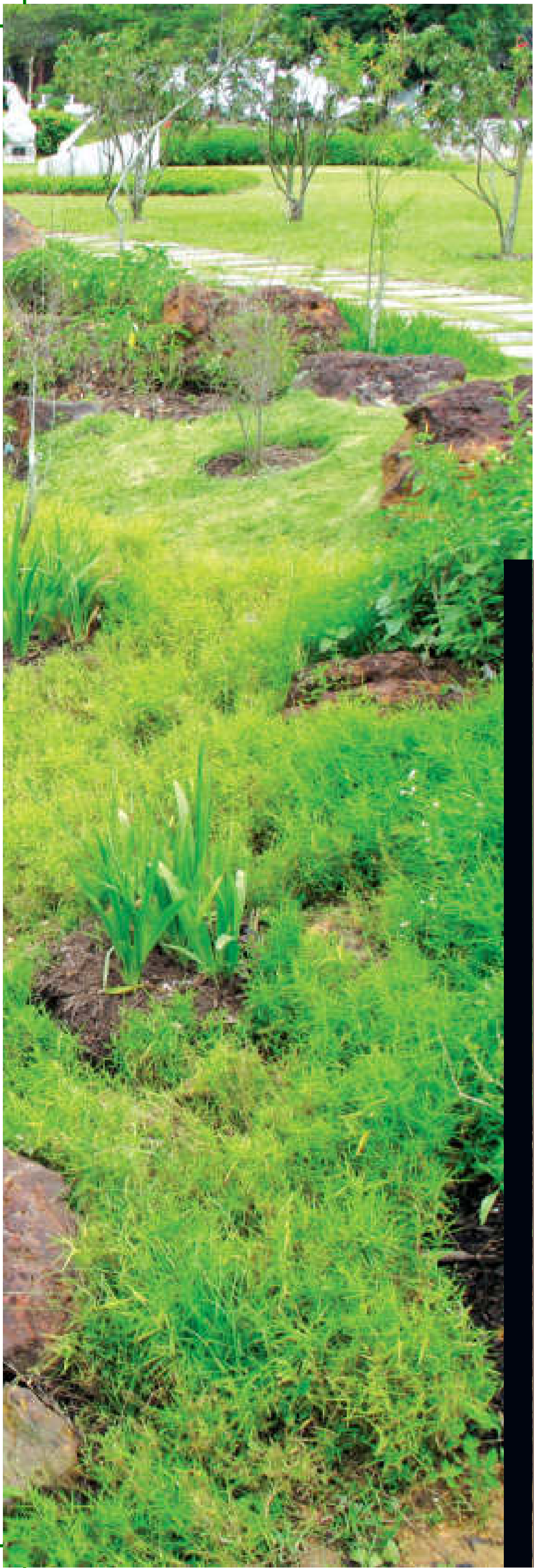
Floating mats can be utilised to harness the potential of waterlogged tolerant terrestrial plants such as Conocarpus erectus *for phytoremediation purposes*

Lessons from Tonle Sap Lake, Cambodia

At Tonle Sap, *one of the largest inland freshwater lakes in Southeast Asia, one can see many floating islands (top) made up of aquatic vegetation (bottom).*

The people living in this lake area tie the aquatic vegetation together and each household tends to its respective family floating vegetation "mats".

For the local people, these floating vegetation "mats" help to increase the availability of prawns and small fishes which are later harvested for food. This is a good example of using aquatic plants to increase the aquatic biodiversity of a waterbody.



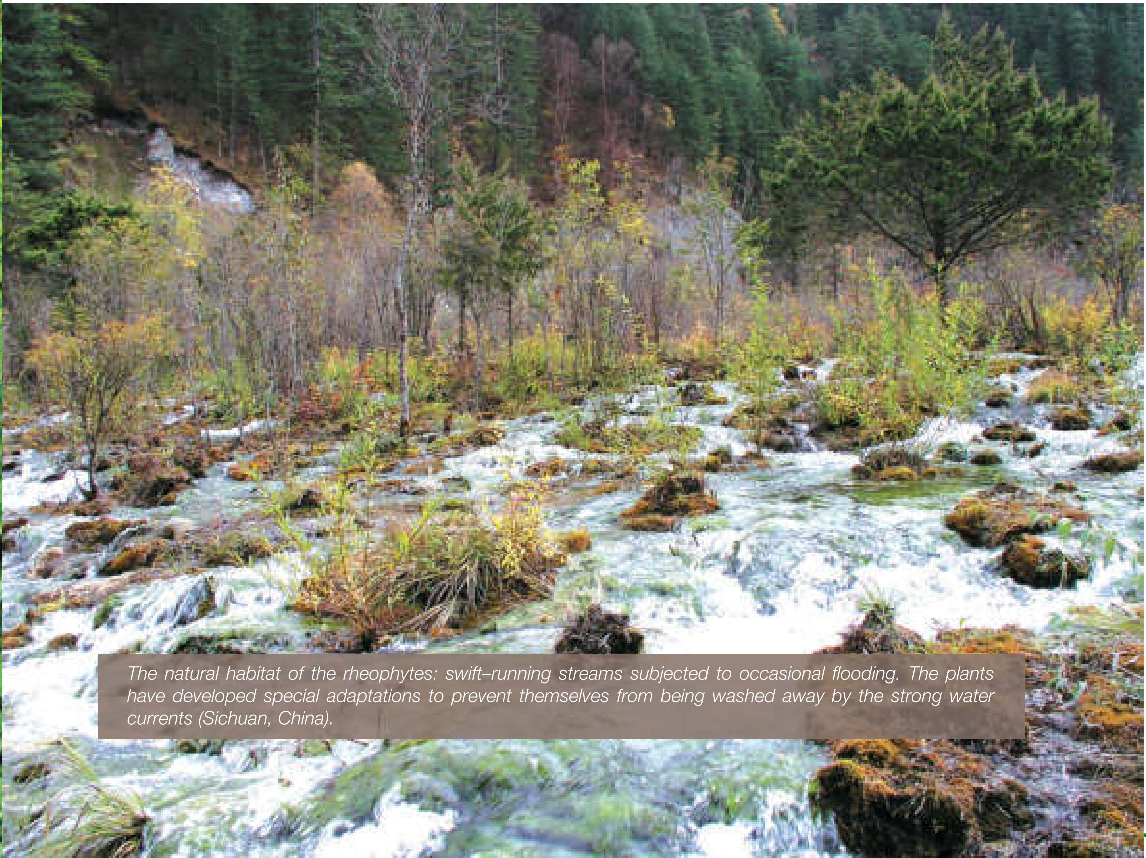
CHAPTER
3

TYPES OF WATER PLANTS

Rheophytes

Osmoxylon lineare *is a beautiful rheophytic plant that is very versatile and can be used to green-up terrestrial landscapes as well as canals and waterbodies*

It was Ridley (1893) who first drew attention to rheophytes as a biological group. Rheophytes are waterlogged tolerant plants with narrow and willow-like leaves called stenophylls, and root systems that are well adapted for secured anchorage in fast-flowing waters. These plants have developed adaptations that allow them to survive in areas of fast flowing waters that are subjected to periodic flash-floodings, which may last from a few hours to several days. The usual velocity of swift-flowing streams is about 1-2 m s^{-1} but during occasional flash floods, it may increase up to 4-5 m s^{-1}. To survive in such a harsh environment, rheophytic plants need to withstand the physical force of swift-running waters, and physiological disturbances arising from the flooded conditions. Rheophytes are therefore good examples of flood-resistant plants that can be used in the canals of Singapore that are subjected to sudden flash floods after heavy downpours.



The natural habitat of the rheophytes: swift–running streams subjected to occasional flooding. The plants have developed special adaptations to prevent themselves from being washed away by the strong water currents (Sichuan, China).

Using characters based on vegetative morphology, rheophytes can generally be divided into three main groups:

1. **Hydrophytic rheophytes**: They are flaccid, permanently submerged aquatic plants with usually floating radical, entire, strap-shaped leaves. The root system is tuberous and fibrous.

2. **Torrenticolous rheophytes**: The vegetative parts are permanently submerged in turbulent waters. They produce fertile, emerged aerial parts semi-annually while the other vegetative parts decay. The leaves or frond-like foliar appendages are often ovoid.

A member of the Podostemaceae growing in the middle of a stream in Suriname, South America (Copyright: Eric Thomassen).

Examples of families represented include:

a. Podostemaceae: The stem and its branches are thalloid in shape and the roots are firmly attached to rocks. They often have floating and divided, leafy segments.

b. Hydrostachyaceae: Leaves are strongly ovoid on a tuberous rhizome which can emit stolons occasionally.

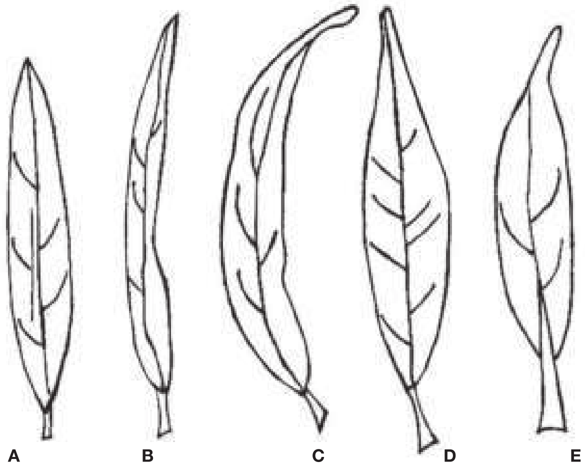
3. **Rheophytic landplants:** They are wholly or partly submerged only when the rivers are in a spate. The leaves are simple, and rarely pinnate.

   a. Mat-rooted rheophytes: Root-system is superficial, forming a netting or mat on rocks and boulders. They are mostly herbaceous.

   b. Non-mat-rooted rheophytes: The root-system will penetrate the gravel, sandbeds or rock fissures. They are woody at the base.

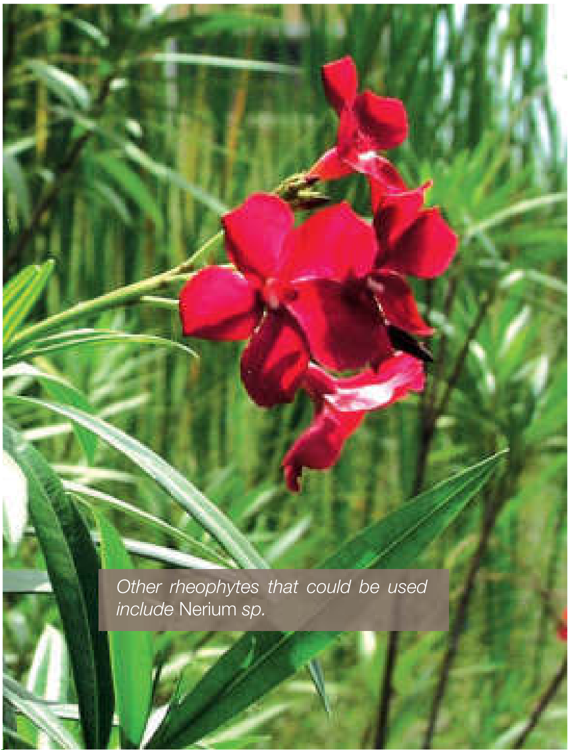
The rheophytic palm, Pinanga tenella, *growing alongside a bank at Temburong River, Brunei. The leaf structure of these palms minimises the damage caused by the fast-flowing water during floods (Copyright: John Dransfield).*

Rheophytes generally have simple leaves although there are some exceptions which have compound leaves. The leaf shapes generally range from oblong-lanceolate to narrow-lanceolate, to almost linear. The narrow leaf-shape is hydrodynamically adapted to withstand rushing water during flash floods as it offers less resistance, thus minimising physical damage to the foliage of these plants growing in this habitat. These combined features enable them to withstand the fast flowing waters and not to be washed away by the waters. Hence in Singapore's context, rheophytes may be grown along a naturalising bank in a zone which is flooded during heavy downpours.



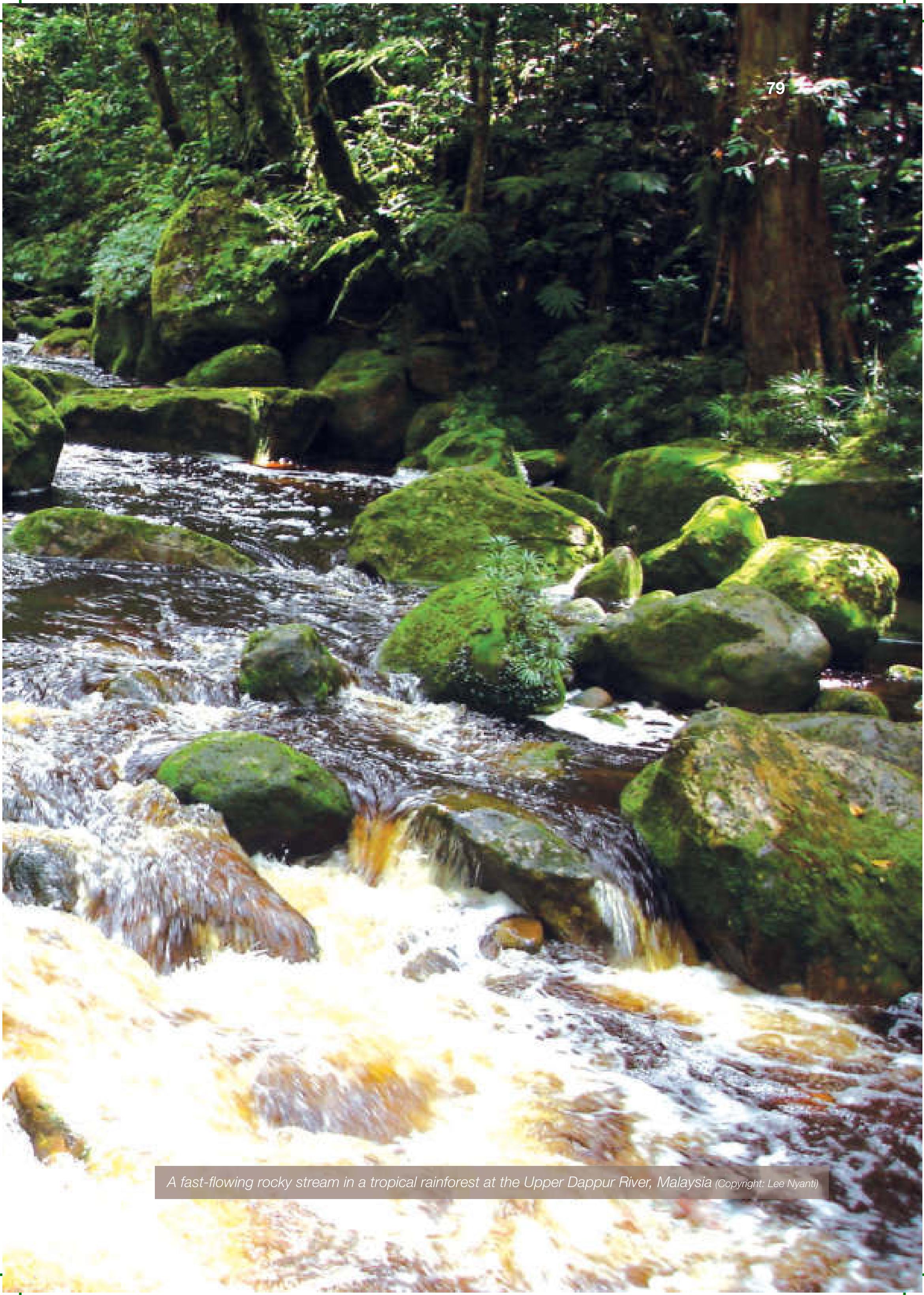
The narrow willow-like leaves (stenophylls) of a series of unrelated rheophytes showing convergent evolution of the rheophytic habit. A. Neonauclea angustifolia *(Rubiaceae); B.* Fagraea stenophylla *(Loganiaceae); C.* Garcinia linearis *(Guttiferae); D.* Syzigium neriifolium *(Myrtaceae); E:* Sauraunia angustifolia *(Actinidiaceae).*

Not many plants can survive the fast-flowing waters in a canal after a heavy downpour. Rheophytes, like Dipteris lobbiana, *which grow alongside a riverbank in Sarawak are a possible group of plants to choose for planting in our urban canals .*



Other rheophytes that could be used include Nerium *sp.*

Other rheophytes that could be used include Aglaia yzermannii *(Copyright: Ivan Polunin).*



A fast-flowing rocky stream in a tropical rainforest at the Upper Dappur River, Malaysia (Copyright: Lee Nyanti)

Rheophytes are most common in the region of Malesia, where they reach their greatest abundance in northern Borneo. Generally, rheophytes have been observed in a limited number of families and genera. In pteridophytes, there are 12 genera with 25 species, while three genera (with three species) are associated with the conifers. For the angiosperms, there are 217 genera with 618 species, thus making a grand total of 232 genera with 646 species. The plant families with the largest numbers of rheophytes are listed below.

Table 5.1. List of plant families with the largest number of rheophytes.

Family	Number of Rheophytic species	Total species**
Podostemaceae	270	270
Rubiaceae	43	2531
Myrtaceae	42	1260
Euphorbiaceae	36	2027
Hydrostachyaceae	25	25
Araceae	24	216
Moraceae (*Ficus*)*	15	800
Asclepiadaceae	14	171
Acanthaceae	12	850
Aponogetonaceae (*Aponogeton*)*	9	39
Lauraceae	9	1240
Melastomataceae	9	574
Rosaceae	8	235

**For these two families, rheophytes are restricted to the genus indicated in the bracket.*
*** The number indicates the total number of species in the family, according to the data given in Airy Shaw's 'Willis Dictionary' (1973).*

In the Southeast Asian region, there is a good diversity of rheophytic plants that potentially can be grown in our drains and canals. For example, on the banks of Sungei Tahan in Taman Negara (Malaysia), the following plants can be found: *Aglaia yzermannii, Antidesma salicinum, Calophyllum rupicolum, Dysoxylum angustifolium, Ficus pyriformis, Gomphandra quadrifida* var. *angustifolia* and *Homonoia riparia*. In Borneo, two stenophyllous palms, *Pinanga tenella* and *Pinanga rivularis* are present in Sarawak, and these two palms can be planted in Singapore.

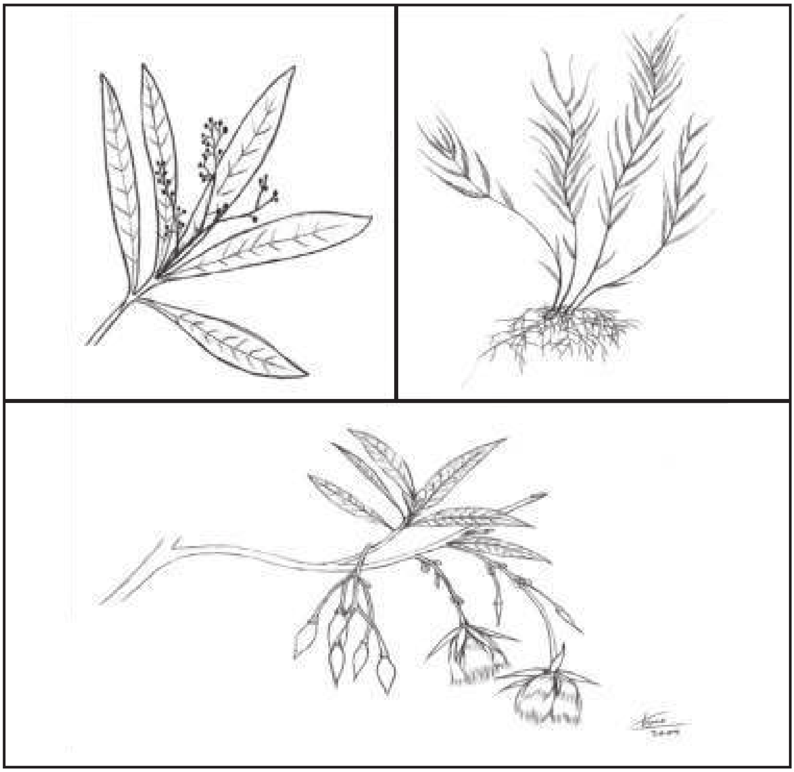
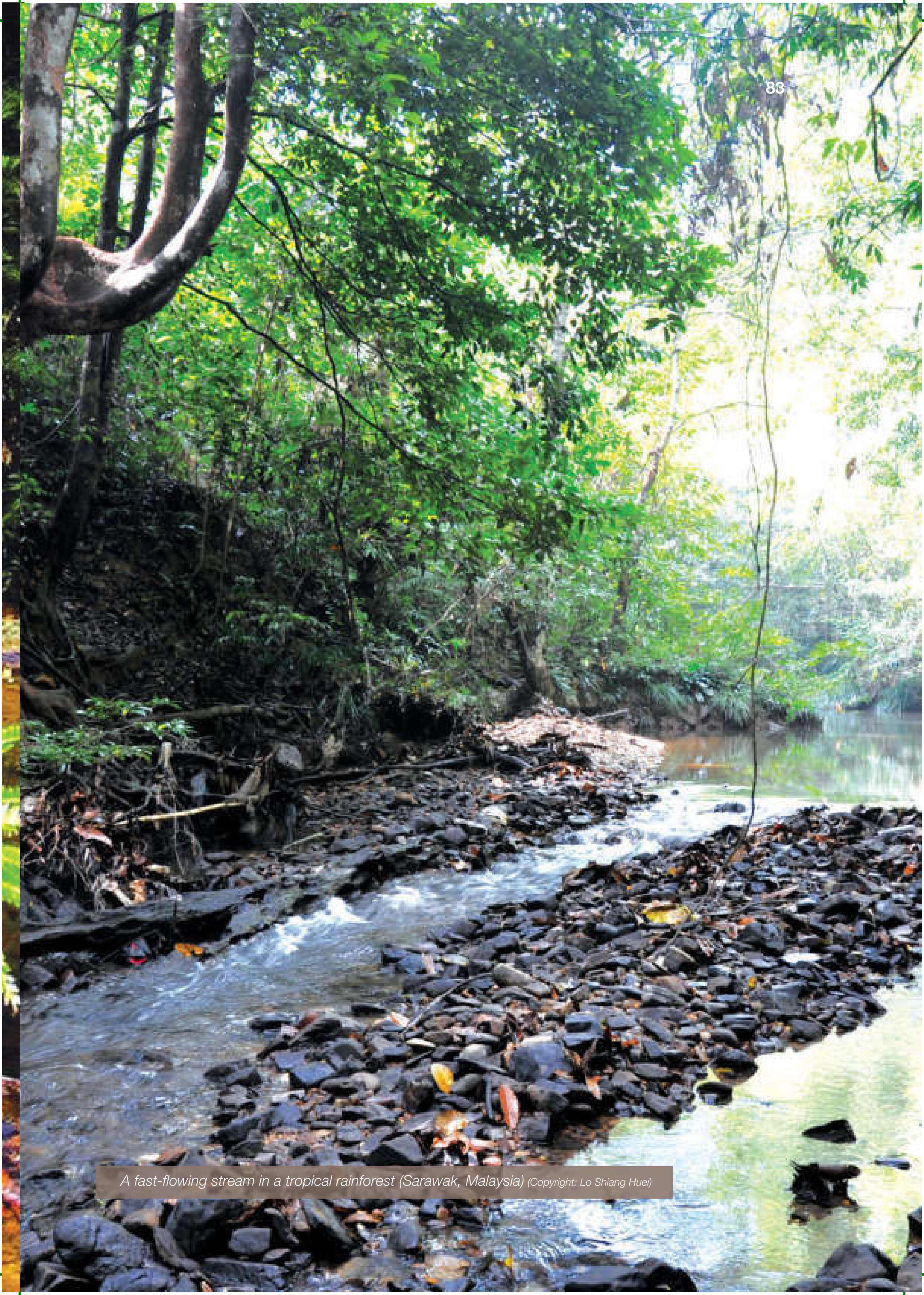


Illustration of the three types of rheophytic plants, showing the distinctive willow-like leaves: Aglaia yzermannii *(top left);* Pentasacme caudatum *(top right) and* Elaeocarpus *sp. (bottom).*

Phyllanthus watsonii *is an endemic riverside plant found only along the Endau River and its tributaries (Endau-Rompin National Park, Malaysia) (Copyright: Chew Keng Lin)*

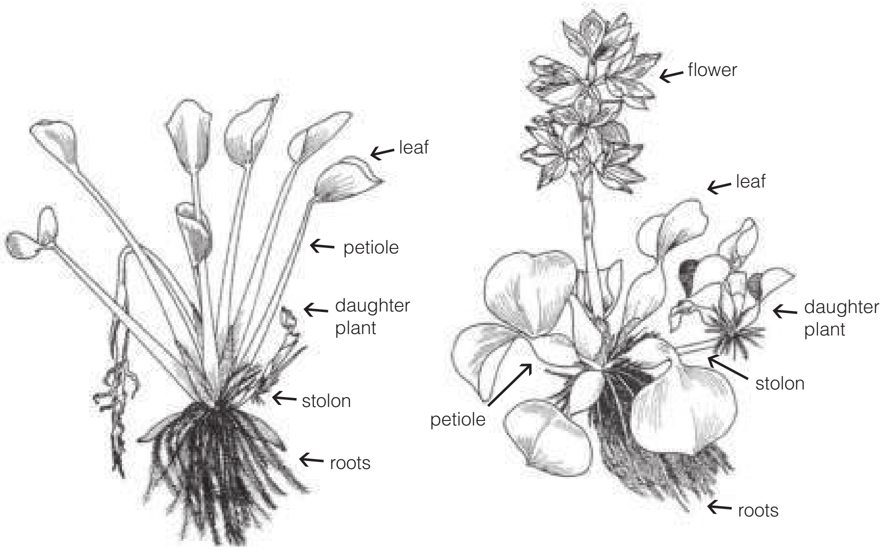


A fast-flowing stream in a tropical rainforest (Sarawak, Malaysia) (Copyright: Lo Shiang Huei)

Floaters

Hygroryza aristata *can be used in water treatment system for the removal of excess nutrients in a waterbody*

Floaters or floating plants are plants which are exposed at or above the water's surface; only their roots, and occasionally the lower parts of the stems, are submerged below the water's surface. They are habitually found in sheltered waters. They usually have tiny or no stems and the leaves are in rosettes or clusters which vary in size, from minute – less than 1 mm long in *Lemna minor* – to about 30-80 cm long structures in Water Hyacinth (*Eichhornia crassipes*). Most of the floaters have water repellent leaves: these are covered with dense hairs or a layer of waxy material. Some of the floaters develop air-filled structures to increase buoyancy, for example, the swollen, air-filled stalks of Water Hyacinth.



*Schematics of a typical floating plant, Water Hyacinth (*Eichhornia crassipes*) with slender petioles (left) and bulbous petioles (right) (Copyright: Wright and Purcell).*

Since floaters are not rooted into soil, all mineral nutrients are obtained from the water, and the growth is most vigorous in waters that are naturally rich in nutrients or enriched by runoff from catchments, such as fertilised agricultural land or urban spaces.

Floaters typically propagate vegetatively, e.g. by budding off from the parent plants or through stolons, with each stolon forming a new rosette plantlet at its tip.

The daughter plants of the Water Lettuce, Pistia stratiotes, *attached to the mother plant by stolons.*

Using Floaters to Improve Water Quality

Water Hyacinth (*Eichhornia crassipes*) is an example of a fast-growing floater that is used commonly as water-cleansing treatment plants. A study conducted in the USA showed that Water Hyacinth can spread at a phenomenal rate of 15 percent of its current surface area per day. At this rate, 20-40 tons of wet Water Hyacinth could be harvested per hectare per day; removing the nitrogenous wastes of over 2000 people and the phosphorus wastes of over 800 people concomitantly (Wolverton & McDonald, 1975).

Water Hyacinth *grown under optimal conditions can remove a large amount of nutrients from the waterbody within a short period of time.*

Based on experiments carried out in the USA, it was also found that under ideal growth conditions, Water Hyacinth recovered the following elements from the waters:

Table 4.1 Elements accumulated by *Eichhornia crassipes* under ideal growth conditions.

Element	Amount recovered (kg/ha/day)
Nitrogen	22-44
Phosphorus	8-17
Potassium	22-44
Calcium	11-22
Magnesium	2-4
Sodium	18-34

(Wolverton and McDonald, 1975)

The use of water plants in large-scale water-cleansing applications must be carried out carefully. When not managed properly, water plants with high proliferation rate such as floaters e.g. Water Hyacinth (*Eichhornia crassipes*), Water Lettuce (*Pistia stratiotes*), Lesser Duckweed (*Lemna minor*) and Giant Salvinia (*Salvinia molesta*), and certain submerged plants e.g. *Hydrilla verticillata*, may cause disruption to the natural aquatic ecosystem by excessive vegetative growth. Under high nutrient conditions (eutrophic conditions), they will produce a massive mat that could potentially obstruct light penetration to the lower layer of the water column, which will affect the survival of aquatic life. Back in 1970s, reservoirs in Singapore were colonised by these fast-growing species and this resulted in high maintenance cost to remove these plants continuously on a regular basis. At present, the amount of fast-growing aquatic plants removed from Lower Seletar Reservoir reaches ten tonnes a week and the maintenance work cost $1,500,000 per year. Consequently, one must be careful in using fast-growing and exotic aquatic plants for water-cleansing purposes in waterways and waterbodies such as reservoirs.

These species should preferably be used in ponds and streams that are not directly connected to the public waterways or grown within structures designed to contain the species and to prevent the uncontrolled growth and unwanted spread into the adjacent waterbodies. They are normally not recommended for a large constructed wetland system unless the user can find a more efficient and economical method for periodic biomass removal.

Floaters (Salvinia molesta) *which are harvested should be disposed off appropriately and not be left at the edge of the waterbody as the nutrient "juice" within the plants would leach back into the water.*

Nevertheless, the key advantage of using fast-growing water plants is to remove nitrogen, phosphorus and the other chemical compounds rapidly and sustainably from the water, provided that the harvesting and disposal of the floaters is carried out properly. Based on careful observations made locally and elsewhere over the last ten years, certain operational aspects in harvesting water plants have to be improved and this aspect of operational management is crucial if one hopes to lower the nutrient content of the water in our waterbodies efficiently. For example, it should be noted that half of the "moisture" (water in plant tissues) content of a floater is loosely contained in the vascular system. This "juice" is usually filled with rich dissolved nutrients. Therefore to prevent the "juice" from leaching back to the waterbodies during the harvesting process, the floaters have to be harvested rapidly and physically contained in waterproof containers. These are either used later for composting or disposed off appropriately at a suitable locality/facility.

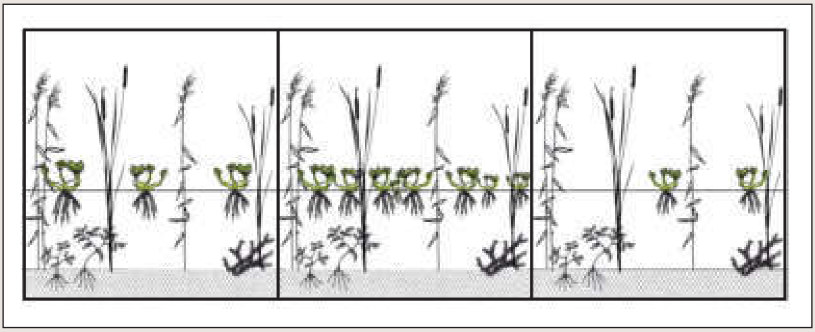
Moving forward, the contractors hired to carry out water plants removal from any waterways and waterbodies must be made aware of the various scientific aspects of the nutrient cycles affecting water quality. Thus, the contractors must try to remove all the freshly harvested biomass (including the nutrient-rich "tissue juices") immediately from the waterways and waterbodies. If there is a time-lapse between harvesting and the transportation of the freshly harvested biomass on site, a significant proportion of the nutrients will potentially leach out of the biomass left on site. Depending on where the pile of biomass is sited while awaiting transportation, some of the leached nutrients may re-enter the waterways or waterbodies. Alternatively, some water-tight enclosures may be deployed on site to serve as a temporary water-tight holding area to contain the freshly harvested biomass and their nutrient-rich liquids. This seemingly mundane and operational aspect (e.g. better coordination between harvesting and transportation, providing containers to collect the "dewatering" liquids) of residue removal of biomass and its associated nutrient-rich liquids will be crucial as we endeavour to lower the nutrient content of the water in our existing waterbodies efficiently, and to seek new water catchments in our urban areas.

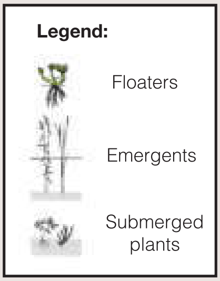
Traditional harvesters are used to remove aquatic plants from a reservoir in Singapore.

A conveyor, attached to a feeder, is used to remove the water plants from the lake and straight onto a waiting lorry for immediate transport (middle and bottom, Copyright: Terry Mealor).

Recent works in NTU have also demonstrated that other floaters like Water Lettuce (*Pistia stratiotes*) and Giant Salvinia (*Salvinia molesta*) are also capable of absorbing large quantities of nitrogen and phosphorus (the two nutrients most frequently associated with eutrophication), and have rapid growth rates. As long as there is enough space for growth and the weather conditions are favourable, new plants are rapidly produced by vegetative means.

By continually removing a portion of the floater population, it is possible to maintain a proportion of rapidly growing plants within the population. This ensures that at least a portion of the floaters is growing and absorbing nutrients at all times. Hence, the judicious use of very fast-growing floaters has its merits in mopping up rapidly the excessive nutrients present in certain eutrophic waterbodies (canals and lakes). The floaters will therefore complement the sustainable but slower nutrient uptake capacities provided by the emergent (woody and non-woody types, which include rheophytes) plants.





*When a waterbody becomes eutrophic, floaters are added to remove the excess nutrients (left). These floaters will multiply rapidly, and absorb the nutrients in large amounts concomitantly. Harvesting and the appropriate disposal of floaters will remove these nutrients from the waterbody (center). The first two processes will be repeated until the nutrient level falls to an acceptable range. Thereafter, the use of floaters may no longer be necessary and emergent plants, like cattails (*Typha angustifolia*), will then absorb the remaining nutrients in the water on a lower but steady rate (right).*

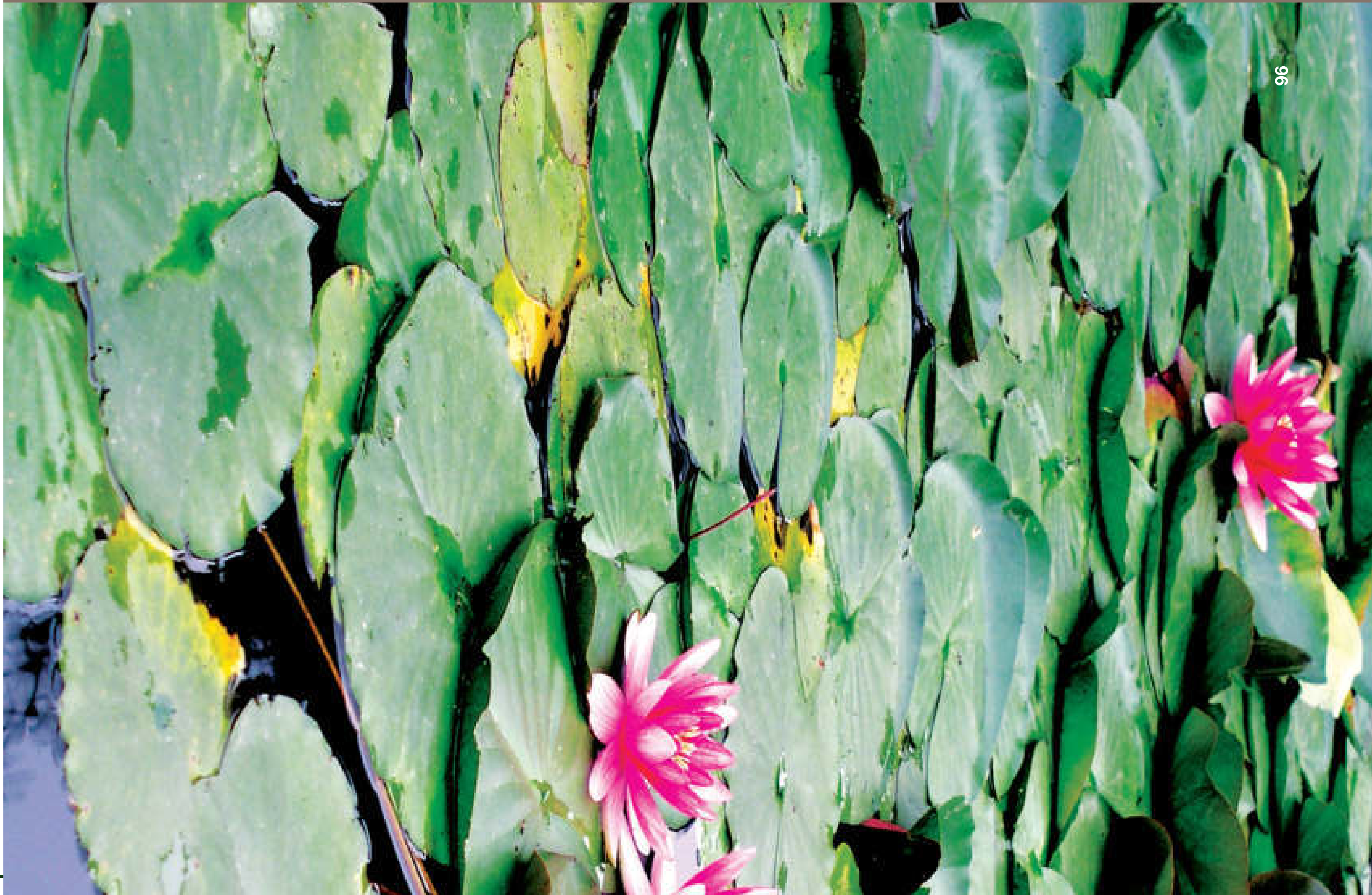
The careful and strategic placement of floaters under contained conditions can provide an immediate solution to reduce nutrient levels rapidly in an effort to prevent any potential algal bloom in waterbodies.

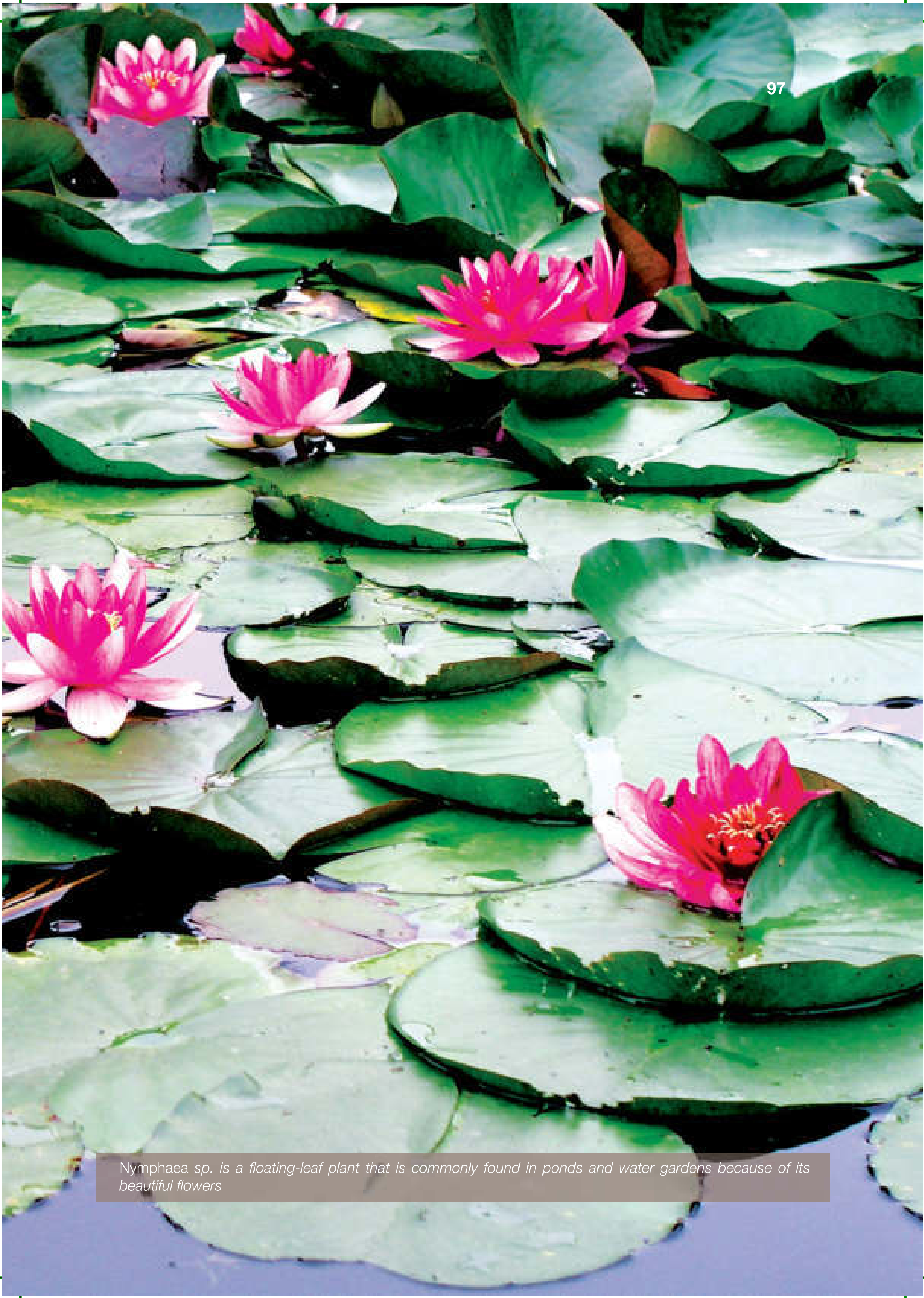
To prevent floaters from being invasive and spreading uncontrollably, floating booms are used to contain them within a designated enclosed area.

Vegetative barriers can also be used to contain floaters within a designated enclosed area.

Floating-Leaf Plants

Nymphoides cordata



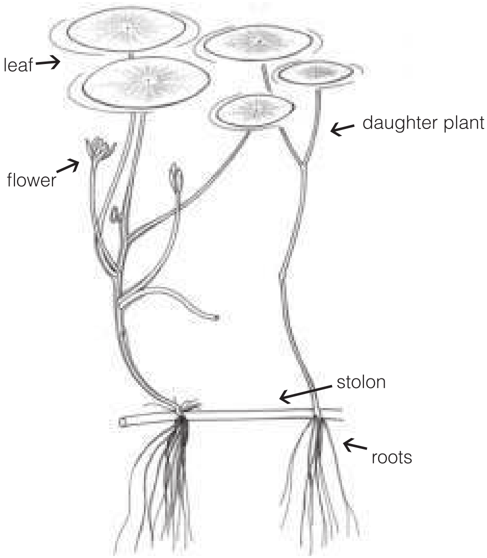


Nymphaea *sp. is a floating-leaf plant that is commonly found in ponds and water gardens because of its beautiful flowers*

The plants in this category are rooted in the muddy substrates of shallow waterbodies, with the lower parts of their stems or the whole leaf stalks usually submerged under water. The stems and leaf stalks are usually weak and soft, and thus their leaves and flowers float on the water surface.

A young and expanding leaf emerging from the shoot-root junction underneath the water, which will then expand and float onto the water surface.

The internal tissues of the submerged parts are usually filled with air spaces and/or reinforced with scattered but structurally-tough vascular bundles to support the floating leaves. Reproduction is normally through vegetative means, such as stolons.



The various plant parts of floating-leaf plant Brasenia schreberi *(top) (Copyright: University of Florida Centre of Aquatic and Invasive Plants) and* Nymphaea *sp. (bottom).*

The most remarkable member of this category is undoubtedly the Giant Water Lily, *Victoria amazonica*, a native of tropical South America. The floating leaves are large, sometimes attaining 2 m in diameter. They are leathery and, unlike most Water Lilies, have 'turned-up' edges several centimeters or more in height, which makes it harder for water to flood the leaf surfaces.

The enormous floating leaves of the Giant Water Lilies, Victoria amazonica.

Nuphar *sp.*

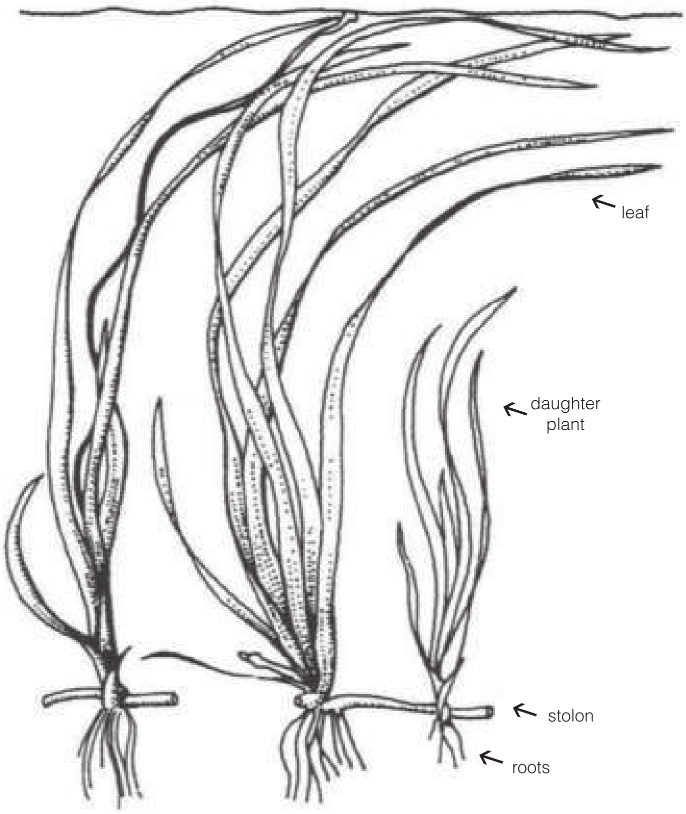
Its beautiful yellow flowers.

Submerged Plants

Gratiola *sp. growing within a submerged* Hydrilla verticillata *colony at the Singapore Botanic Gardens*

Cryptocoryne griffithii is an endangered submerged plant in Singapore

Submerged species are located beneath the water surface, and only their flowers and the tips of their leaves occasionally emerge above the water. The plants are rooted in the mud at the bottom of the waterbody. The stems are short, upright and fleshy, such as in *Blyxa aubertii*; or long, prostrate and tough, as in the seagrasses; or long, slender and flexible, like those of *Hydrilla verticillata*.

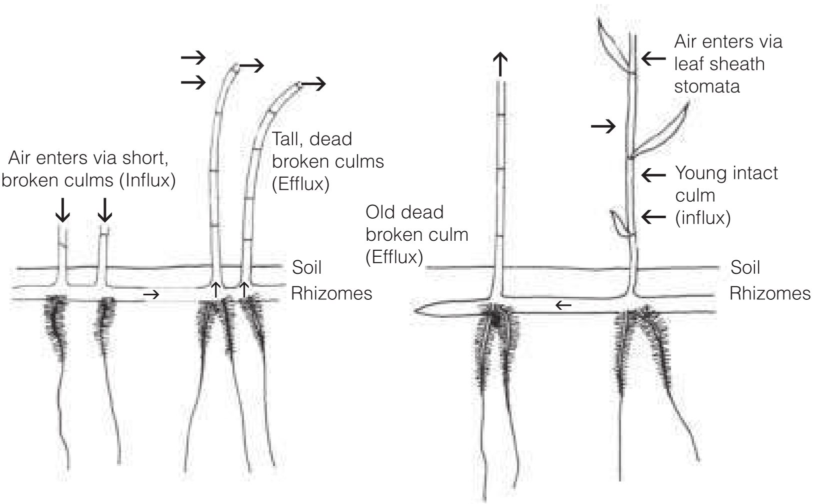


The various plant parts of a submerged plant, Vallisneria americana
(Copyright: University of Florida Centre of Aquatic and Invasive Plants).

The leaves of submerged plants may be short, thin, narrow or sometimes even deeply dissected. This is to increase the plant surface area available for gas exchange and nutrient absorption and also to reduce resistance to water movement in order to minimise damage from water currents.

Alternanthera sessilis *is a submerged plant, with only the leaves and flowers (inset) emerging above the water surface under certain circumstances.*

Their roots, stems and leaves are generally filled with inter-connecting air chambers within the tissues. The thin diaphragms in the air chambers prevent pressure from the surrounding water from collapsing their chambers. When the pressure is high, the plant parts are firm and flexible, and are able to avoid damage from water movement. The air chambers also provide buoyancy to the stems and leaves, raising them nearer to the better-lit water surface.



The movement of air from the rhizomes into the roots and out of the roots back into the surrounding (Redrawn from Colmer, 2003, Copyright: John Wiley & Sons).

The submerged parts of these plants have little or no cuticle over their surfaces, and possess thin cell walls. These structural adaptations allow them to absorb mineral nutrients directly from the water. Generally, most submerged species have well-developed root systems that are embedded in the substrate. For species that are not embedded, abundant root hairs are produced at the end of the roots.

The spathe of Cryptocoryne pallidinervia *(Copyright: Lo Shiang Huei)*

Vegetative reproduction is the primary means by which submerged species colonise waterbodies. However, some submerged plants also reproduce sexually under certain circumstances, and they have interesting ways of bringing about the pollination of their flowers in an aquatic environment. The flowers are unisexual and borne on long, slender and flexible stalks. Female flowers have feathery stigmas and they usually bloom upon reaching the water surface. Male ones are normally formed deep in the water and they detach from the parent plant at maturity, float to the surface and then release the pollen. An exception is the eelgrass *Zostera*, which has both female and male flowers underwater.

A pondskater and two submerged plants, Rotala *sp. (yellow leaves on the left) and* Hydrilla *sp. (green leaves on the right).*

Attractive white flowers of Ottelia alismoides

Flower of Cabomba aquatica

Emergents

A wide variety of emergents, both woody and non-woody, on the edge of Eco-Lake, Singapore Botanic Gardens

The native and endangered aroid, Lasia spinosa, *is an emergent that is found only in pristine freshwater habitats such as the freshwater swamp forest at Nee Soon, Singapore. This plant has a unique and distinctive black-purple flower (inset) and has the potential to be an attractive ornamental plant.*

Emergent plants are waterlogged tolerant plants rooted in the substratum. The roots, lower parts of the stems, and in some cases some of the leaves, are submerged. However, unlike floating leaf plants, the majority of the upper part of the emergent plants is usually above the water surface. The aerial parts are similar to those of terrestrial plants, while the root systems are generally more extensive in order to provide adequate oxygen supply to the roots. In some instances, especially for the woody shrubs and trees, breathing roots such as pneumatophores may be produced.

The breathing roots of Taxodium distichum.

Different soft-stemmed emergents on the fringe of a pond at Sengkang Riverside Park, Singapore

These emergent plants usually grow in shallow waters or in waterlogged soil near the margins of lakes, streams and estuaries. Under certain circumstances, the soft-stemmed emergents, such as *Typha* sp. or *Lepironia articulata*, can reproduce rapidly. Given their high density growth patterns, they have an absolute competitive edge over other plants for space and sunlight. Therefore, once an area is colonised by these soft-stemmed emergents, it may be difficult for the other plants to get established. As a result, such soft-stemmed emergents often grow in pure stands in some habitats.

Colonies of Typha angustifolia *growing at Sengkang Riverside Park, Singapore.*

Unlike the fully the submerged or floating aquatic plants, in which vegetative reproduction often predominates, these plants also have the option to reproduce by seeds. Examples of such plants are the cattails (*Typha* spp.) and a number of sedges and rushes, water irises, arrowheads (*Sagittaria* spp.) and water plantains (*Alisma* spp.). Cattails, sedges and rushes are generally wind pollinated while the water irises, arrowheads and water plantains are insect pollinated.

Thalia geniculata *is insect pollinated (top) while* Typha angustifolia *is pollinated by wind (bottom).*

Although some of the well-known emergent species are soft-stemmed herbaceous plants, woody plants like scrubs, shrubs and trees are also present. Emergent woody shrubs such as Cicada Tree (*Ploiarium alternifolium*) and Sendudok (*Melastoma malabathricum*), do occur along the shoreline slopes of tropical wetlands, and in stream riparian zone sites. Several species of small woody trees such as Willows (*Salix* sp.) and Weeping Tea-Tree (*Leptospermum brachyandrum*) are common in wet sites around the world. Species of larger trees, such as Phtol (*Diospyros cambodiana*), Indian Putat (*Barringtonia acutangula*), Chinese Swamp Pine (*Glyptostrobus pensilis*) and Bald Cypress (*Taxodium distichum*), can also establish themselves in wet sites of stream riparian zones or floodplains that are seasonally flooded.

Examples of local woody emergents: Melastoma malabathricum *(left) and* Ploiarium alternifolium *(right).*

Mangroves and the Other Plants of Coastal Habitat

Certain species associated with mangroves and coastal habitats such as Cerbera odollam *can be used for landscaping purposes around freshwater bodies*

The beautiful red flowers of Lumnitzera littorea at Kolam Ayer (Singapore)

Mangroves are found along Singapore's coastlines. They are easily recognisable at low tide, when the characteristic roots of some species are revealed, such as those of Bruguiera *spp.*

Mangrove forests occur in flooded marine and brackish environments in the tropics and subtropics. The plant species living in this environment are specially adapted to waterlogged conditions, changing salinity and unstable soils. Altogether there are about 70 mangrove species globally, belonging to 19 families. Mangroves are generally tall trees at maturity, but they can become shrub-like when the growing environment is unfavourable (hypersalinity, low temperatures, pollution, etc.). Mangrove forests also consist of other plant species, including mangrove ferns, palms and other species which are known collectively as the mangrove associates. Interestingly, the extreme saline conditions, lack of gaseous oxygen in the soils, and exposure to the physical pounding by waves have caused the trees to develop physiological and other structural adaptations, such as specialised roots, in order to grow in such unfavourable environments. They often have stilt or prop roots, and pneumatophores which are specialised aerial 'breathing roots' containing pores, which help the mangrove trees to obtain oxygen from the atmosphere since the soil is often waterlogged and highly anaerobic.

Another special feature associated with many typical mangrove tree genera, such as *Bruguiera*, *Ceriops* and *Rhizophora*, is that they have seeds which germinate while still attached to the parent tree. This is known as vivipary, and this special adaptation helps the seedlings to establish faster once they fall from the parent tree. This interesting biological phenomenon helps to explain, in part, the successful colonisation and establishment of many viviparous mangrove species in this ecologically-harsh habitat.

A viviparous propagule of Bruguiera sexangula.

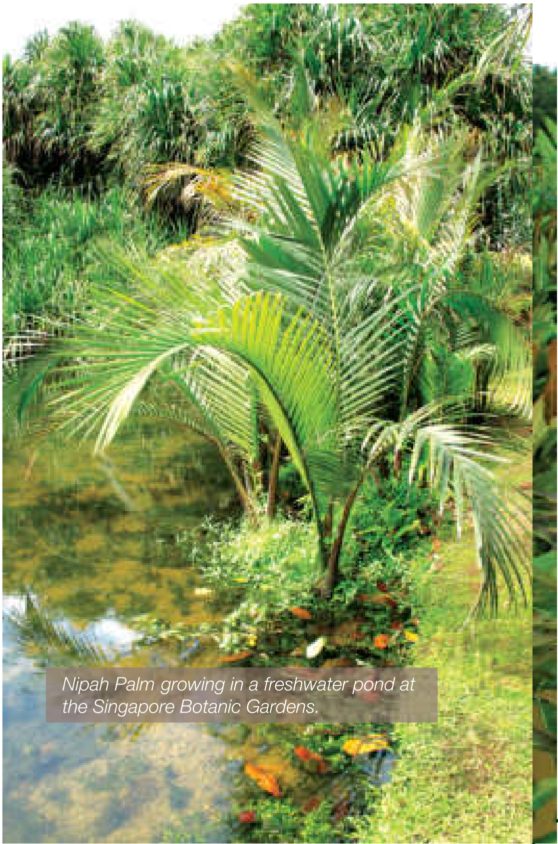
The growth of Pemphis acidula *under freshwater conditions.*

In an established and undisturbed mangrove forest, the plants are generally distributed in three distinct zones, namely *Avicennia-Sonneratia* zone, *Bruguiera-Rhizophora* zone and the back mangrove zone. The *Avicennia-Sonneratia* zone is the most seaward fringe of the mangrove, where the soil is soft and loose and flooded by both low and high tides. Immediately behind that zone is the *Bruguiera-Rhizophora* zone, which is on higher ground and flooded less frequently by high tides. The soil here is more compact than in the previous zone. The back mangrove zone has soil that is only inundated by equinoctial and other exceptionally high tides. It contains more clay and has the most compact soil of the three zones. The classic zonations of mangrove forests may not be observed in certain habitats, as there are other stronger disrupting anthropogenic (man-made) or ecological factor(s) affecting the otherwise natural distribution of the mangrove species.

Acrostichum speciosum *growing on mud-lobster mounds within the shaded canopy of a natural mangrove forest* (Rhizophora-Xylocarpus-Bruguiera *type*) *environment.*

In terms of botanical richness, the back mangrove has the largest number of species. This richness is driven by the presence of many mangrove/coastal associates. Interesting combinations of mangrove plants and mangrove/ coastal associates can be found in this mangrove-terrestrial land transition zone. These botanical combinations may range from a simple thicket of mangrove ferns, to more complex associations of *Bruguiera sexangula-Sonneratia ovata-Rapnea porteriana* forest type, and *Rhizophora-Lumnitzera* forest full of epiphytic ant-plants (*Hydnophytum* sp.) and mistletoes (*Scurrula* sp.). Moving further inland and beyond the normal and frequent tidal influence, a unique brackish-water plant community, known as Nipah swamp forest, usually develops. This swamp forest is dominated by Nipah Palm (*Nypa fruticans*), which forms pure stands along the banks of meandering rivers.

Nipah Palm growing off the coast at Pulau Ubin.



Nipah Palm growing in a freshwater pond at the Singapore Botanic Gardens.

Another special group of plants that is prominent in the mangroves are the mangrove ferns. Mangrove ferns are found mostly in the landward side of the mangroves, which is in the back mangrove. They grow best on the elevated ground of mud lobster mounds, where the ground is usually higher and beyond inundation. In Singapore, the mangrove ferns are among the first pioneering plants to colonise the landward side of the mangroves and coastal forests, especially when there is some disturbance (e.g. land clearing, or a huge gap due to a tree fall) to the natural habitats.

Acrostichum aureum *planted along the water edge of a pond at Sengkang Riverside Park, Singapore.*

The relative scarcity of ferns in the seaward side of the mangrove and coastal communities is because the ferns are intolerant of prolonged submersion by seawater. In osmotic terms, seawater is "physiologically dry", and only specialised tree species like *Avicennia* can overcome this physiological limitation and survive in the saline environment. Currently, there are only two species of mangrove ferns, and both of them belong to the genus *Acrostichum*. The widespread availability of these two mangrove fern species in commercial nurseries around Singapore has made them favourite planting materials for waterscapes and general landscaping purposes.

A young frond of Acrostichum aureum*, a fern found commonly in the mangroves (left). This mangrove fern can be carefully incorporated aesthetically as a nice botanical addition for a freshwater pond, in addition to the other freshwater water plants (right).*

In Christmas Island, there is a patch of very old mangrove forest (*Bruguiera gymnorhiza-Bruguiera sexangula* forest type) growing under freshwater conditions for over 100 000 years (Woodroffe, 1988)!

This observation, in addition to the other anecdotal evidence that certain mangrove species can thrive in freshwater conditions, highlights the potential for certain mangrove species to be used in freshwater aquatic environment in Singapore. Hence, a short selection of suitable mangroves is included in this book.

Acrostichum aureum, *a mangrove fern growing as part of the oriental traditional landscape environment at the Chinese Garden, Singapore.*