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Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review

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Application of Floating Wetlands for Enhanced Stormwater Treatment: A Review

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1 Executive Summary

The removal of metals, such as copper and zinc, from urban stormwater has been identified as a priority by the Auckland Regional Council. Conventional stormwater treatment devices, such as ponds, have proven limited in their ability to remove the fine suspended particle fraction with which significant proportions of these metals are associated. This report examines the potential of developing and applying a novel "floating treatment wetland" concept for the provision of enhanced stormwater treatment, particularly with regards to copper, zinc and fine particulate removal.

Constructed treatment wetlands have traditionally involved the use of free-floating aquatic plants, or sediment-rooted emergent wetland plants, either with water flowing through the root zone (subsurface flow) or amongst the stems (surface flow). Floating treatment wetlands (FTWs) are an innovative variant on these systems that employ rooted, emergent plants (similar to those used in surface and subsurface flow applications) growing as a floating mat on the surface of the water rather than rooted in the sediments. Because of this feature, floating treatment wetlands offer great promise for rainfall-driven stormwater treatment applications as they are little-affected by fluctuations in water levels that may submerse and adversely stress bottom-rooted plants.

Although not a very common type of wetland ecosystem, floating wetlands occur naturally in many parts of the world and offer some useful insights into the long-term function and operation of artificially created floating treatment wetlands. Natural floating wetlands typically consist of a 40- 60cm deep floating organic mat supporting plant growth, the upper portion of which is comprised of densely intertwined live, dead and decaying roots with some litter collection on the surface. Below the active root zone a layer of low-density decomposed peat and decaying plant detritus develops, the depth of which is usually dictated by the rooting depth of the plants. Beneath the peat layer a zone of relatively clear free-water exists, that varies in depth (0 – 2m) with the lake or wetland water level. On the base of the wetland basin, beneath the free-water zone, a layer of organic sludge develops over the native subsurface material.

Whereas attached wetlands can experience alternate periods of flooding and drying, the water level with respect to the vegetation in a floating wetland is effectively constant. The boundary between saturated and unsaturated soil remains constant, which minimises hydrologic factors as a source of variation in plant growth and other biogeochemical processes. Since floating wetlands rarely experience inundation or flooding of the wetland surface, the natural floating substrates are typically characterised by being predominantly organic in origin, with very little mineral content. Self-buoyancy in natural floating wetlands is achieved via two main processes:

- the entrapment within the matrix of gases generated during anaerobic metabolism of organic deposits; and
- the occurrence of air spaces within the living biomass, particularly the rhizomes, of particular vegetation.

Over the past two decades, artificially created floating wetlands have been studied in various parts of the world for a range of applications, such as water quality improvement, habitat creation, and aesthetic enhancement. Systems created for water quality improvement, termed Floating Treatment Wetlands (FTWs), have been used for the treatment of:

- Combined stormwater-sewer overflow.
- Sewage.
- Acid mine drainage.
- Piggery effluent.
- Poultry processing wastewater.
- Water supply reservoirs.

Although a number of articles describing planned or proposed stormwater applications were discovered, no reports of actual experience with the use of FTWs for stormwater treatment were found in the literature.

Numerous techniques have been used for the creation of floating wetlands and a number of commercially available systems are available throughout Europe and North America. The most common approach to constructing floating wetlands is through the creation of a floating raft or frame supporting a mesh on which plants are grown. Coconut fiber or peat are often used as a growth medium. Buoyancy in such systems is generally achieved through the use of sealed sections of plastic pipe or tubing (PVC, PE, PP), sealed drums or polystyrene foam pontoons. A low cost method has been developed in India using naturally buoyant bamboo. A number of companies (e.g., Bestmann Green Systems, AGA Group) produce modular rafts (triangular or square) that can be readily joined together to form floating wetlands of various shapes and sizes. On a relatively large scale, Oceans Ark International have developed an approach (the "Restorer") for treating wastewater in lagoons that involves the use of multiple linear floating wetlands with synthetic textile curtains hanging beneath to provide additional substrate for biofilm attachment and to create a lengthy serpentine flow path. Fine bubble aerators are used throughout to increase dissolved oxygen concentrations and enhance mixing.

A second, rather elegant and well-developed approach to the construction of floating wetlands involves the use of a matrix with intrinsic buoyancy which itself serves to support the growth of the plants. Examples include the spun polyester matrix with injected buoyant polystyrene manufactured by Floating Islands International (USA) and the floating plastic netting materials produced by the Huck Group (Germany).

Published data on the treatment performance of the various FTW applications are limited. In general, it seems that FTWs have been effective at removing suspended solids and nutrients, although reported phosphorus removal efficiencies are somewhat variable. The only metal removal reports found were for the first year of a pilot FTW system constructed at Heathrow Airport in London for the treatment of glycol-laden de-icing water. Copper removal was approximately 20-30%, while removal of zinc was ineffective. However, the floating structure in this system was apparently constructed using galvanized steel materials which may have acted as a source of metals such as zinc, whilst the limited time frame of the study renders the information of limited value.

In the context of urban stormwater treatment within the Auckland region, copper and zinc have been identified as two metals of concern, especially from commercial and industrial catchments. Studies have demonstrated that as stormwater travels through a catchment, dissolved copper and zinc adsorb to particulates suspended within the stormwater, and that as the distance from the source increases, these metals tend to become increasingly concentrated within finer particulate fractions. Thus, an effective treatment system needs to be capable of capturing these fine particulates and immobilizing the associated metals.

Compared to conventional pond and wetland systems, FTWs are considered to possess a number of advantages that may enhance certain contaminant removal processes. The cover and shelter provided by the floating mat promotes conditions conducive to settling by reducing turbulence and mixing induced by wind, waves and thermal mixing. Compared to conventional sediment-rooted wetlands that are predominantly restricted to water depths of less than 0.5m, FTWs can be constructed deeper to provide extra water volume, reduce flow velocities and enhance settling.

Plant roots are believed to play a key role in treatment processes within FTWs by virtue of the contact that is afforded as the water passes directly through the network of hanging roots that develops beneath the floating mat. Plant roots provide a living surface area for development of biofilms containing communities of attached-growth micro-organisms responsible for a number of important treatment processes. The thick network of roots and associated biofilms are effective at physically trapping particulates within the water column, which subsequently slough off the roots as heavy particles that are more amenable to settling. Given that a significant proportion of copper and zinc in Auckland stormwater is associated with fine particles, the enhanced sedimentation processes afforded by FTWs may make them particularly effective at removing these metals.

Complexation of metals with root biofilms, root exudates, humic compounds and other large molecular weight organics followed by deposition may play an important role in metal removal under FTWs. Adsorption of copper and zinc onto iron oxide plaques that commonly develop on wetland plant roots may occur. However, this is likely to provide only temporary removal.

Once deposited within the benthic sediments, immobilization processes will become important to ensure that the bound metals do not become remobilized. Generally, anaerobic conditions within the sediments will favour the immobilization of metals. Those metals complexed with large molecular-weight organics will tend to remain bound under anoxic or reducing conditions, whilst zinc will become strongly immobilized as zinc sulphide and copper may form insoluble elemental copper.

A number of factors are likely to promote the development of reducing conditions within the sediments (and water column) underlying a floating wetland. These include: (1) the regular supply of organic matter from the floating plant material; (2) the presence of inundated, waterlogged conditions which limits gaseous oxygen diffusion into the sediments; (3) the elimination of re-oxygenation of the water column via photosynthetic algae; and (4) the obstruction of diffusion of oxygen across the air-water interface and reduced wind and wave induced aeration due to the protection provided by the floating mat. While reducing conditions will favour the immobilization of captured metals within a FTW system, some form of re-oxygenation of the water leaving the FTW will generally be required prior to discharge into a natural waterway. Re-aeration may be achieved by incorporating an open-water pond section after the FTW, through the use of active aerators or the use of a passive cascade outlet structure. Overall, the level of oxygen depletion in the water column beneath a FTW system may be partially manipulated by controlling the proportion of pond surface that is covered by floating wetland. The redox status within the water column and sediments beneath a stormwater FTW, and the effect of percentage cover, need to be further investigated with regard to copper and zinc removal.

There is some potential for incorporation of materials with a high metal sorption capacity within the floating mat of a FTW in order to enhance removal of dissolved copper and zinc. Potentially suitable media include zeolites, vermiculites, bauxsol, activated carbon, and bio-sorbents such as peat, plant, algal and shell materials. The effectiveness of this approach will be somewhat limited by the amount of interaction between the stormwater and the sorbent material contained within the floating mat. The pumping and circulation of water vertically through the floating mat may be required to optimize metal removal through such a process.

Potentially suitable plant species for FTWs in New Zealand include emergent sedges from the genera *Carex, Cyperus, Schoenoplectus* and *Baumea* and rushes from the genus *Juncus*. Taller-growing native species such as the larger sedges (e.g., *Baumea articulate* and *Schoenoplectus tabernaemontani*) and raupo (*Typha orientalis*) are likely to develop extensive root systems and be particularly good at trapping suspended particles, but will experience greater wind resistance and will render small islands vulnerable to over-turning during higher winds. Thus, the use of taller species may be limited to larger FTW systems that are securely anchored.

Open textured coarse peat or coconut fiber materials that do not become too heavy or anaerobic once saturated are likely to be the most suitable media for plant establishment on floating wetlands. The incorporation of pumice or perlite as a light-weight bulking material may also be beneficial.

A potentially significant impediment to the establishment of plants on FTWs may be damage by birdlife that will be attracted to the floating island. This issue will need to be addressed through field scale trials. One option might be the deployment of pre-planted floating mats that have been vegetated under nursery conditions.

A number of questions exist surrounding the design and practical implementation of FTWs as a stormwater quality improvement device. At this stage, FTWs show great promise for applications where they are retro-fitted onto existing detention ponds in order to enhance their treatment performance. In two-stage pond systems it is suggested that the most suitable location for FTW elements will be within the second pond following the sediment removal forebay. FTWs may also be beneficial for upgrading surface flow wetlands that have suffered vegetative decline due to inappropriate water depths or for incorporation into deep water zones.

A conceptual stormwater treatment train has been suggested for newly constructed systems that consists of a forebay upfront for removal of coarse sediments and flow attenuation, a surface flow wetland for some removal of organics, suspended solids and nutrients (this component may not be necessary), followed by a FTW for fine particulate and metal removal. The final stage of the treatment system would consist of an open water pond to facilitate re-aeration of the water prior to discharge. This conceptual design is preliminary at this stage and requires substantial investigations in order for it to be further refined.

There is currently no design basis available for sizing a FTW system to achieve a desired pollutant removal objective. Fundamental experimental work is required in order to define the relationship between loading rate per unit surface area of FTW (either hydraulic or contaminant loading rate) and the typical removal rates or effluent concentrations that can be expected from such systems. This would then enable the surface area of FTW required to achieve a given effluent concentration to be estimated for design purposes.

2 Introduction

Ponds and wetlands have become widely accepted stormwater quality improvement devices over the past two decades. This growing popularity has been largely due to the fact that pond and wetland based systems offer the advantages of providing a relatively passive, natural, low-maintenance and operationally simple treatment solution whilst enhancing habitat and aesthetic values at the same time. However, a number of limitations have emerged with the application of wetland and pond systems for stormwater treatment. For example, while ponds are generally effective at removing coarse suspended sediments, they are less effective at removing finer particulates and dissolved contaminants. To provide enhanced treatment, a wetland can be placed downstream of a pond. However, sediment-rooted wetland vegetation can only tolerate relatively shallow water depths and can be susceptible to chronic die-back in event-driven stormwater systems if inundated for excessive periods. Consequently, conventional wetland systems need to be relatively large in order to provide sufficient hydraulic buffering to prevent extreme fluctuations in water level or are typically designed with high-flow bypass mechanisms that result in significant proportions of the flow receiving only minimal treatment during large rainfall events. Floating treatment wetland systems that incorporate emergent wetland plants growing in a hydroponic manner on floating rafts offer a potential solution to these problems by enabling the incorporation of treatment wetland elements into deeper pond-like systems exposed to water level fluctuations.

Within the Auckland region, copper and zinc have been identified as significant contaminants of concern in urban stormwater, particularly from catchments dominated by commercial and industrial land uses (Griffiths and Timperley, 2005). Consequently, the Auckland Regional Council (ARC) has recently released a proposed "Auckland Regional Plan: Air, Land and Water" which include provisions specifically aimed at promoting practices that minimize the quantities of contaminants discharged from industrial and trade sites (Pennington, 2006).

Studies have demonstrated that as stormwater moves away from the contaminant source, the proportion of copper and zinc in the dissolved phase decreases as these metals become adsorbed to suspended particles (Griffiths and Timperley, 2005). Furthermore, as the stormwater travels further from the source, the concentration of copper and zinc associated with the smaller particle size fraction tends to increase. The fine and colloidal particle size fractions (<63 μm) remain in suspension even at low flow velocities, and are therefore difficult to remove through conventional physical settling processes. Consequently, there is a need for stormwater quality improvement devices that are effective at removing the fine suspended particulate fraction of the stormwater and the associated metal contaminants in order to minimize the impacts on downstream aquatic ecosystems.

ARC (2004) assessed the effectiveness of stormwater treatment ponds of various sizes at reducing copper and zinc loadings and concluded that, although ponds can reduce the rate of contaminant accumulation in receiving estuaries, the level of treatment currently attainable will not be adequate to prevent adverse effects in the long term. The report went on to state that in highly urbanized catchments, where opportunities to retro-fit traditional treatment technologies (such as ponds) are limited, more innovative treatment options will need to be considered. Floating treatment wetlands may represent a potentially suitable solution for improving the performance of stormwater treatment ponds at removing fine particulates, copper and zinc within the Auckland region.

A floating treatment wetland basically involves the growth of emergent wetland plants on a structure that floats over a pond. Water receives treatment as it passes through the root mass that develops beneath the floating wetland. Fine particles may potentially become entrapped within this hanging root mat and associated biofilms. Floating treatment wetlands have been used for a number of applications world-wide, including treatment of airport de-icing runoff and acid mine drainage. However, there are no reported applications to date for the treatment of urban stormwater. Furthermore, there have been no conclusive investigations conducted into the key treatment processes involved with floating treatment wetlands. Thus, there is a lack of understanding of some of the fundamental processes responsible for treatment in such systems, particularly with regard to metal removal. There is also a distinct lack of information surrounding relationships between key design parameters, such as hydraulic contact time or relative surface area, and treatment performance. It is therefore not currently possible to design a floating treatment wetland system to achieve a given set of water quality objectives with any great deal of confidence. Thus, it is the aim of this report to review and interpret information relevant to the development and application of floating treatment wetlands for the removal of copper and zinc from stormwater within the Auckland region and to provide directions for future research needs on this topic.

2.1 Study brief

The ARC Stormwater Action Plan (2004) includes provisions for the development of "improved solutions" for reducing the amounts of contaminants carried into aquatic environments by urban stormwater. As part of this, NIWA was commissioned by the ARC in 2006 to begin a series of investigations into the use of floating wetlands for stormwater treatment, including the initiation of experimental trials and a literature review.

This report provides a review of available floating wetland information and related wetland treatment concepts and processes relevant to enhanced fine particulate and metal removal. The objectives of the review are:

- to synthesise relevant information that has been gleaned from research into natural floating wetland ecosystems;
- to review case studies of the use and performance of floating wetlands for water quality enhancement and treatment;

- to provide an overview and interpretation of the processes likely to be important to the removal of fine particulates, copper and zinc in floating wetlands treatment stormwater;
- to summarise the potential methods and materials for constructing floating wetlands;
- to provide advice on appropriate vegetation types and planting methods; and
- to recommend approaches for retrofitting existing retention ponds with floating wetlands (size, relative surface cover, positioning), and incorporate within multi-component treatment systems.

3 What are Floating Treatment Wetlands?

Constructed treatment wetlands are engineered systems designed to enhance the processes and interactions that occur in natural wetlands between water, plants, microorganisms, soils and the atmosphere in order to remove contaminants from polluted waters in a relatively passive and natural manner. Constructed treatment wetlands typically involve flow of contaminated water through the shoots (surface-flow or free-water surface; Fig 1) or root-zone (subsurface-flow or submerged bed; Fig. 2) of emergent species of sedges, rushes and reeds. A third approach has also been used for wastewater treatment involving the use of free-floating aquatic plants which float either as thin layer on the water surface (e.g., duckweed and azolla) or have specially-adapted buoyant leaf-bases (e.g., water hyacinth, water lettuce and salvinia) as depicted in Figure 3.

Floating treatment wetlands (FTWs) are a variant on these systems that employ rooted, emergent plants (similar to those used in surface and subsurface flow applications) growing as a floating mat on the surface of the water rather than rooted in the sediments (Fig 4). In floating treatment wetlands, plants may either be supported on a floating raft structure and rooted in some sort of matrix or soil media, or (as in many natural floating marshes) self-supported on intertwined mats of their own buoyant roots and rhizomes, and accumulated plant litter and organic matter. Because they float on the water surface, floating treatment wetlands are little-affected by fluctuations in water levels that may submerse and adversely stress bottom-rooted plants. Floating treatment wetlands may be likened to a hydroponic system, as the plants acquire their nutrition directly from the water column in which their roots are suspended, rather than from the soil. They also share some similarities with subsurface flow treatment wetlands, in that treatment occurs as water flows through the root zone of the plants, rather than amongst the stems.

The terminology used in naming floating wetland systems, both natural and artificial, is extremely varied. Virtually all of the major natural floating wetland ecotypes around the world have been given a different name, typically of local origin. Because of the relatively novel status of artificial floating wetlands used for water treatment, there is still no consistent terminology that has been broadly applied. A summary of some of the most commonly applied nomenclature for natural and artificial floating wetlands is given in Appendix 1.

As artificially created floating wetlands become increasingly used for water treatment there is a need to derive a commonly applicable and somewhat generic term for such systems. The term: “Floating Treatment Wetland” seems most broadly useful. However, such floating marshes employing emergent plants should be differentiated from treatment systems utilising free-floating aquatic plants (e.g., duckweed or water hyacinth) which, although sharing a number of similarities, are structurally and functionally different to the systems being discussed here.

Figure 1.
Longitudinal cross-section of a typical Surface Flow Wetland treatment system. Adapted from Brix (1993).

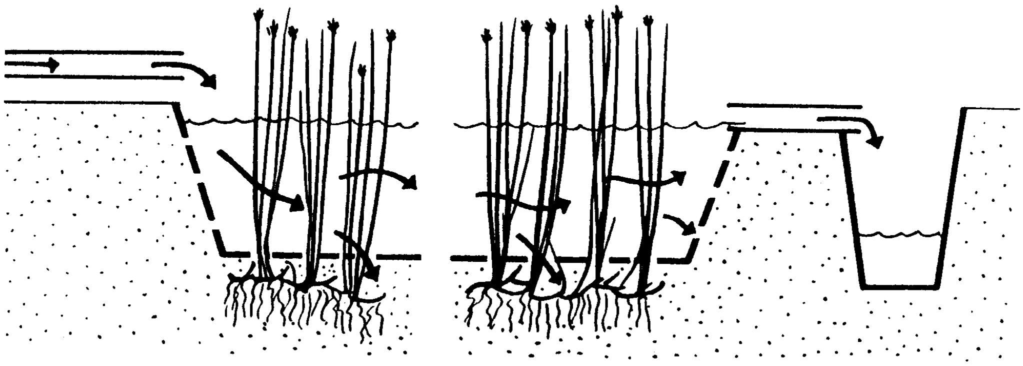


Figure 2.
Longitudinal cross-section of a typical Sub-surface Flow Wetland treatment system. Adapted from Brix (1993).

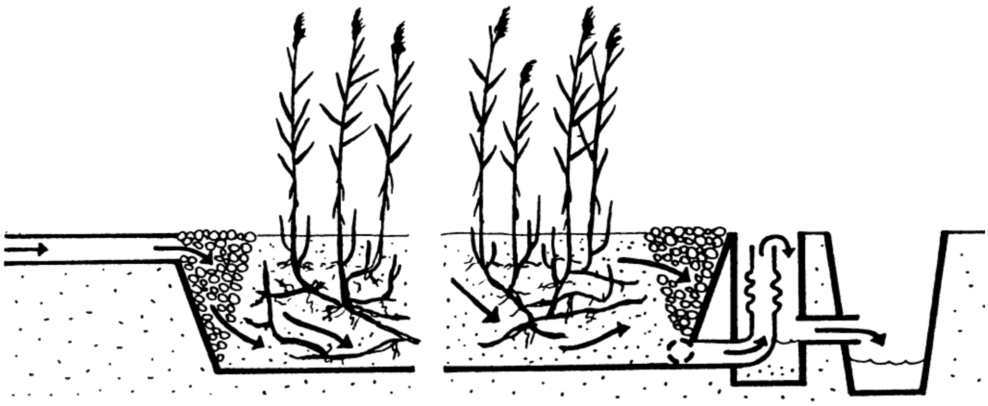


Figure 3.
Longitudinal cross-section of a typical free-floating aquatic plant wastewater treatment system. The species depicted is *Eichornia crassipes* (Water Hyacinth). Source: Brix (1993).

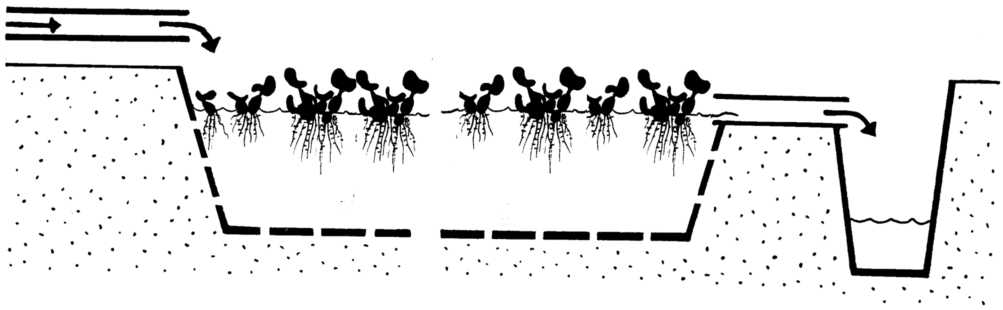
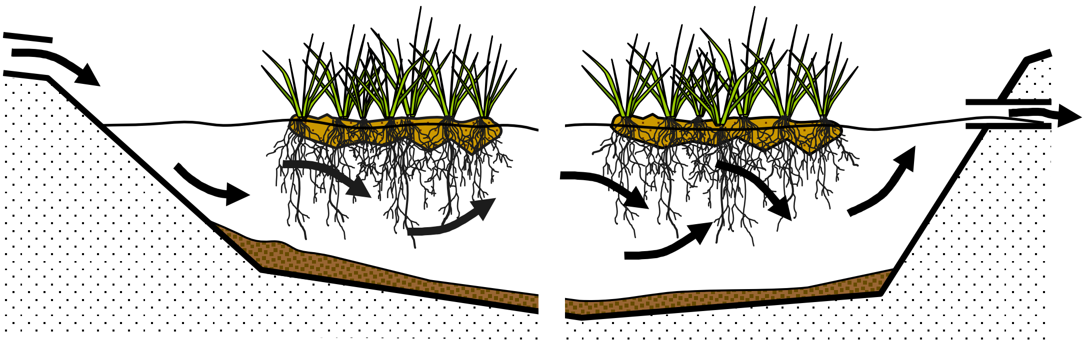


Figure 4.
Stylised longitudinal cross-section through a typical floating treatment wetland system with partial cover of pond surface with floating wetlands. Note that the water depth can vary in such a system.



Floating treatment wetlands are distinguished from free-floating aquatic plant systems by the fact that they utilize larger emergent wetland plants growing on a somewhat consolidated floating mat, as opposed to an unconsolidated mass of small, individual buoyant plants lacking any significant mat. Despite the differences, free-floating aquatic plants systems, particularly those using larger species such as water hyacinth, can provide a useful insight into how a floating treatment wetland might function and perform. Free-floating aquatic plant systems have been used to reduce particulate and organic loads in sewage and industrial wastewaters. The prevention of algal growth via shading and the reduction of wind and thermal mixing can tend to make these systems more effective at removing suspended solids and organic matter than regular facultative pond systems (Reed et al. 1995; Vymazal et al. 1998). The extensive roots system hanging below water hyacinth plants provides a large surface area for attached growth microorganisms. The high growth and uptake rates of many free-floating plants can also result in significant removal of nutrients and metals if there is enough land area available and the plants are regularly harvested. Metal removal also occurs through the chemical precipitation and adsorption on substrate and plant surfaces, with mature plants sloughing root material which becomes bound in the benthic sludge (Reed et al. 1995). Many of these processes are also likely to be important in floating treatment wetlands using emergent macrophytes.

Whilst free-floating aquatic plant systems show a lot of promise, many of plants suitable for such systems are not native species to New Zealand and have been identified as serious weeds. Species such as water hyacinth originate from more tropical climates, rendering them particularly susceptible to frost. There may be some potential for the use of native species such as *Lemna minor* and *Azolla filiculoides*. However, these small species do not develop extensive root systems for biofilm development and would require specific structures to counteract wind-driven movement and prevent them from being washed out of the system during rainfall events. The requirement for regular harvesting for nutrient and metal removal renders free-floating aquatic plant systems a rather labor-intensive approach. Thus, the use of treatment systems reliant on free-floating aquatic plants is considered inappropriate for stormwater treatment in New Zealand. They tend to have limited application outside tropical and subtropical climate zones.

3.1 Natural Floating Wetlands

The knowledge that has been gathered about naturally occurring floating marshes can provide some valuable insights into the likely long-term performance, dynamics and processes within artificial floating treatment wetlands, especially given the lack of available information on such treatment systems.

Sasser et al. (1991) define a natural floating marsh community as:

"*a marsh of vascular vegetation having a significant mat of live and dead roots, peat and detritus, that floats over a layer of free water. The marsh mat is compact and thick enough to support the weight of a person and, because it floats, is only rarely, if ever, inundated.*"

Floating marshes may comprise small, mobile floating islands, or extensive, stationary vegetated mats covering hundreds of hectares of water surface (Ellery et al. 1990; Mallison et al. 2001). Although not particularly common around the world, natural floating wetlands tend to have fascinated people through the ages, so that Van Duzer (2004) has been able to compile a global bibliography of more than 1800 citations and articles in 20 languages stretching back over 3 centuries on floating wetland islands.

Large areas of freshwater tidal floating marsh exist on the northern Gulf Coast of the US, which is where much of the research into the structure and ecology of natural floating wetlands has been conducted to date. It is believed that many of these mature marshes have broken loose from the underlying mineral substrate to float on the water surface (Sasser et al. 1991; Swarzenski et al. 1991; Mitsch and Gosselink, 2000). As summarised by the above authors, floating marsh ecosystems also occur in:

- the Danube Delta (dominated by the common reed, *Phragmites australis*);
- along the lower reaches of the Sud in Africa (dominated by papyrus);
- South America (lakes of the varzea or "flooded forest" within the Central Amazon, and high elevation lakes in Peru);
- North Dakota and Arkansas in the USA;
- Tasmania, Australia;
- Germany;
- The Netherlands; and
- England.

The floating marsh substrate typically consists of a thick organic mat, entwined with living roots, that rises and falls with the ambient water level (Swarzenski et al. 1991; Mitsch and Gosselink, 2000). Thus, the ecological processes in a floating wetland may be profoundly different to those of the more common attached marshes (Sasser et al. 1991). Whereas attached marshes can experience alternate periods of flooding and drying, the water level in a floating wetland is effectively constant with respect to the vegetation. The boundary between saturated and unsaturated soil remains constant, which should minimise hydrologic factors as a source of variation in plant growth (Sasser et al. 1995a) and other biogeochemical processes. Since floating marshes rarely experience inundation or flooding of the marsh surface, the floating substrates are typically characterised by being predominantly organic in origin, with very little mineral content (Swarzenski et al. 1991).

In some cases, the development of floating wetland islands on natural lakes and wetlands has been viewed as a negative process, particularly where they impact on recreational activities. Mallison et al. (2001) summarise the main problems associated with the undesirable accumulation of floating wetlands, particularly along shorelines, in Florida as:

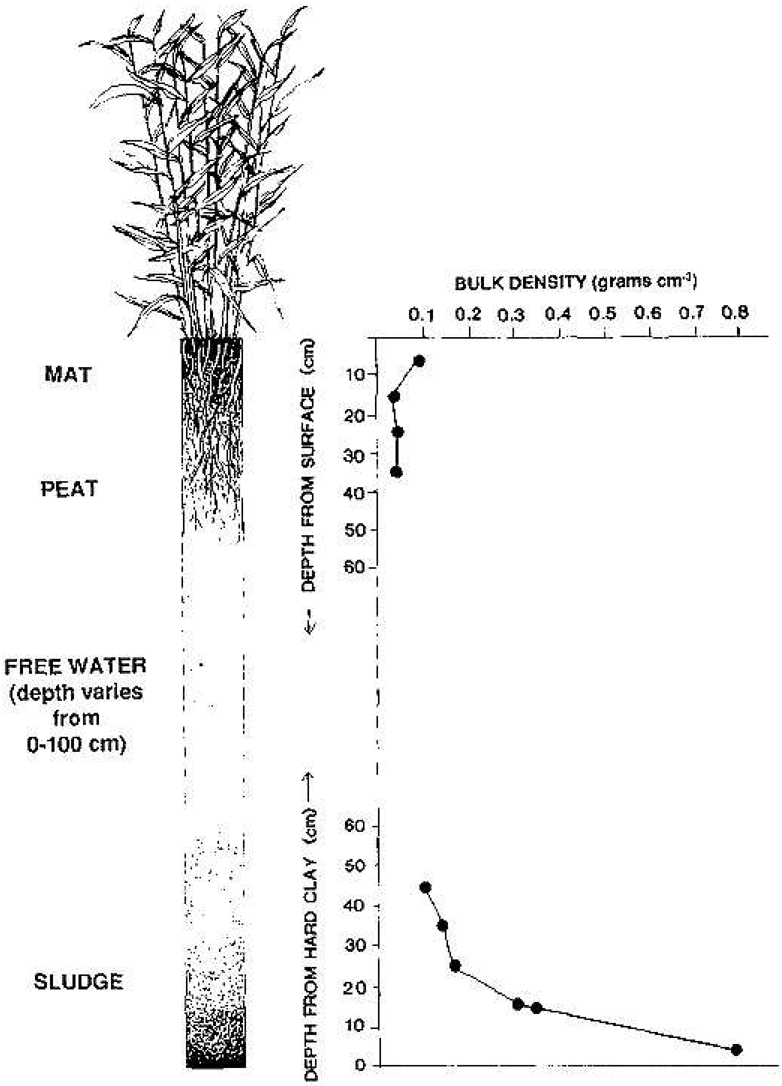
- Blockage of lake-access points, such as docks and boat ramps).
- Interference with recreation and navigation.
- Shading-out and displacement of desirable submerged and emergent vegetation.
- Increased organic matter content and decreased dissolved oxygen concentration under extensive mats leading to declining fish habitat.

Consequently, much work has been done in Florida to develop methods for the removal of floating wetlands in order to promote the expansion of bottom-rooted submerged vegetation (Mallision et al. 2001).

3.2 Structure of Natural Floating Wetlands

Sasser et al. (1991) examined vertical cores from a large natural floating marsh in Louisiana and derived a characteristic structural cross-section of a floating wetland as shown in Figure 5. The relative depths of the different zones have been found to vary at different sites depending on vegetation type and prevailing hydrologic conditions (Sasser et al. 1995b).

Figure 5.
Characteristic core cross-section through a natural floating marsh at Lake Boeuf, Louisiana USA (source: Sasser et al. 1991).



The floating mat varies in thickness from about 40 to 60 cm. In general, the upper 25-35 cm, termed the "mat zone", consists of a layer of densely intertwined live, dead and decaying roots with some litter collection on the surface (Sasser et al. 1991; Swarzenski et al. 1991; Sasser et al. 1995b). Below the active root zone a layer of decomposed peat and decaying plant detritus develops that clings to the overlying roots. This peat-like material typically has a lower bulk density than the older peat accumulations that occur in conventional peat bogs, probably due to a reduced degree of compression in the floating mats (Hogg and Wein, 1987; Sasser et al. 1995b).

Beneath the peat layer a zone of relatively clear free-water exists, that varies in depth with the lake/marsh water level. On the base of the wetland basin, beneath the free-water zone, a layer of organic sludge forms that changes with depth from a highly decomposed peat ooze at the free-water interface to a more compacted, but still highly decomposed, peat overlying the native subsurface material (often clay). The depth of the free-water zone (from the underside of the floating mat to the basin surface) in natural systems is typically between 1 and 2 m on average, but varies with water level (Azza et al. 2000; Sasser et al. 1991). In some cases, the free-water zone is not clear, but rather a column of turbid, organic ooze (Sasser et al. 1995b).

The combined mat and peat layers move vertically with changes in the water level. The boundary between the aerobic and anaerobic zones is typically less than 5 cm below the surface of the floating mat (Hogg and Wein, 1987). Swarzenski et al. (1991) report that it is the mat layer that provides buoyancy, while the peat layer contributes very little to flotation.

The study of Hogg and Wein (1987) on a *Typha* dominated floating marsh indicated that mat growth occurs mainly from within through deposition of below-ground organs (roots and rhizomes) rather than by accumulation of material at the mat surface. Unlike other wetland soils, the floating mat does not act as a sink for particulate matter contained in the water column below, but may in fact function as a source of particulate matter for the water column as organic matter detaches from the underside of the floating mat (Gantes et al. 2005).

The structure, composition and thickness of the floating mat can be affected by the growth habit and productivity of the dominant plant species. For example, Azza et al. (2000) reported that papyrus dominated mats consisted of a loosely structured, relatively thin raft of criss-crossing interconnected woody rhizomes, with the interstices filled by a dark-brown slurry of organic debris loosely held in place by dense outgrowths of adventitious and lateral roots. In an adjacent area dominated by *Miscanthidium*, the mat was more solid, compact and thicker, consisting of a very fine mesh of interlaced adventitious and lateral roots and root hairs tightly bound into a spongy mass. Azza et al. (2000) concluded that the looser structure of the papyrus mat allowed a freer exchange of water from the free-water zone into the mat, and therefore an enhanced capability for pollutant transformations, than in the denser mat of *Miscanthidium*.

The thickness of the floating marsh substrate (combined mat and peat layers) tends to reach a fairly stable equilibrium in natural systems, with reported thickness of around 50 cm being common (Hogg and Wein, 1987; Sasser et al. 1991; Swarzenski et al. 1991), although mats with a thickness of 1.2 m have been reported for *Miscanthidium* dominated wetlands in Lake Victoria, Uganda (Kansiime and van Bruggen, 2001). It seems that the mat and peat layers ultimately reach a maximum thickness, beyond which vertical accretion is balanced by the loss of peat-like organic material that detaches and falls from the bottom of the floating substrate. The ultimate thickness of a mat tends to be related to the maximum rooting depth of the vegetation, as the roots play an important role in binding the organic material together (Sasser et al. 1995b).

These counterbalancing processes which determine the equilibrium mat thickness may be obstructed in a floating treatment wetland where an artificial substrate, such as the Floating Islands International (FII) polyester matrix, is used for plant and flotation establishment. Although Hogg and Wein (1987) state that mat growth occurs predominantly from the accumulation of below-ground organs, the artificial matrix may provide a barrier against the downward migration of organic material that is deposited on the surface as plant litter. In a natural system, much of this material would eventually (over many years) migrate downwards into the peat layer, and ultimately become detached from the bottom of the floating mat and deposited in the benthic sediments. It is unclear what long-term effects a synthetic barrier may have on mat flotation and formation dynamics. In the short term, is likely to mean that the artificial floating wetland is characterised by free roots hanging below the matrix, rather than encompassed within a layer of floating peat as is the case in natural systems. In the longer-term, the accumulation of peat and moisture-retentive organic litter above the synthetic matrix may cause the floating wetland to sink progressively lower in the water column until it eventually becomes too heavy to maintain buoyancy. However, it may take a number of decades for such a condition to be reached, and therefore may not be of real concern in the context of a treatment system.

3.3 Formation and Buoyancy of Natural Floating Wetlands

In a natural floating wetland, self-buoyancy is maintained as a result of two main factors, as described by Hogg and Wein (1988a):

- the entrapment within the matrix of gases generated during anaerobic metabolism of organic deposits; and
- the occurrence of air spaces within the living biomass, particularly the rhizomes, of the vegetation.

The relative contributions of these two processes to the buoyancy of a particular marsh will vary depending on the plant species, age, growth-phase and methane generation rates from accumulated organic sludge. These processes will also tend to vary seasonally, due to the effect of temperature on metabolic activity and gas production, and the growth rate of the plants (Hogg and Wein, 1988a and 1988b). Thus, the processes contributing to mat buoyancy tend to be most active during summer (Swarzenski et al. 1991).

There are believed to be three main processes by which the development of natural floating wetlands is initiated (Clark and Reddy, 1998: cited in Somodi and Botta-Dukat, 2004; Ellery et al. 1990):

1. *The delamination/separation of unvegetated organic substrates or peat from the benthic detrital sediments which float to the water surface and become colonised by a variety of aquatic plants (post-emergence).* The floating peat mat provides ideal conditions for the germination of a range of wetland plant

species as it remains moist but rarely becomes completely inundated. These floating wetlands are usually small (< 2 m^2), isolated, mobile units (Ellery et al. 1990). Their formation may be favoured by shallow water conditions. Rates of encroachment across open water can be relatively slow. Flotation is primarily a result of methane entrapment within the peat mat. There has been considerable research into this process in The Netherlands in regards to regeneration of cut-over peat bogs (e.g., Smolders et al. 2002; Tomasse, et al. 2003). These studies have demonstrated that peat and groundwater quality are important factors, with flotation being enhanced by poorly humified (partially decomposed) peat and circum-neutral pH which favour methane production.

2. *The extension of positively buoyant plants out over open water from the edge of a channel or lake margin or from an unattached nucleus formed by floating aquatic vegetation.* Floating wetland formed in this way can exhibit rapid rates of encroachment across open water if suitable plant species are present (Ellery et al. 1990). The roots and rhizomes of the plants eventually bind together an organic peat-like mat which may trap methane and further enhance flotation and establishment of other plant species. Floating wetlands formed in this way can range from small fringing wetlands to extensive areas covering several hectares.
3. *The flotation of units of rooted vegetation and substrate that become separated from the benthic sediments often due to gradual flooding*. These can often form large areas of floating wetland.

In the context of artificially creating floating treatment wetlands, an artificial structure may only be necessary to provide flotation during the initial years to facilitate plant establishment until auto-buoyancy is achieved. This may mean that, in order to establish floating wetlands, simple or inexpensive materials could be used which are then either removed or decompose once the wetlands become established an attain self-buoyancy. However, it is important to realise that plant species selection is a critical factor in maintaining a self-buoyant floating wetland. Furthermore, auto-buoyancy is dependent on the generation of methane either within the sediments or the organic mat itself, which may not be achievable in all treatment applications. Whilst this shows promise, there is currently insufficient information available to adequately guide such an "assisted self-buoyancy" approach with the level of certainty that is required for most treatment applications.

3.4 Vegetation of Natural Floating Wetlands

Globally, a number of different species are known to have the ability to form or populate floating wetlands. Pioneer floating mat forming species include *Typha latifolia*, *T. angustifolia*, *Phragmites australis*, *Panicum hemitomon*, *Glyceria maxima*, *Carex lasiocarpa*, *Menyanthes trifoliate*, *Myrica gale*, and *Chamaedaphne calyculata*. Once formed, a floating mat typically becomes populated by a broad range of other wetland species that occur in the vicinity. For example, Sasser et al. (1995a) found a total of 45 different vascular plant species growing on a large floating marsh dominated by

Panicum hemitomon (maidencane), indicating that such systems can become quite important in terms of biodiversity.

The vegetation type plays a role in determining the structural characteristics and composition of natural floating wetlands. For example, Mallison et al. (2001) examined 116 natural floating wetlands in Florida and identified five main types based on vegetative characteristics and dominant taxa. Based on the physical characteristics of the floating mats, these could be grouped into two main classes:

- deeper mats containing larger amounts of organic matter in addition to plant roots, generally dominated by larger plant taxa (termed: "mud tussocks"); and
- shallower mats composed primarily of plant roots with little or no organic matter, generally dominated by smaller plant taxa (termed: "floating-type tussocks").

These authors also concluded that the composition of floating mats dominated by wetland grasses (*Sacciolepis striata* and *Panicum hemitomon*) or bur marigold (*Bidens spp.*) and smartweed (*Persicaria spp*) was approximately 75% live root and 25% organic matter. In contrast, the composition of floating mats dominated by *Typha* spp., Pickerelweed (*Pontederia cordata*), or facultative vegetation (occur in wetlands and uplands) was approximately 50% live root, 50% organic matter. The rooting depth of the predominant plant species is also a major factor in determining the thickness of the mat.

3.5 Water Quality Characteristics of Natural Floating Wetlands

3.5.1 Dissolved Oxygen

Sasser et al. (1991) reported consistently low dissolved oxygen concentrations (0.2-1.0 ppm) in the floating wetland mat and underlying free-water zone of a natural floating marsh in Louisiana. This would suggest that a dense cover of floating wetland over a pond will be more conducive to the generation of anaerobic conditions in the water column than an uncovered pond would be. The cover of floating vegetation provides a barrier against aeration due to wind, air diffusion across the air-water interface and excludes photosynthetic algae. The decomposition of organic matter sourced from the floating vegetation mat also acts to deoxygenate the water column.

3.5.2 Nutrients

Sasser et al. (1991) monitored the nutrient concentration within a natural floating marsh in Louisiana over a 16 month period, including the interstitial water within the floating mat. They reported that N and P concentrations within the floating marsh system were consistently higher than adjacent lake and sediment-rooted swamp water, and concluded that the floating marsh acted as a net exporter of nutrients. For example, both dissolved N and P concentrations in the free-water zone of the floating marsh were on average four times higher than in the adjacent lake water. They concluded that the mineralisation of and dissolution of the organic floating substrate and underlying sludge sediments were likely to be the cause of the elevated N and P concentrations in the floating marsh system. Their data indicated a seasonal pattern of highest free-water nutrient concentrations during summer when mineralisation of the floating organic mat and sludge deposits were highest, whilst P concentrations in the interstitial mat water tended to be highest during winter when plant uptake and microbial activity was lowest.

The study of Sasser et al. (1991) indicated that the seasonal return of elements to the free-water column may be more significant in a floating wetland system compared to a substrate attached wetland. This may be related to the fact that the plant root mat and associated peat deposits have a much greater potential for interaction with the water column. There is a high likelihood that any dissolved elements liberated from decomposing root or peat material suspended in the floating mat will return to the underlying water column. Furthermore, any floating plant or peat material has to pass through the free-water zone, where it may be washed from the system or re-mineralised, before it can reach the more permanently bound sink of the underlying sediments.

Sasser et al. (1991) summarised the likely pathways for N and P transformations and fluxes in a large natural floating marsh in Louisiana as follows:

- organic matter production by plants, death of plant parts and their incorporation into the floating mat, followed by N enrichment as the organic matter gradually descends through the mat to the peat zone and ultimately in to the sludge deposits on the underlying wetland floor;
- mineralisation and dissolution of the sludge and peat, producing high concentrations of TKN in the free-water zone;
- microbial immobilisation and translocation of NH_4-N from the root mat to the aerial plant tissue may create a vertical gradient of decreasing dissolved interstitial NH_4-N concentrations as you move up through the floating substrate.

These authors observed two gradients of the same nutrients within the same system. On one hand, the solid phase becomes enriched as it moves downward through the mat and is decomposed. This would be a long-term process operating on the order of tens to hundreds of years. On the other hand, the dissolved nutrients that are enriched in the free-water under the floating mat are drawn upward by the transpiration stream, and root absorption and microbial activity decrease their concentrations in the upper levels of the marsh substrate. The turnover rate for this part of the cycle would be more rapid and in the order of days or weeks. It is likely that similar patterns would exist for other elements.

Azza et al. (2000) reported that the concentration of NH_4-N decreased significantly moving vertically upwards from the marsh bottom through the free-water zone and into the dense mat of *Miscanthidium* dominated marsh. They concluded that this was due to a low permeability of the dense mat resulting in a greatly extended residence time within it. The same was not true for an adjacent area dominated by papyrus due to its looser mat and greater interaction between the free-water and the root mat. However, these results are confounded somewhat by the fact that the NH_4-N concentrations were approximately one order of magnitude greater in the free-water zone of the *Miscanthidium* site than at the papyrus site where concentrations were often close to apparent background levels. This makes a direct comparison between the plant species difficult.

3.5.3 Pathogens

Kansiime and van Bruggen (2001) estimated that a papyrus zone of the floating marshes of Nakivubo wetland (Uganda) were achieving a two log reduction in faecal coliform concentrations, whereas a *Miscanthidium* zone achieved a one log reduction. These authors concluded that morphological differences between the two species and their associated mats accounted for differences in pathogen die-off. They found that the finer, more roughly textured roots of papyrus resulted in a much greater number of faecal coliforms being attached to these root surfaces. The papyrus mat also had greater amounts of organic debris falling from the underside of the mat through the free-water column, providing additional surface areas for the attachment of faecal coliforms and subsequent sedimentation.

4 Floating Treatment Wetlands

4.1 Applications of Floating Treatment Wetlands for Water Quality Improvement

Artificially created floating wetlands have been used for a limited range of applications to date, such as water quality improvement, habitat enhancement (e.g., Burgess and Hirons, 1992) and aesthetic purposes in ornamental ponds. In terms of water quality improvement, the main applications have been for the treatment of:

- Stormwater (e.g., Kerr-Upal et al. 2000; Revitt et al. 1997).
- Combined stormwater-sewer overflow (e.g., Van Acker et al. 2005).
- Sewage (e.g., Ash and Troung, 2003; Todd et al. 2003).
- Acid mine drainage (e.g., Smith and Kalin, 2000).
- Piggery effluent (e.g., Hubbard et al. 2004; Ash and Troung, 2003).
- Poultry processing wastewater (e.g., Todd et al. 2003).
- Water supply reservoirs (e.g., Garbutt, 2004).

Plant roots are believed to play a major role in treatment processes within floating wetland systems by virtue of the fact that the water passes directly through the extensive root system hanging beneath the floating mat (Figure 6). Hence, one of the key pathways for contaminant removal in floating wetland systems is believed to occur via the sequential processes of release of extracellular enzymes, development of biofilms and promotion of flocculation of suspended matter, at the surface of the submerged plant organs (Oliveira and Fernandes, 1998). Other processes that may be important include plant uptake of nutrients and metals, enhancement of anaerobic conditions (and associated biogeochemical processes) in the water column beneath the floating mat, and promotion of settling and binding of contaminants in the sediment pool.

Figure 6.
Raised floating wetland showing the extensive root development beneath the floating mat. System pictured uses the AquaGreen™ floating mat produced by Bestmann Green Systems in Germany.

Case studies of the main floating treatment wetland applications to date are summarised below.

4.1.1 Treatment of Glycol Laden Stormwater at Heathrow Airport

Floating wetlands have been trialled at Heathrow Airport since 1994 for the treatment of stormwater runoff containing glycol derived from de-icing compounds. The main purpose of this system was for the removal of glycol and associated BOD. The site included two 3 x 5m floating reed beds, which were apparently constructed over tanks rather than ponds, and are pump-dosed from a balancing reservoir. Data pertaining to pollutant removal and microbial characteristics from the initial two years of operation are reported in Revitt et al. (1997) and Chong et al. (1999).

A full-scale system has subsequently been built at Heathrow airport which includes a 1ha rafted reed bed canal system (Figures 7-9) as part of the treatment train (Revitt et al., 2001; Richter et al., 2003). The rafts are apparently constructed from stainless and galvanized steel structures mounted atop floats. The floating wetlands are contained within a concrete canal system designed to optimise hydraulic efficiencies and promote plug-flow. The use of concrete and steel in the construction of the Heathrow system makes it a relatively expensive approach that is unlikely to be appropriate or cost-effective for stormwater applications. There is currently limited published data available on the treatment performance of this system.

Figure 7.
Full-scale floating treatment wetland system for removal of glycol from de-icing water at Heathrow Airport, UK.

Figure 8.
View of the floating rafts at the Heathrow Airport floating treatment wetlands.

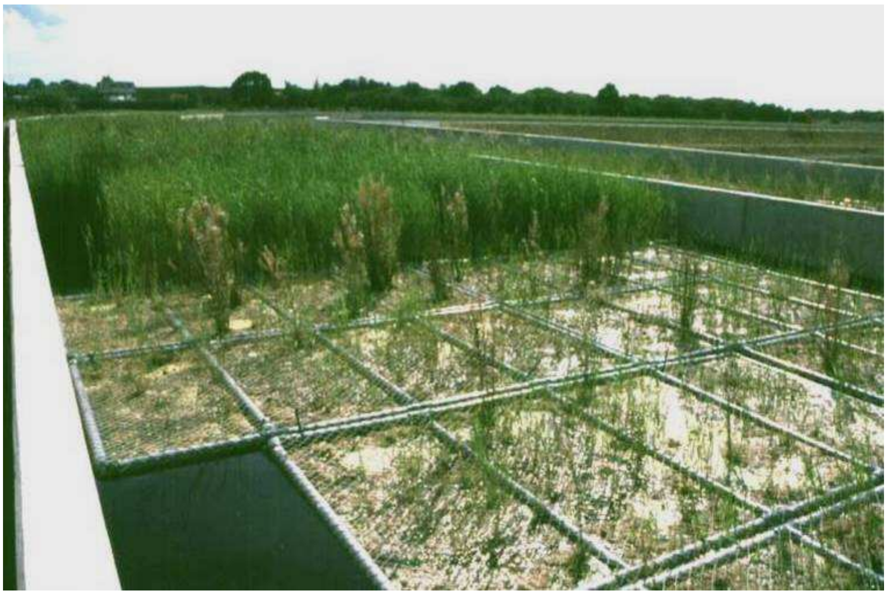


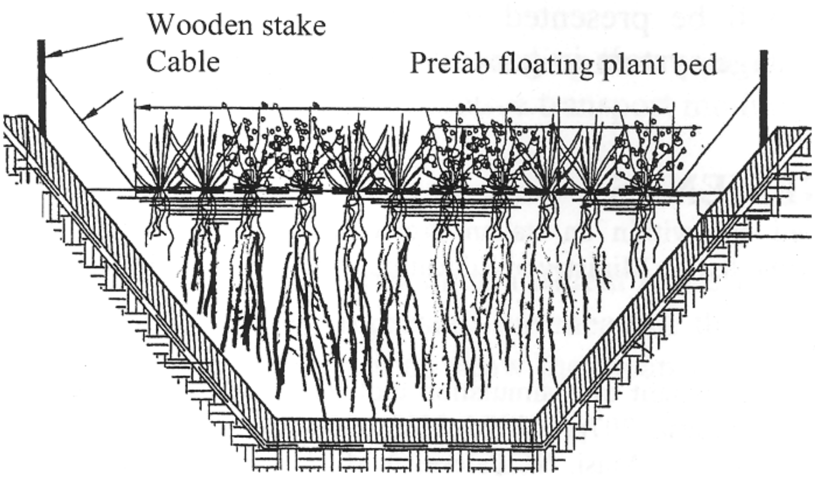
Figure 9.
Close-up of a section of raft within the Heathrow Airport floating treatment wetland system.

4.1.2 Treatment of Combined Sewer Overflows in Belgium

Van Acker et al. (2005) describe systems employed in Belgium by Aquafin for treatment of combined sewer overflows (Figure 10). This system is designed to deal with the variable, event-driven nature of combined sewer overflows and therefore has some structural and design elements that are of interest.

The first stage of the system consists of a sedimentation basin, lined with hardened bitumen, to reduce the energy of the incoming water and minimize the resuspension of settled sediments. Water then flows through a long basin that has near complete coverage of floating wetlands and is designed to enhance plug flow. A floating baffle prevents large floating debris from entering the floating wetland component of the system. The floating rafts were supplied by Bestmann Green Systems in Germany and consist of floating coconut fibre beams planted with sedges (Carex sp.), reed (Phragmites australis), bulrush (Schoenplectus latifolia), reedmace (Typha sp.) and yellow flag (Iris pseudacoris) (Figure 11). The fibre beams float with the aid of synthetic foam sections and polyethylene netting and are anchored to the sides of the basin. The system is designed to maintain a minimum water depth of 60cm to ensure that the plants do not dry out.

Figure 10:
Cross section of a floating wetland treatment system for treatment of periodic wastewater discharges from combined sewer overflows in Belgium.



Preliminary performance data showed removal of 33-68% COD, 66-95% SS, and 24-61% TP, but variable TN removal. During a visit in October 2005, it was noted that the water beneath the floating wetland was anaerobic, which is likely to be limiting nitrogen removal in particular. Most of the commercially available floating wetland systems incorporate mechanical or fine-bubble aeration systems to enhance aerobic treatment processes.

Figure 11:
Floating wetland rafts treating for combined sewer overflows at Bornem in Belgium (Photo C.C. Tanner October 2005).

4.1.3 Swine Wastewater Treatment

Hubbard et al. (2004) conducted a trial of floating wetlands for treatment of swine lagoon wastewater. They examined the nutrient uptake rates of three periodically harvested plant species (cattail, *Typha latifolia*; soft rush, *Juncus effusus*; and maidencane, *Panicum hematomon*) and concluded that vegetation can be successfully grown as floating mats in wastewater lagoons with periodic biomass removal, and that this technique can provide a means for animal producers to remove a portion of the nutrients from their wastewater lagoons. The study focused on plant uptake and did not report any wastewater nutrient concentrations.

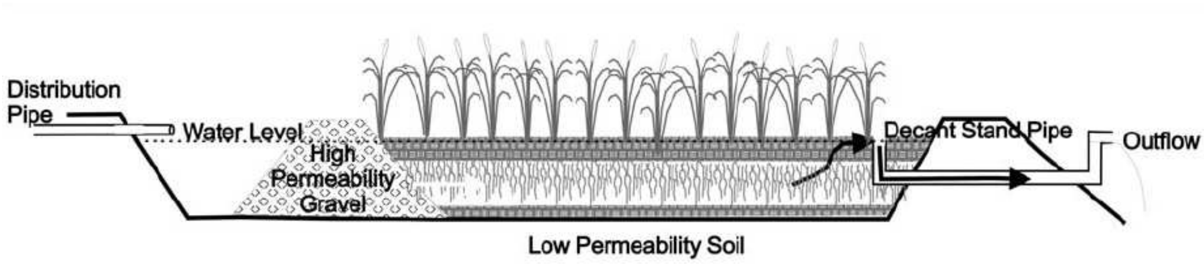
4.1.4 Acid Mine Drainage

Acid mine drainage (AMD) is formed when mining operations expose sulphidic minerals to oxygen and water. The oxidation of these minerals leads to acid formation and the mobilization of substantial amounts of metals and trace elements present in the parent rock. This process can continue long after mine closure. Hence, wetlands (including floating wetlands) have become an increasingly popular option for on-going, low-maintenance treatment.

Whilst mine drainage water often contains many of the same metals that are of concern in urban stormwater (e.g., copper and zinc), the concentrations of metals and sulphates tend to be much lower, and pH closer to neutral in stormwater when compared to mine drainage. This can lead to some important differences in the metal removal processes in wetlands used for these two applications. Nevertheless, some important and useful insights can be gained from the application of floating treatment wetlands for acid mine drainage treatment.

Smith and Kalin (2000) report data from a number of floating wetland systems using floating *Typha* mats for treatment of acid mine drainage and wastewater. The systems described are depicted in Figure 12. Smith and Kalin (2000) coin the term Floating Vegetation Mat (FVM) wetland to describe their approach. Initially developed for the application of metals, sulphate and acidity removal from acid mine drainage, the intention of the floating mat of vegetation in these systems is to provide a barrier against re-oxygenation of the water column in order to induce anoxia, and to provide a continuous source of organic carbon for biomineralization of metals in both the floating mat and bottom sediments.

Figure 12:
Cross-sectional schematic of floating wetland treatment system design for acid mine drainage as per Smith and Kalin (2000).



Smith and Kalin (2000) report of the following applications where floating vegetation mats have been trialled since 1989 in Canada:

- over flooded open pits excavated during a zinc/lead mining operation (ASARCO, Buchans, Newfoundland, Canada);
- over a test cell system for biological AMD treatment from nickel/copper tailings (INCO, Coppercliff tailings area, Sudbury, Ontario, Canada);
- over natural wetlands receiving run-off from a waste rock pile releasing nickel and arsenic (Cameco Corporation, northern Saskatchewan, Canada); and
- on an asphalt-lined settling pond for aluminium oxide and coke particle removal (Alcan, Kitimat, British Columbia).

The first three applications were for acid reduction and metals removal, whilst the last application was for suspended solids removal. These systems have proven to be a useful technology for retro-fitting onto existing acid mine drainage storage dams or tailings ponds in order to improve treatment efficiencies.

4.1.5 Floating Wetlands for Improving River Water Quality in India

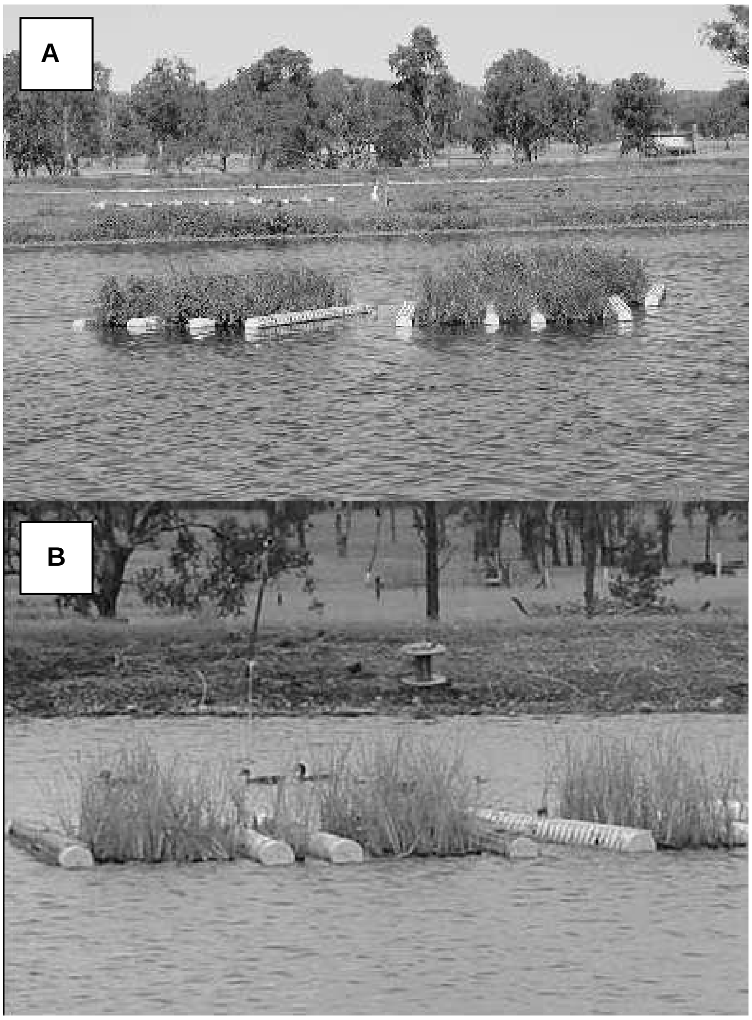
Professor Billore of Vikram University in Ujjain, India is currently conducting a research project into the use of floating wetlands to restore water quality to the holy River Kshipra. To date, a 200 m^2 of floating wetlands have been installed in the least turbulent part of the River Kshipra as a demonstration model (Figure 13). The floating rafts are constructed locally using low-cost materials such as bamboo. This project is the first innovation of this kind in India. No data has been published to date on the treatment performance of this system.

Figure 13:
Demonstration floating wetland installed on the River Kshipra in India.

4.1.6 Vetiver Grass Pontoon System for Treatment of Sewage and Swine Wastewater

In recent years, there has been an increasing interest in the use of floating wetlands planted with vetiver grass (*Vetiver zizanioides*) for the treatment of sewage and piggery effluent, although there is very little published literature on the subject in refereed scientific journals. One example of the application of this technology is at the Toogoolawah sewage treatment plant located in South-east Queensland, Australia, where floating wetlands planted with vetiver (termed the Vetiver Grass Pontoon System) have been retrofitted onto existing waste stabilisation ponds in order to improve the treatment performance (Ash and Truong, 2003). In this application, 21 vetiver pontoons (each 2.4 m x 2.4 m) were installed on three ponds (dimensions of ponds not reported) and planted with 300 individual plants per pontoon (Figures 14). The pontoons have reportedly caused an improvement in the nitrogen and phosphorus removal performance of the ponds. These systems seem to predominantly rely on the relatively high nutrient and metal uptake rate of this grass species for water quality improvement. Ash and Truong (2003) suggest that the number of pontoons required will depend on the required treatment performance, particularly if nutrient removal is the purpose.

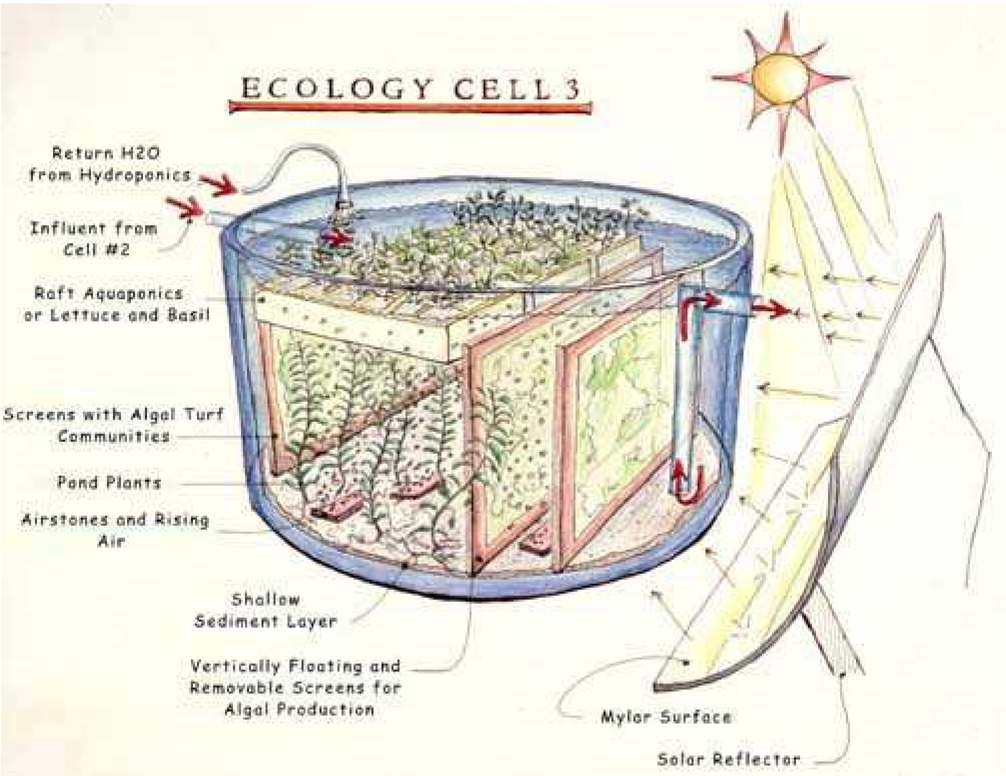
Figure 14.
Vetiver grass pontoons shortly after planting (**A**) and two months later (**B**) at the Toogoolawah sewage treatment plant, QLD, Australia (Source: Ash and Troung, 2003).



4.1.7 The Advanced Ecologically Engineered System ("Living Machine")

Floating wetlands and hydroponically grown plants are a key component of the Advanced Ecologically Engineered System (AEES) or "Living Machines" developed by John Todd and associates in the USA for the treatment of, and resource recovery from, sewage and other wastewaters (Todd et al. 2003). An AEES generally consists of a series of tanks consisting of a range of treatment elements manipulated to provide various conditions conducive to pollutant removal and resource recovery. The system includes a component where wetland and other vegetation are grown hydroponically on racks with the roots hanging in an aerated water column to provide diverse microhabitats for effective treatment (Todd et al. 2003), as depicted in Figure 15.

Figure 15.
Component of a typical Advanced Ecologically Engineered System containing floating vegetation.



4.1.8 The floating AEES Restorer system

Representing a further development of the AEES approach, the floating AEES Restorer is a linear floating wetland system that has been specifically designed to be retrofitted onto ponds (such as waste stabilisation ponds) in order to improve treatment performance (Figures 16 and 17). The AEES Restorer uses floating rafts with racks to support wetland vegetation, with the aim of incorporating constructed wetland processes into a pond system (Todd et al., 2003). The floating wetlands are configured in a way that creates a serpentine flow path through the system in order to optimise hydraulic efficiencies. These systems also include a textile curtain that hangs beneath the floating wetland rafts to act as fixed-film reactors. Fine bubble linear aerators are installed on the pond floor along the open water sections in order to create aerobic conditions and enhance mixing.

Figure 16.
Drawing of wastewater treatment pond fitted with floating AEES Restorers. The diagram shows the serpentine flow pattern through the AEES Restorer system and the fixed-film reactors installed beneath the planted Restorers. (Source: Todd et al. 2003).

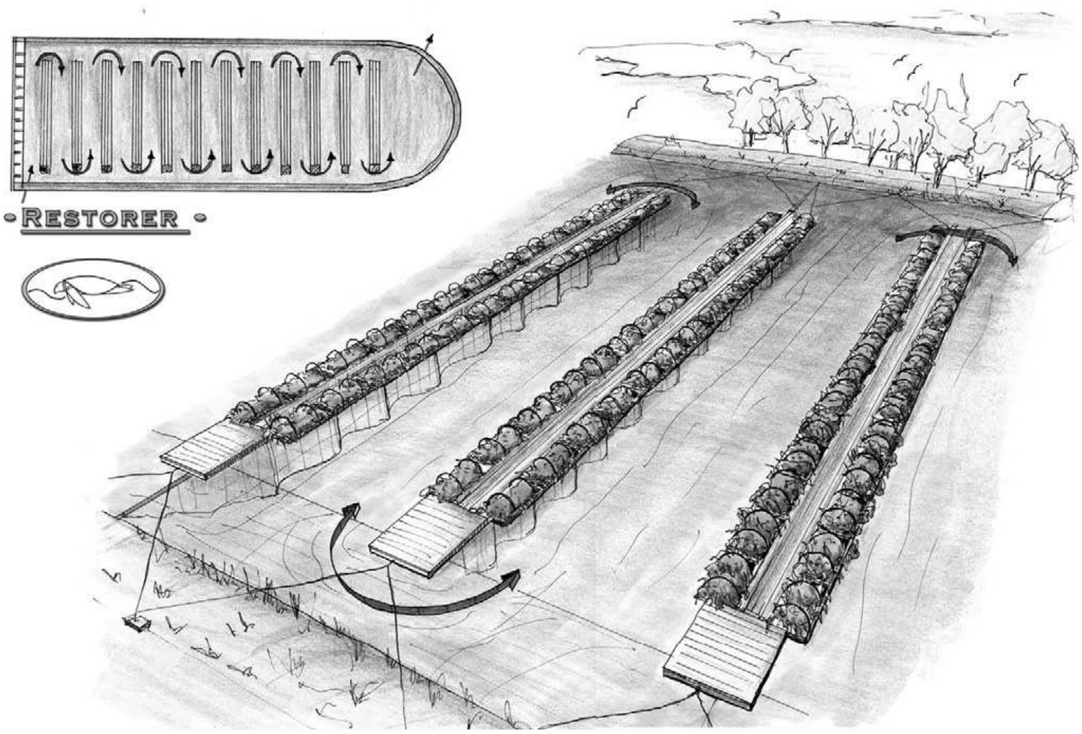
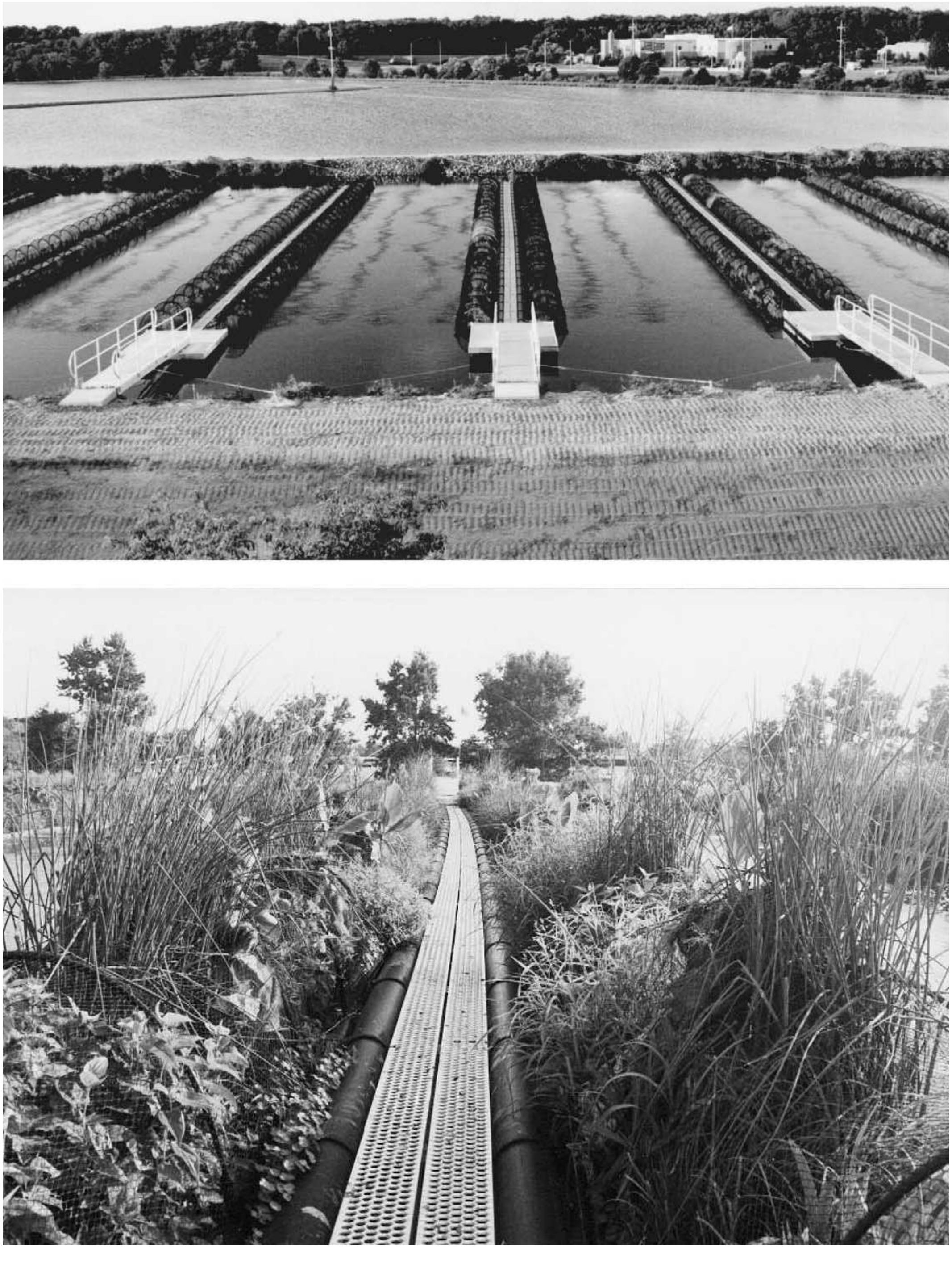


Figure 17.
Photographs of AEES Restorers in a poultry processing wastewater lagoon in Maryland, USA. **A** shows five of the 12 Restorers installed in sequence. Each Restorer is 5 m wide and 44 m long. Gentle linear aeration in the open water channels provides efficient mixing and aeration. The diverse plant communities are shown close-up in photograph **B**. Plant roots grow directly into the water column and provide the necessary surface area for efficient attached growth treatment. (Source: Todd et al. 2003).



Another example of the application of the floating AEES Restorer technology exists in southern China where a 500 m long Canal Restorer was installed in 2002 to treat a heavily polluted canal. As typical in this part of China, the canal receives raw sewage from approximately 12000 people and stormwater from the surrounding residential complex as well as municipal and commercial facilities such as a school, a temple, restaurants, and a car wash. Utilizing diverse local Chinese plants, the floating Restorer has transformed the sewage canal into an attractive floating garden (Figure 18). A synthetic fabric hanging below the floating Restorer provides additional surface area for attached growth bacteria. A low-intensity fine bubble aeration system distributes air along the canal which acts to both aerate the water and force dispersion of the water through the plant roots and synthetic fabric. A recirculation line is also fitted at the downstream end of the canal which returns a portion of the flow to the upstream end to prevent the short-circuiting of wastewater entering the canal near the outlet. Preliminary performance data indicated that the canal Restorer was successfully achieving secondary quality effluent standards, minimizing odor problems and dramatically improving the water clarity.

Figure 18.
Views of a floating AEES Restorer system installed in a polluted canal receiving raw sewage and stormwater in southern China.

4.1.9 Floats growing rooted procumbent macrophytes

Wen and Recknagel (2002) developed and trialled a planted float system for removal of dissolved phosphorus from irrigation drainage channels in South Australia. Their approach involved the use of artificial floats hosting rooted procumbent (having stems that trail along the ground) macrophytes (*Ludwigia peploides*, *Myriophyllum aquaticum*, *Paspalum paspalodes* and *Cotula coronpifolia*) which spread out over the water surface from the edges of the float. The system relies heavily on regular harvesting of the plant material. The study was conducted using small scale (10 cm x 25 cm) polystyrene floats in small troughs within a growth chamber. Thus, the usefulness of the results is limited by issues of scale.

4.2 Water Quality Characteristics of Floating Treatment Wetlands

This section provides an overview and discussion of the performance of floating treatment wetlands for water quality improvement applications. There is currently only limited published data available from floating treatment wetlands, none of which directly pertains to urban stormwater treatment.

4.2.1 Dissolved Oxygen

There is very little published data available on the effect of floating treatment wetlands on dissolved oxygen. Evidence from natural floating wetlands indicates that even under relatively oligotrophic (nutrient poor) conditions, the water underlying a floating wetland will typically be low in dissolved oxygen (e.g., Sasser et al. 1991). A number of factors are likely to contribute to the depletion of dissolved oxygen in the water column under floating wetlands. These include:

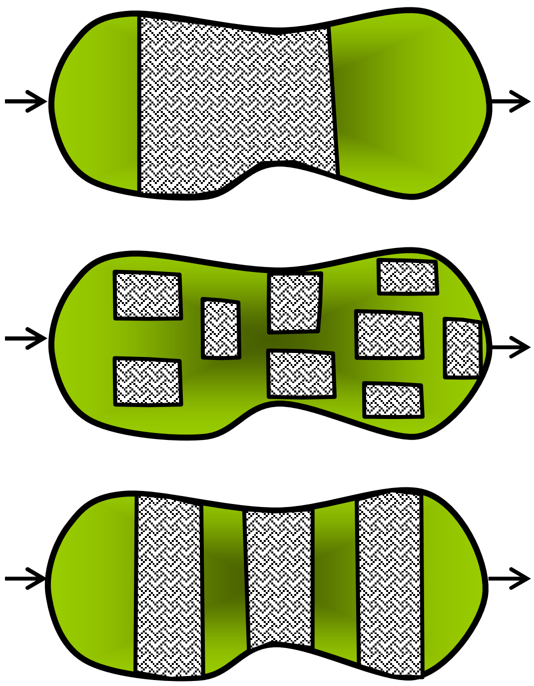
- The oxygen demand imposed by the regular supply of organic matter from the floating plant material.
- The elimination of re-oxygenation via photosynthetic algae due to exclusion of light by the floating mat.
- Minimal diffusion of oxygen across the air-water interface due to obstruction by the floating mat.
- The reduction in the turbulent introduction of air caused by wind and waves due to the protection provided by the floating mat.

Whilst low dissolved oxygen concentrations are beneficial for some treatment processes, such as denitrification and metal sulphide formation (discussed in a subsequent section), anoxic conditions are undesirable for other treatment processes and may impede healthy root development under the floating mat. It is for these reasons that many of the commercially available floating wetland systems for wastewater treatment, such as the Restorer system, include an aeration system on the bottom of the pond. In such wastewater applications, aerobic conditions are particularly beneficial for the decomposition of organic matter and for nitrification. In the context of stormwater treatment, the release into a natural waterway of anoxic water from a treatment system will generally be unacceptable.

The use of active aeration in a stormwater treatment system may not always be practical or desirable. An aeration system requires electricity and adds additional operational complexity to what are typically passive systems. The use of air diffusers also increases mixing and turbulence which may impede sedimentation processes and possibly lead to the re-suspension of contaminants contained within the sediments.

A more passive approach for introducing oxygen into the water column may be to include open water sections throughout or following a floating treatment wetland system, thereby facilitating the processes of algal photosynthesis and diffusion. In this way, the manipulation of the ratio of pond to floating wetland coverage may be an important design parameter for controlling the dissolved oxygen status of the water. Open water zones could be incorporated into the design in various ways, as illustrated in Figure 19. Another option could be to include a re-aeration cascade at the outlet of the stormwater treatment device.

Figure 19.
Aerial view of three different design approaches for achieving a mixture of pond and floating wetland coverage in a stormwater detention basin. The cross-hatched areas represent floating wetlands, whilst the green shaded areas represent open water zones.



4.2.2 Oxygen Demanding Substances

Revitt et al. (1997) found that the pilot-scale floating treatment wetlands at Heathrow Airport performed poorly in terms of BOD removal. However, the mean influent BOD concentration was 5.5 mg/L and therefore close to the probable background concentration for such a system. The systems achieved a mean COD concentration reduction of 31%. The authors hypothesised that COD removal occurred through the process of filtration of particulate organics by the root system hanging beneath the rafts.

4.2.3 Nutrients

The Heathrow Airport pilot-scale floating wetlands did not perform as well as adjacent subsurface and surface flow wetlands in terms of NH_4, NO_3 and PO_4 removal during the first year of operation (Revitt et al., 1997). The poorer P removal performance of the floating wetlands (relative to the other wetland systems) may be partly due to the lack of a substrate for sorption of PO_4. It is unclear from the paper of Revitt et al. (1997) whether the different wetland technologies being trialled were receiving equivalent loading rates, which makes it difficult to derive clear conclusions from the comparative performance.

Kansiime et al. (2005) conducted a mesocosm study of the nutrient removal performance of floating papyrus plants receiving secondary treated sewage in Uganda. The plants were grown in 30 L buckets and batch fed effluent every seven days. TN and NH_4-N concentration reductions stabilised at approximately 80-90% after 15 weeks of growth, whereas the mean percentage reduction of TP and ortho-phosphate stabilised at approximately 70-80% after 21 weeks of growth. The nutrient removal performance of floating papyrus generally exceeded that of papyrus rooted in gravel substrate. Floating plants displayed greater root development than the same plants grown in gravel, with the authors estimating that floating plants developed a larger root surface area (ca. 422,000 cm^2) than the plants rooted in gravel (ca. 207,000 cm^2).

Sekiranda and Kiwanuka (1998) conducted a similar mesocosm study to that of Kansiime et al. (2005), except they examined the nutrient removal performance of floating and gravel-rooted *Phragmites mauritianus* in 40 L buckets receiving daily pulses of anaerobic sewage treatment pond effluent to achieve an average residence time of 5 days. An operating water depth of 0.3 m was maintained and the flow regime was operated in a vertical up-flow configuration. There was generally very little difference between the gravel-rooted and floating mesocosms in terms of nitrogen removal, with both systems achieving greater than 97% reduction in the concentration of NH_4-N. However, control buckets without plants or gravel also achieved high removal of NH_4-N (92.5%). In contrast to Kansiime et al. (2005), Sekiranda and Kiwanuka (1998) found that the gravel rooted systems achieved a significantly greater reduction in TP and PO_4-P concentrations than the floating *P. mauritianus* mesocosms. This difference was reportedly due to a greater amount of P associated with plant biomass in the gravel-rooted plants.

Floating treatment wetlands (termed Artificial Floating Meadows) have been trialed in Hungary for removal of nutrients from lake water (Gulyas and Mayer; 1993 cited in: Lakatos, 1998). A pilot experiment was conducted using water from the Danube River with additions of 5 mg/l of NO_3^--N and 2 mg/l of reactive phosphorus. The retention time in the artificial floating meadow was two weeks. Final results indicated that the floating meadow removed 85% of the total nitrogen content. However, phosphorus removal was poorer at 40%. In addition, with the onset of winter and colder temperatures, the efficiency of both nitrate and phosphate removal was reported to decrease.

4.2.4 Suspended Solids

Smith and Kalin (2000) measured the mass of solids trapped amongst roots of a two year old floating *Typha* vegetation mat on an acid mine drainage pond. They reported that 0.29 kg of solids were trapped per 15 m^2 of root surface area per m^2 of FTW during the second growth year. This equates to 0.02 kg of solids trapped per m^2 of root surface area. Using root surface area data from a seven year old system (114 m^2 root surface area per m^{-2} FTW), the authors estimated that a mature system would capture approximately 2.2 kg of solids per m^2 of floating vegetation. This would account for 37% of the annual load of SS received by the pond under investigation, assuming complete coverage of the pond with floating vegetation mats. They postulate that the actual long term trapping of suspended solids would be substantially higher than that estimated from a single measurement, given that trapped solids would be periodically sloughed from the roots and settle to the bottom of the pond, thereby opening up more root surfaces for entrapment.

4.2.5 Zinc

In the study of Revitt et al. (1997), the average concentration of zinc (Zn) in the effluent from the pilot scale floating treatment wetlands at Heathrow Airport was greater than that of the influent during the first year of operation. The authors did not comment on why the floating wetlands acted as a source of zinc. One possible explanation may be the release of zinc from galvanised metals if significant amounts of these materials were used in the floating structures.

4.2.6 Copper

The mean copper (Cu) removal efficiency achieved by the Heathrow Airport pilot scale floating treatment wetlands was 20-30% during the first year, which was comparable to the adjacent surface and subsurface flow wetlands (Revitt et al. 1997).

4.3 Comparison of Floating Treatment Wetlands with conventional stormwater ponds and other wetland systems

Floating treatment wetlands possess a number of important structural and functional differences to ponds and conventional sediment-rooted wetlands. Some of these are depicted in Figures 20 and 21.

Ponds are typically designed to exclude rooted vegetation. They are generally effective at removing suspended solids through sedimentation, although less effective at removing dissolved and colloidal pollutants. Ponds can also provide ideal conditions for the growth of algae. Although providing some beneficial functions in terms of pollutant processing, excessive algal growth can lead to a decline in water quality through the resurgence in the concentration of suspended solids and organic matter in the water.

Conceptually, a floating treatment wetland can be considered as a pond with a mat of wetland vegetation floating over the top of it (Figure 20). The inclusion of a floating wetland over the pond surface provides a barrier against light penetration into the water column, thereby limiting the potential for algae growth.

One of the main advantages of floating treatment wetlands over conventional sediment-rooted wetlands is their ability to cope with the variable water depths that are typical of event-driven stormwater systems (Kerr-Upal et al. 2000). A significant problem encountered with stormwater treatment wetlands is the die-back of rooted vegetation if water levels remain high for extended periods of time, or scouring channels develop during peak flows. In order to overcome these problems, wetlands often need to be relatively large to provide sufficient hydraulic buffering and maintain shallow water depths in the range of 0.3 - 0.5 m (Figure 21). The ability of a floating wetland system to instantaneously adjust to fluctuating water levels overcomes these issues and facilitates the creation of a wetland based system with a greater water depth. For example, many of the floating treatment wetlands encountered in the literature were designed to maintain a minimum water depth of 0.6 m or greater in order to ensure that they don't dry out completely. Such water depths would eventually drown sediment-rooted vegetation in a conventional wetland.

By deepening the wetland, the effective volume of the treatment system is increased which has the effect of increasing the length of time that water spends within the system (the "retention time"). For many pollutants, particularly those involving time dependent chemical or biological reactions, the retention time plays an important role in determining the level of treatment. Thus, the ability of floating treatment wetlands to operate at greater water depths than conventional wetlands may mean that they are capable of achieving a higher level of treatment per unit surface area (increased areal efficiency).

It is conceivable that plant assimilation of nutrients and other elements, such as metals, may be higher in a floating wetland system compared to a sediment-rooted wetland, as the roots hanging beneath the floating mat are in direct contact with the stormwater to be treated. Furthermore, the plant roots are not in contact with the bottom sediments or soil and only have access to nutrients contained within the floating mat and in the water column, much like a hydroponic cultivation system. This is in contrast to a sediment-bound wetland where the plant roots acquire nutrition directly from the soil matrix.

Figure 20.

Cross-section of a typical floating treatment wetland and pond showing main structural elements.

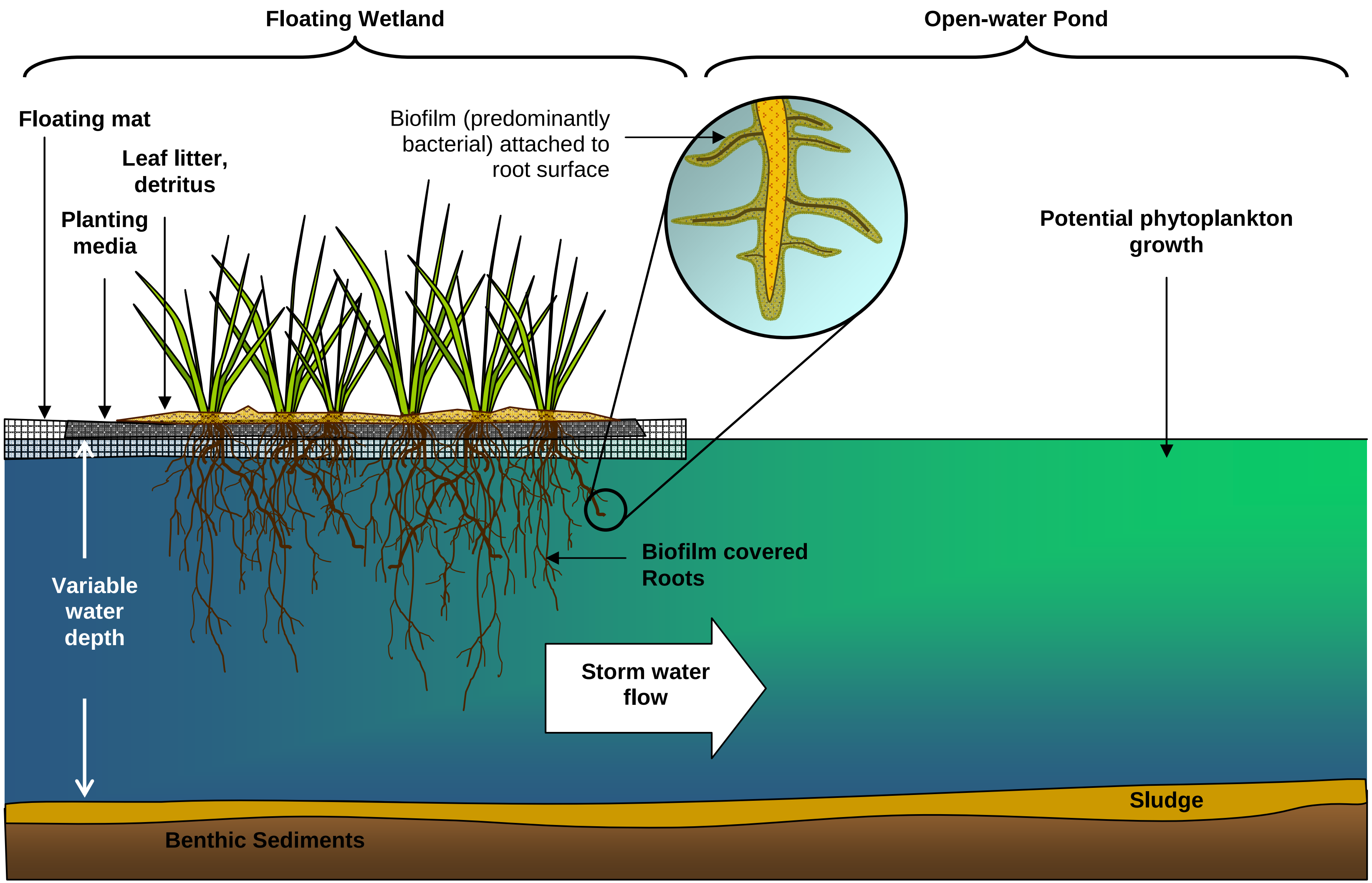
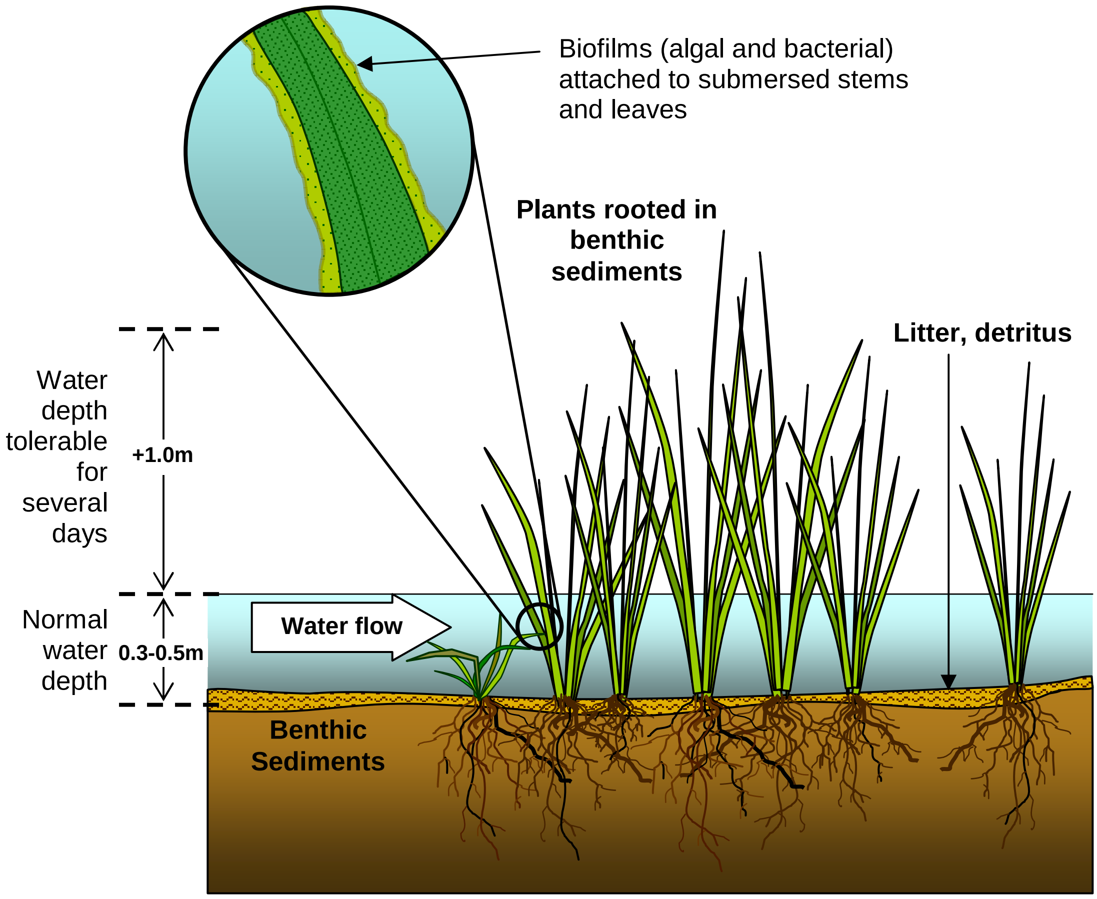


Figure 21.
Profile of a typical sediment-rooted surface flow wetland showing key structural elements and water depth requirements.



Differences are also likely to develop in the dominant attached growth microbial communities in floating treatment wetlands when compared to sediment-rooted surface flow wetlands. As depicted in Figure 20, the biofilms that develop on the plant roots hanging beneath the floating mat are likely to play an important role in treatment. Due to the exclusion of light under the floating mat, these root biofilms are likely to be predominantly bacterial. By contrast, the biofilms that establish on the stems and leaves of plants in a surface flow wetland are likely to include algae, periphyton and bacteria. By contrast again, the microbial community in an open-water pond system is likely to be dominated by planktonic species of algae and bacteria. These differences are likely to have an effect on the removal efficiencies and pathways of certain contaminants.

In comparing the floating wetland approach with the more conventional constructed wetland and pond designs, Kalin and Smith (1992) and Smith and Kalin (2000) report that the following conditions are created within floating wetlands which are conducive to the removal of suspended solids:

- Minimal turbulence and elimination of particle re-suspension by wind-driven water circulation.
- Laminar flow in the open water pathway between the floating mat and the pond bottom.
- More effective utilisation of wetland volume, including greater realised residence/particle settling time.
- Self-renewing root matrices intercepting, absorbing then sloughing heavy particles that will settle more easily.
- Large sediment storage capacity in system which can be easily dredged without excessive damage to plant system.
- The floating vegetation mat provides a barrier against re-oxygenation of the water column, inducing anoxia, and providing a continuous source of organic carbon for the biomineralisation and stabilization of particular elements, such as metals, in the sediments (this aspect may or may not be beneficial, depending on the application).

Depending on the materials and structure used, floating wetlands are particularly suitable for modular applications, where the number (and % coverage) of floating wetlands can be easily increased in order to improve treatment performance if necessary (providing sufficient basin area is available). The benefits of modular expansion would be particularly beneficial for the upgrading of sewage treatment ponds as the population being served gradually increases over time.

Floating wetlands may be perceived to enhance the aesthetic values of a stormwater treatment pond, depending on the shape, structure and vegetation used. There may also be some additional benefits in terms of provision of habitat for wildlife, such as birds. A floating wetland can provide protection for birds against some predators. However, the attraction of wildlife may also have deleterious effects on water quality through the introduction of faecal material, nutrients and disturbance.

4.4 Floating Treatment Wetland Construction Methods and Materials

A wide range of materials have been used to date in the construction of floating wetlands. Kerr-Upal et al. (2000) suggest that the following factors should be considered when determining the materials and construction methods used in creating floating wetlands:

- durability
- functionality
- environmental sensitivity
- weight
- buoyancy
- anchoring
- flexibility, and
- cost.

Typically, in floating treatment wetlands, buoyancy is provided artificially through the use of a floating structure or raft which supports the growth of the plants. For example, Floating Islands International inject expanded polystyrene foam into their polyester matrix in order to provide the desired level of buoyancy. In other applications, sealed PVC or PP pipes, polystyrene sheets, bamboo or inflatable vinyl pillows have been used to provide flotation. In general however, there are two main approaches that have been adopted:

- The construction of a buoyant frame that supports some sort of mesh on which the plants grow.
- The use of a buoyant material which itself serves to support the growth of the plants.

A third approach that warrants consideration is to create conditions that facilitate the development of an auto-buoyant plant mat. This may involve the provision of small buoyant structures that support the initial development of appropriate plants species that have an affinity for creating auto-buoyant mats such as appropriate plants species that have an affinity for creating auto-buoyant mats such as *Typha* spp.

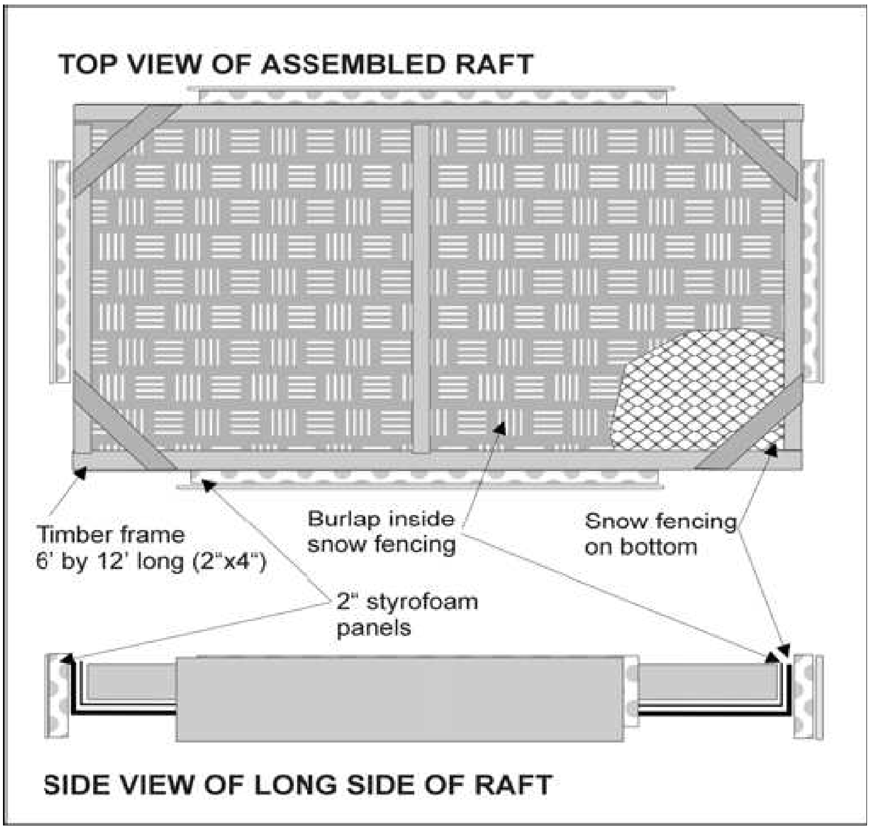
Generally, the most common approach involves the creation of a floating raft or pontoon that consists of a buoyant frame enclosing a permeable material into which wetland vegetation can be planted and establish. In many cases, a floating frame is constructed using sealed lengths of PVC or other plastic pipes. These may be joined together to form a buoyant square or rectangular frame, or used as individual linear sections that are connected in some other way to form a floating frame. There are a number of companies in the UK, such as ARM Reedbeds Ltd, who custom manufacture such systems for treatment applications.

Kerr-Upal et al. (2000) report of other applications where rafts have been made from iron and/or timber frames supported by sealed plastic float tanks (Pyrovetsi, 1997) or Styrofoam (Fager and York, 1975).

Hubbard et al. (2004) conducted a trial in which they constructed 1 m^2 floating platforms using PVC pipe, chicken wire mesh and fibrous matting material. Each frame consisted of an outer square and an inner "t-cross" made from PVC pipe. Chicken wire and fibrous matting was then attached to the sides and supported by the middle t-cross.

The Floating Vegetation Mat (FVM) systems described by Smith and Kalin (2000) consisted of 2.4 m by 4.8 m frames constructed from timber with plastic snow fencing or fish netting stapled across the bottom to support the developing vegetation mat (Figure 22). Styrofoam and plywood panels were attached to the sides in order to provide artificial buoyancy necessary for the first two to three growing seasons before the mat became thick enough and had trapped sufficient gas volume to become auto-buoyant. Rafts were lined with burlap in order to hold the growth medium during the first growing season until wetland plants became established.

Figure 22.
Design of floating treatment wetland structure using buoyant frame and suspended mesh (source: Smith and Kalin, 2000).



Hoeger (1988) described rafts designed (in Germany by the predecessor of the Bestmann Green Systems company) as 2.1 m equilateral triangles enabling them to be connected to form a wide range of shapes and sizes. These rafts were constructed of polyethylene, polyurethane and neoprene materials welded together (no additional details provided). Today, Bestmann Green Systems produce a range of floating wetland products collectively marketed under the AquaGreen™ product name. They still produce the equilateral triangle system, termed "Floating Wetland Islands", although the floating frames are now manufactured out of welded stainless steel and have a side length of either 3 m or 6 m (Figure 23).

Figure 23.
The equilateral triangle design of the AquaGreen™ Floating Wetland Islands manufactured by Bestmann Green Systems in Germany. (photo: BGS catalogue).

Van Acker et al. (2005) describe a system employed in Belgium for combined sewer overflow treatment that was supplied by Bestmann Green Systems. These comprise thick coconut fibre mats supported by polyethylene nets and polystyrene foam. This product was an early incarnation of what is now marketed under the name of AquaGreen™ "Floating Wetland Blanket" (Figure 24). The Belgium system was planted with sedges (*Carex* sp.), reed (*Phragmites australis*), bulrush (*Schoenplectus latifolia*), reedmace (*Typha* sp.) and yellow flag (*Iris pseudacoris*). Bestmann Green Systems often supply the Floating Wetland Blankets pre-planted with wetland vegetation that has been established in the nursery so as to ensure optimal plant establishment.

Figure 24.
Floating wetland rafts treating periodic wastewater discharges from combined sewer overflows at Bornem in Belgium.

The UK based A.G.A. Group have developed a rather elegant approach using a modular system of square units (termed “Eco-Islands”) that can be joined together to form floating wetlands of varying size and shape (Figures 25-26). The floatation booms are manufactured from UV protected High Modulus Polyethylene with welded ends which incorporate a fixing system to join the individual booms and the modules to form larger floating wetlands (Figure 27). A base is constructed out of 3 mm bezinal coated wire that supports vegetated coir (coconut fibre) pallets. Hardened plants that have pre-matured in the coir pallets are typically used to improve the resilience and speed of establishment of the plants.

Figure 25.
Single Eco-Island being deployed with pre-established plants (A.G.A. Group).

Figure 26.
Several Eco-Island units joined together to form a large floating wetland (A.G.A. Group).

Figure 27.
Close-up of buoyant booms and fixing system used in construction of Eco-Island floating wetlands (A.G.A. Group).

In India a low-cost method of floating wetland construction has been developed using locally available resources. Floating rafts are constructed using lengths of large diameter bamboo interwoven with mats of natural fibre (Figures 28-30). The articulated nature of the bamboo means that it contains sealed chambers of air throughout the stem which are naturally buoyant. Although these systems may degrade after several years, it is likely that the vegetated mat will have attained auto-buoyancy by that time, particularly if appropriate plants are used.

Figure 28.

Floating wetland rafts constructed from bamboo and mats of natural fibre in India.

Figure 29.

Floating wetland rafts being deployed in the Kshipra River in India.

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Figure 30.
Underside of a floating wetland raft in India showing early root development and trapped solids.

A number of other approaches have been specifically developed that deviate away from the conventional approach of constructing a floating frame that supports a substrate for planting. These novel approaches incorporate buoyancy within the matrix into which the vegetation is planted, and tend to come ready-made.

Floating Islands International (FII) have developed a floating wetland system comprised of non-woven coarse polyester fibre matrix injected with polystyrene foam to form a floating platform (Figures 31 and 32). Plant roots and rhizomes can spread and grow through the matrix, with their roots extending down into the water below (Figure 33). The matrix can also incorporate various plant growth media and potentially also reactive/sorptive media (e.g., zeolites or P-sorbing materials) to promote contaminant removal.

The matrix is made from recycled PET bottles (e.g., carbonated drink bottles) and is similar in structure to commonly available kitchen scourer pads. The material used by FII is pigmented brown to give it a natural appearance. Its open, fibrous structure results in a low density flexible matrix with high surface area and porosity (>90%). Marine-grade polystyrene foam is used to bond together between two and four 50 mm thick layers of the matrix material (which on its own is slightly negatively buoyant) and provide the required level of buoyancy. Alternative floatation devises such as polystyrene foam blocks, and gas-filled tanks and pipes could also be employed.

An increasing number of these FII floating wetlands are being deployed in North America on ornamental ponds and to provide improved habitat for birds and fish

(Figure 34). Trials are currently underway in New Zealand to identify suitable native plant species for stormwater treatment applications (Figure 35).

Figure 31.
Small (~0.18 m^2) FII floating islands produced for use in domestic ornamental ponds. The island is comprised of 2-4 50 mm thick layers of non woven polyester mesh sheets injected with marine polystyrene to provide buoyancy and bond the layers together.

Figure 32.
Larger (~2.3 m^2) FII floating island produced for ornamental pond use. Showing injected patches of marine polystyrene and pockets cut out to hold growing media.

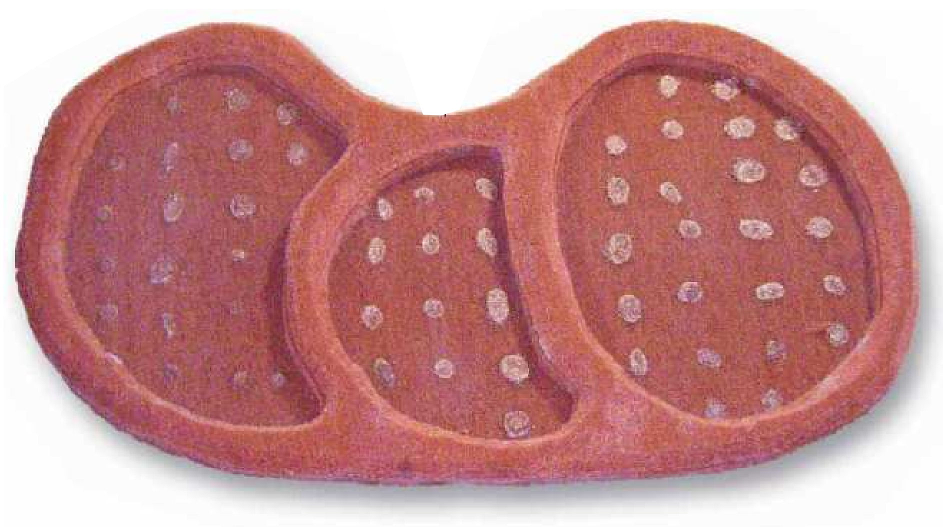


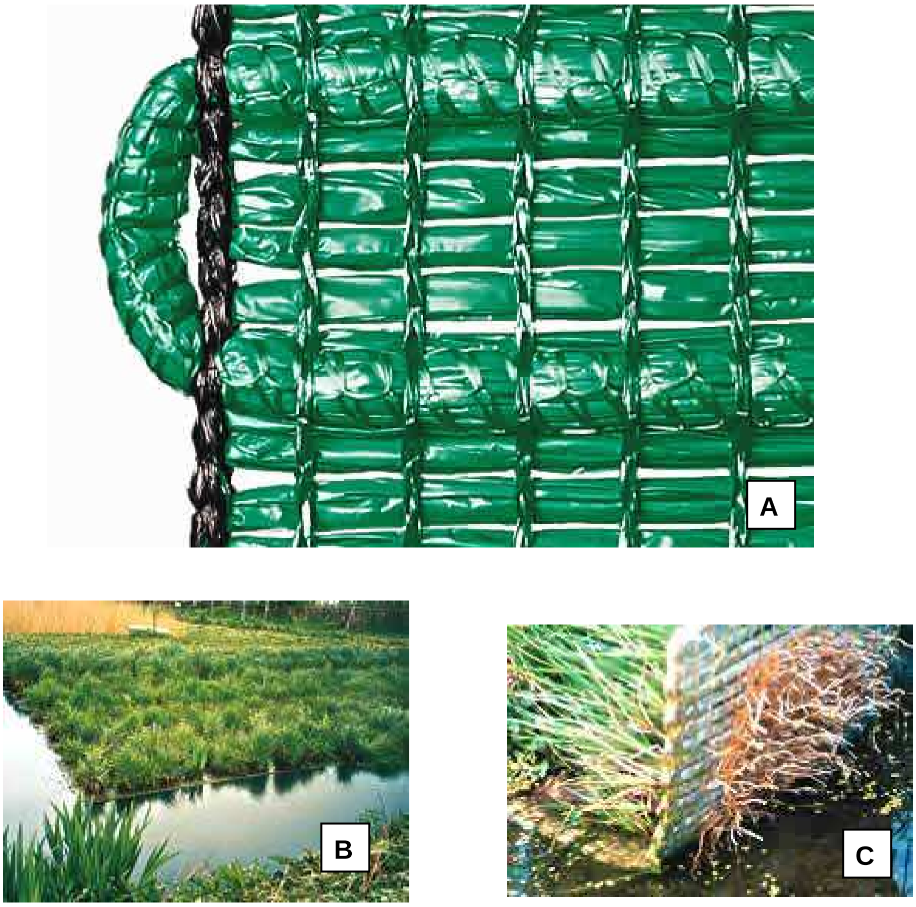
Figure 33.
Small planted FII unit showing extensive root development beneath the matrix.

Figure 34.
FII Floating wetland deployed in an ornamental lake in Montana USA to enhance water quality and aesthetics.

Figure 35.
Small Floating Islands International unit planted with a range of native New Zealand sedges and rushes.

Another product using intrinsic floatation within the planting matrix for creation of floating wetlands has been developed by Bestmann Green Systems using materials manufactured by the Huck Group in Germany. Their product, termed “Repotex-I”, consists of a coarse woven buoyant textile matting (Figure 36). Buoyant materials are woven into the matting which directly supports the growth of plants. These systems have been deployed in Germany for water quality enhancement purposes.

Figure 36.
Close-up of the woven structure of the Repotex-i mat (A) manufactured by the Huck Group and marketed by Bestmann Green Systems in Germany and used for floating wetland creation (B). Root penetration can be seen in C.



5 Processes Relevant to Copper and Zinc Removal from Stormwater in Floating Treatment Wetlands

5.1 General metal removal performance of wetlands

Natural and constructed wetlands can be very effective sinks and/or transformers of metals and metalloids (Dunbabin and Bowmer, 1992; Gambrell, 1994; Horne and Fleming-Singer, 2005; Kadlec and Knight, 1996; Odum, 2000). Data for a range of natural and constructed wetlands receiving municipal wastewater or urban run-off shows concentration reductions of 38–96% copper and 42–96% zinc with mass removals up to 8.2 g copper and 11.2 g zinc m^{-2} yr^{-1} for large-scale systems (Kadlec and Knight 1996).

Much of the metal contaminants in urban stormwater are associated with fine particulate matter (Timperley et al. 2001). Constructed wetlands are generally considered to provide better conditions for removal of fine sediment fractions and associated contaminants from urban stormwaters than detention pond systems (Bavor et al. 2001; Wong et al. 1999). Results specifically for metal removal in stormwater treatment wetlands are relatively limited. Scholes et al. (1998) reported ~100% zinc removal and 92% copper removal during a storm event for an urban stormwater treatment wetland in the UK. More recent UK studies of road runoff treatment in a wetland system over two storm events (Shutes et al. 2001) showed 75 and 40 % removal of suspended solid loads, and 60 and 66% removal of zinc loads, but negative removal of copper (88 and 97 % increases in load). Pontier et al. (2001) found variable water quality and contrasting spatial distribution of copper and zinc accumulation in the sediments of two similar wetland systems on the same highway, suggesting quite variable behaviour for these systems. Birch et al. (2004) reported an average removal efficiency of 65% for copper and 52% for zinc for a wetland in a residential catchment in Sydney. Results summarised by Strecker et al. (1992) also show instances of negative removal (generation) of both copper and zinc for constructed wetland treating urban stormwaters, although median removals were around 40%.

Studies of metal removal performance for constructed stormwater treatment wetlands in Auckland have shown that wetland systems can be highly effective for removal of priority metals from urban stormwaters. Leersnyder (1993) reported 92% and >99% copper and 99% and 90% zinc removal, respectively, for the Pacific Steel and Hayman Park pond/wetland systems, which were only partially vegetated. Hickey et al. (1997) reported concentration reductions for the Unitec stormwater wetlands of 62-96% soluble copper and 67-94% total copper, and 69-85% soluble zinc and 81-92% total zinc before they were fully vegetated. In a more recent evaluation of this system with full vegetation cover Larcombe (2002) reported mass removals of 29-97% soluble copper and 56-93% total copper, and 81-99 % soluble zinc and 69-95% total zinc for 9 monitored storm events.

Wetlands have also been used extensively for de-acidification and metal removal from acid mine drainage (Brenner, 2001; Kalin, 2001; Sheoran and Sheoran, 2006). These systems tend to be designed for subsurface-flow and may incorporate limestone media and organic-rich substrates to increase alkalinity and promote sulphide reduction. However, information from these systems is considered to be of only limited relevance to urban stormwater treatment because of the significantly different chemistry and highly elevated metal concentrations common for AMD.

5.2 Forms of Metals in Wetland Environments

Metals are distributed amongst several phases and forms within aquatic ecosystems, which have varying levels of toxicity and mobility. Metals associated with stormwater, such as copper and zinc, exhibit partitioning between aqueous and solid phases via various physical, chemical and biological interactions. New Zealand studies have demonstrated that as stormwater moves away from the contaminant source, the proportion of copper and zinc in the dissolved phase decreases as these metals become adsorbed to suspended particles (Griffiths and Timperley, 2005). Furthermore, as the stormwater travels a great distance from the source, the concentration of copper and zinc associated with the smaller particle size fraction tends to increase.

The main pools of metals in constructed wetlands are located in the benthic sediments, either incorporated into minerals, adsorbed, precipitated or complexed with organic matter, in suspended particulate matter, in colloidal material and in the water column as a soluble fraction consisting of hydrated ions and complexes, both organic and inorganic (Dunbabin and Bowmer, 1992; Hawkins et al. 1997). The soluble and colloidal fractions are generally considered to be the most available and toxic to biota.

Partitioning may occur by precipitation of inorganic metal compounds, complexation and adsorption to a variety of sorbent materials, such as organic matter, bacterial and algal cell walls, Fe/Mn oxyhydroxides and clay minerals (Pontier et al. 2001). In general, partitioning is affected by the concentration of ionic species and sorbents, the presence of competing cations or sorbents, redox potential, pH, temperature and contact time.

5.3 Metal Removal Processes in Aquatic Ecosystems

Processes of metal removal and immobilisation in aquatic systems include physical filtration and sedimentation, adsorption, precipitation, complexation, cation exchange, uptake by plants and microbes, and microbially-mediated reactions including oxidation and reduction (Dunbabin and Bowmer, 1992; Odum et al. 2000).

5.3.1 Physical Filtration and Sedimentation

In free water surface wetland systems, wetland plants slow the flow water allowing fine particles to settle out (Odum et al. 2000). Metal removal via sedimentation is typically not a simple straight forward physical process. Rather, it is often preceded by other chemical processes such as sorption, precipitation and co-precipitation which aggregate metals into particles that are large/heavy enough to sink. For fine colloidal metals, sedimentation may depend on floc formation, which is enhanced in wetlands by high pH, concentration of suspended matter, ionic strength and high algal concentration (Sheoran and Sheoran, 2006). Flocs may also adsorb other suspended particles, including metals.

Pond systems are effective at reducing flow velocities and promoting sedimentation. A floating wetland system can be expected to take advantage of the sedimentation processes of both types of systems (ponds and wetlands), as they can be deeper than conventional wetlands, whilst the hanging root mat is likely to create a resistance to flow through the system, thereby enhancing the removal of sediments and associated metals (Sheoran and Sheoran, 2006). The hanging root mat and associated biofilms also act to filter and entrap fine suspended particles from the water column (Smith and Kalin, 2000). These entrapped particles are subsequently sloughed off the roots as heavier, more readily settleable particles. In this way, it is conceivable that a floating treatment wetland with a well developed root mass will provide more conducive conditions for the physical removal of fine particles and associated metals than either a pond or surface flow wetland system. Once deposited within the benthic sediments, the gradual burying of bound metals should place them in a reducing environment where immobilisation processes will become more effective (Gambrell, 1994).

In contrast to conventional free water surface wetlands, where sediment-rooted macrophytes can act to bind and hold sediments preventing their turbulent resuspension (Braskerud, 2001), it might be expected that a floating wetland will be more susceptible to scouring of sedimentary deposits during high flow events. However, this may be offset by the fact that floating wetlands can operate with a greater water depth which should have the effect of reducing flow velocities and lowering turbulence when compared to shallow surface flow wetlands. A floating wetland is likely to operate in a similar manner to a sedimentation pond or basin, with the added advantage that the floating vegetation cover will minimise wind-driven turbulence.

5.3.2 Chemically-based Pathways for Metal Removal

The chemical forms, biogeochemical transformations and fate of metals in aquatic systems are strongly influenced by redox and pH conditions, and interactions with inorganic and organic compounds. Gambrell (1994) summarises the general chemical forms of metals in soils and sediments, in order of decreasing mobility and plant availability, as:

- Water-soluble metals (readily mobile and plant available):

- Soluble as free ions, e.g., Zn^{2+}.
- Soluble as inorganic complexes.
- Soluble as organic complexes.

- Exchangeable metals bound to soil surfaces by cation exchange processes (weakly bound, readily mobilised).
- Metals precipitated as inorganic compounds (potentially mobile).
- Metals complexed with large molecular-weight humic materials (potentially mobile).
- Metals adsorbed or occluded to precipitated hydrous oxides (potentially mobile).
- Metals precipitated as insoluble sulphides (potentially mobile).
- Metals bound within the crystalline lattice structure of primary minerals (unavailable).

Wetland soils tend to be characterised by having relatively high organic matter contents and consequently very high cation exchange capacities (Faulkner and Richardson, 1989). Although metals bound to surfaces by cation exchange processes tend to be only weakly bound and easily mobilized by changes in redox and pH conditions, the effectiveness of cation exchange could be enhanced by the incorporation of specific sorbent materials, such as zeolites, into the floating mat. This is discussed further in the following section.

Metals that are precipitated as inorganic compounds generally include metal oxides, hydroxides, and carbonates. The stability of these inorganic compounds is controlled primarily by the pH. In general, metals tend to be effectively immobilised at near-neutral to somewhat alkaline pH levels. If however, pH becomes moderately to strongly acid, these metals may become released to more mobile forms.

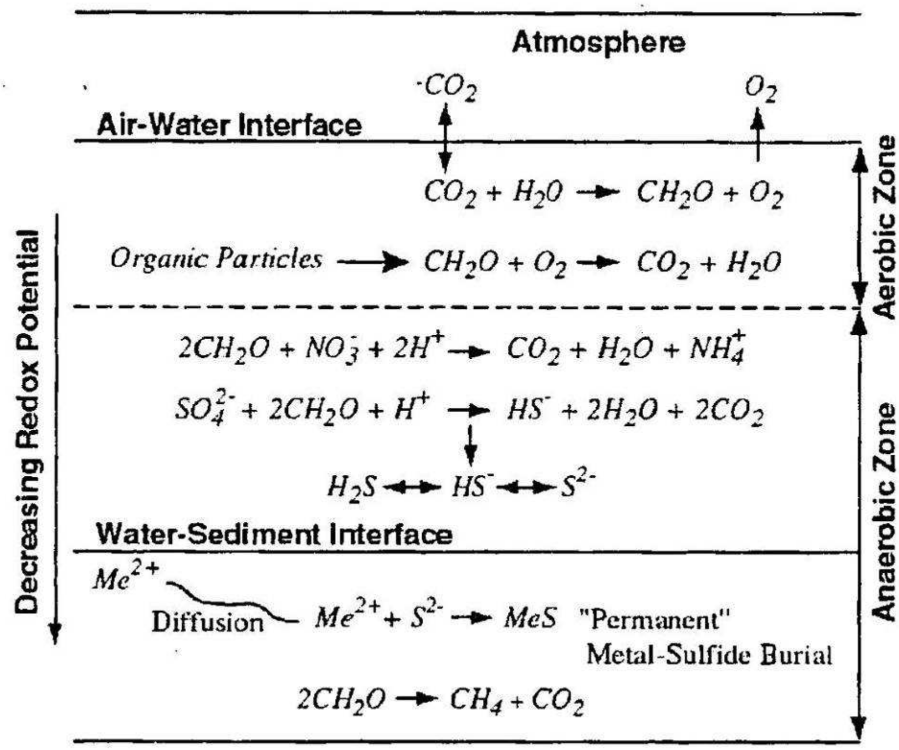
Metals complexed with large molecular-weight organics tend to be effectively immobilised, particularly under anoxic or reducing conditions (Gambrell, 1994). In the wetland environment, metals are complexed or chelated with a range of organic materials such as algae, bacteria, detritus and organic matter coatings on layer silicate clay or other mineral surfaces. The contact afforded in a floating wetland system between metals in the water column and the hanging plant roots, and associated biofilms and detritus may therefore favour the complexation of copper and zinc with organic ligands. Wetland plant roots are also known to release soluble organic compounds and low molecular weight acids which can act as effective chelating agents and contribute to the complexation of metals (Schwab et al., 2005). There may also be large potential for complexation and adsorption of copper and zinc with humic materials within the peat-like mat that forms in the floating wetland over time. Peat forms a very good adsorbent for metals, with a high surface area (>200 m^2/g) and porosity (95%), and chemical properties that promote chelation, cation exchange and chemical adsorption (Wase and Forster, 1997). However, removal of metals through peat sorption would be controlled by the degree of contact and interaction between stormwater and the floating mat, which may be somewhat limited in a passive floating wetland system. The hydraulic interaction between the stormwater passing through the free-water zone and the peat-like accumulations in the floating mat needs further investigation.

Under aerobic conditions, oxides of iron, manganese and aluminium tend to form and effectively adsorb or occlude most trace and toxic metal cations. Copper and Zinc tend be strongly concentrated in iron oxide phases (Dunbabin and Bowmer, 1992). However, these hydrous oxides generally do not form, or they become soluble, under the typically reducing, flooded soil conditions present in wetlands (Gambrell, 1994). In some situations, iron oxyhydroxides may be effective in controlling metal retention where conditions waver between reducing and oxidising. Within the floating wetland environment, oxygen may be present in micro-sites surrounding the hanging roots of plants containing aerenchyma (porous tissue facilitating gas transfer through plant), in open water sections harbouring photosynthetic algae, and in a thin layer at the sediment-water interface. These oxidised zones may therefore stimulate the formation of hydrated iron and manganese oxides, which adsorb cations such as Cu^{2+} and Zn^{2+} from solution (Dunbabin and Bowmer, 1992; Laanbroek, 1990). In particular, Cu^{2+} and Zn^{2+} may tend to be adsorbed by the iron oxyhydroxide plaques that form on the roots of aerenchymous wetland plants that leak oxygen through their roots (Doyle and Otte, 1997; Jacob and Otte, 2003; Kosolapov et al. 2004; Vale et al. 1990). Once bound within these iron plaques, the metals may then be taken up by the plants, accumulate within the floating mat, or slough off the roots as settleable sized particles to ultimately become buried in the sediments. However, if the sediments are particularly reducing, the adsorbed metals may subsequently become remobilized and either released or re-bound or precipitated in different forms e.g., sulphides.

The degradation of organic matter, present at high concentrations in most wetland sediments, drives the formation of sediment redox gradients. Most wetland sediments become anoxic within a few cm of the surface due to high microbial activity and low diffusivity of oxygen through the overlying water. Once oxygen and nitrate are depleted, sediment microbes turn to iron (III) and manganese (IV) as terminal electron acceptors. Under reduced conditions, and at pH greater than 7, copper will tend to accumulate as insoluble nonionic native copper (Hawkins et al., 1997). Below the oxic region, certain bacteria also survive by reducing SO_4^{2-}, resulting in the production of free hydrogen sulfide. Iron, zinc and many other trace metals react rapidly with these dissolved sulfide species to produce metal sulfide compounds that are quite stable and characterized by low solubility (Gambrell, 1994; Jacob and Otte, 2003, Lovley 1993). Thus, sediment processes can act to permanently sequester these elements into metal sulfide and nonionic phases, greatly reducing their bioavailability and toxicity (Gambrell, 1994; Hawkins et al. 1997). As long as reducing conditions are maintained within the sediments, metal sulphides will remain effectively immobilised (Gambrell, 1994; Kosolapov et al. 2004; Odum, 2000; USEPA, 1999). Figure 37 depicts the process of metal sulphide burial in free water surface wetlands which can lead to long-term immobilisation. Metal sulphide formation is important in the treatment of acid mine drainage which generally contains high concentrations of sulphate. Systems receiving stormwater are likely to be less conducive to the formation of metal sulphides.

The oxidisation of sulphide containing sediments for extended periods results in the disassociation of sulphides and the subsequent release of associated metals. This release tends to be much more pronounced than it is when metal-humic material associations become oxidised (Gambrell, 1994). This is an issue that needs to be considered if and when accumulated sediments are dredged or removed from stormwater treatment ponds and wetlands.

Figure 37.
Metal sulphide burial process in a free water surface wetland. (Source: USEPA, 1999).



In carbon deficient waters, such as some stormwaters and mine drainages, the rate of sulphate reduction and associated metal removal in constructed wetlands can be limited by the availability of carbon to act as an energy source for the heterotrophic sulphate reducers (Kosolapov et al. 2004). A lack of organic carbon in the influent water may also limit the development of reducing conditions required for sulphate reduction. In such carbon-deficient waters, the rate of organic matter production and turnover of the wetland plant biomass may become a critical rate-determining factor. It can be hypothesised that the following characteristics of a floating wetland system are likely to contribute towards the development of anoxic conditions within the underlying sediments:

- Presence of inundated, waterlogged conditions which limits gaseous oxygen diffusion into the sediments.

- Decomposition of organic matter generated by the floating vegetation leading to the consumption of dissolved oxygen.
- Release of soluble organic compounds as exudates from the plant roots.
- Reduced potential for oxygen diffusion across the air-water interface due to physical barrier of floating mat.
- Reduction in re-aeration via wind-driven turbulence.
- Limited growth of photosynthetic algae due to elimination of light penetration through water column.
- Elimination of sediment-rooted macrophytes under the floating mat which would otherwise create oxygenated micro-sites within the wetland rhizosphere.

The significance of the above factors in creating reducing conditions will be somewhat determined by the proportion of water surface covered by floating wetland, the age of the system and the oxygen demand and sulphate content of the influent water and wetland soils.

Further investigation is warranted to determine whether sulphide production is a significant metal removal pathway under the redox conditions that develop in a floating wetland system treating stormwater, and whether it is the availability of carbon or sulphate that is the ultimate rate limiting factor.

If conditions in the water column remain relatively oxic, then sequestration of metal sulphides will be restricted to the deeper, reduced sediment layers and anaerobic zones within the floating wetland matrix. The rate of diffusion of dissolved metals into these deeper, reduced zones conducive to sulphate reduction is likely to be low unless long hydraulic residence times are provided in the treatment wetland. However, if copper and zinc are initially bound into larger particles, they may eventually be bound as insoluble complexes (ZnS) or nonionic forms (elemental copper) through settling, burial and eventual incorporation into the deeper, more reducing sediments. Binding of copper and zinc into larger particles in a floating wetland system may occur either through plant uptake, coagulation of colloidal forms of these metals, or adsorption onto plant organic matter, root biofilms, peat accumulations within the floating mat, clay particles or oxides of iron and manganese.

In summary, the oxidation status, and its fluctuations, within the water column, wetland sediments and floating mat will affect the forms, stability and mobility of metals including copper and zinc. Given the wide range of physico-chemical conditions possible within floating wetland-based treatment systems and the potential to manipulate these to some degree, it is not clear which removal mechanism will predominate or which offers the best mix of priority metal removal and overall water quality outcomes. For example, maintenance of anaerobic conditions in the water column below floating wetlands may increase overall metal removal efficiency by promoting precipitation of metal sulphides, but create conditions unsuitable for aquatic biota (e.g., low oxygen concentrations). One advantage that a floating wetland may have over conventional wetland systems is that a relatively constant water level will be maintained with reference to the plant rhizosphere and peat mat due to its flotation. Thus, the redox conditions should remain relatively stable within the floating mat.

5.3.3 Use of specific media to enhance sorption of copper and zinc

There are a number of materials that have a relatively high capacity for sorbing metals and may therefore have the potential to enhance the removal of soluble metals in floating treatment wetlands via incorporation into the floating mat. Potentially suitable sorbents include:

- zeolites (e.g., Erdem et al. 2004; Färm, 2002; Pitcher et al. 2004);
- vermiculites (e.g., Malandrino et al. 2006);
- bauxsol (a by-product of aluminium refining) (e.g., Munro et al. 2004);
- activated carbon; and
- biosorbents, such as peat, plant, algal and shell materials (Färm, 2002; Viraraghavan and Ayyaswami, 1987).

Of these, zeolites offer possibly the greatest potential in New Zealand due to their natural abundance and high sorption capacity. Zeolites are naturally occurring hydrated aluminosilicate minerals that possess a net negative charge and therefore have a high affinity for sorbing metals through cation exchange (Erdem et al. 2004). There may also be scope for the use of biosorbents in floating treatment wetlands to compliment the naturally occurring accumulations of plant litter and peat that tend to build up within floating wetland mats.

One limitation to the incorporation of metal sorbents into floating treatment wetlands is that there is only limited scope for interaction between the water column and the floating mat where the sorbents would be contained. In order to become effective, recirculation of the stormwater vertically through the floating wetland using a pump may be required to optimize the contact between metal ions and the sorbent material. The relative benefits of such a system, in terms of additional metal removal, would have to be weighed up against the added operational complexity and requirement for pumps and electricity.

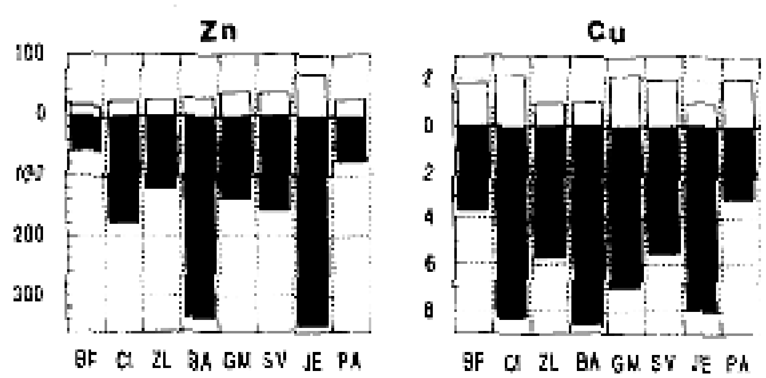
5.3.4 The role of Plants in Metal Removal

Emergent macrophytes play a critical role in metal speciation and mobility in wetlands directly through filtration, plant uptake, adsorption and cation exchange, and indirectly by modifying the substratum through oxygenation, buffering pH and adding organic matter (Dunbabin and Bowmer, 1992; Jacob and Otte, 2003; Kosolapov et al. 2004; Williams, 2002). Depending on the combination of these factors, plants may have a net effect of enhancing mobilisation or immobilisation.

Redox potential and pH are important factors influencing metal solubility in sediments and aquatic ecosystems. As discussed previously, wetland plants that leak oxygen through their roots have the potential to alter the redox conditions within small zones of the rhisosphere, which may act to enhance or decrease long-term metal immobilization depending on the predominant processes.

Whilst copper and zinc are known to accumulate in plants, total plant uptake is generally small compared to sediment sequestration and typical influent metal loads in wetland systems (Dunbabin and Bowmer, 1992; Kosolapov et al. 2004; Wójcik and Wójcik, 2000). Furthermore, only a small proportion of the metals taken up by emergent aquatic plants are translocated into aboveground biomass with the highest concentrations typically being found in the roots (Dunbabin and Bowmer, 1992; Tanner, 1996; Weis and Weis, 2004). This was demonstrated by Tanner (1996) for eight species growing in dairy farm wastewater (Figure 38). Thus, harvesting of emergent aquatic macrophyte stems from wetlands for the purpose of metal removal will generally be impractical.

Figure 38.
Comparison of mean above (white) and below-ground (shaded) tissue metal concentrations (μg g) for eight wetland plant species (BF = *Bolboscoenus fluviatilis*, CI = *Cyperus involucratus*, ZL = *Zizania latifolia*, BA = *Baumea articulata*, GM = *Glyceria maxima*, SV = *Schoenoplectus validus*, JE = *Juncus effusus*, PA = *Phragmites australis*) receiving dairy farm wastewater (Source: Tanner, 1996).



The senescent litter produced by wetland plants may also act as an important biosorbent for metals (Miretzky et al. 2006; Schneider and Rubio, 1999), with dried reed shoots showing higher sorption affinities for metals (including copper and zinc) than for many other biomaterials (Southichak et al. 2006).

There has been some research conducted into the use of hydroponically grown terrestrial plants for the removal of metals from aqueous solutions, in a phytoremediation process termed *rhizofiltration* (Dushenkov et al. 1995). Rhizofiltration refers to the use of plant roots to adsorb, concentrate, and precipitate heavy metals from polluted effluents. The metal contaminated plant material may then be dried, composted and incinerated. Dushenkov et al. (1995) demonstrated that the roots of hydroponically grown *Brassica juncea* (Indian mustard) were capable of removing substantial quantities of Cu^{2+}, Cd^{2+}, Cr^{6+}, Ni^{2+}, Pb^{2+}, and Zn^{2+} from aqueous solutions, predominantly through uptake and the formation of insoluble inorganic compounds, such as lead phosphate. The plants showed apparently no signs of phytotoxicity during the study. However, these trials were conducted with small-scale plants, over short time periods (<96 hours exposure) and using aerated solutions with extremely high metal concentrations (e.g., 7mg/L of Cu^{2+}, and 100 mg/L of Zn^{2+}). Thus, although these trials show encouraging results, their findings are somewhat limited in their applicability to stormwater treatment.

It is unclear at this stage what the predominant redox status within the mat of a floating stormwater treatment wetland is likely to be. However, it can be assumed that the conditions will be somewhat less reducing than the typically highly-reducing conditions within the flooded marsh soils under which the majority of wetland plant metal uptake rates have been assessed to date. It is likely that the redox status of a floating wetland mat will lie somewhere between that of a typical sediment rooted marsh and an upland soil. Because of this and the suspension of plant roots within the water column rather than the sediment (fostering direct uptake from the water column), relative plant uptake rates of copper and zinc maybe somewhat higher than those reported in the literature for other wetland plants, and warrants specific investigation. Whilst harvesting plant biomass may not be practical in a stormwater treatment system, high uptake rates may result in a significant accumulation of metals within the litter and organic peat-like deposits that accrete within a floating wetland mat, as well as deposited in the benthic sediments.

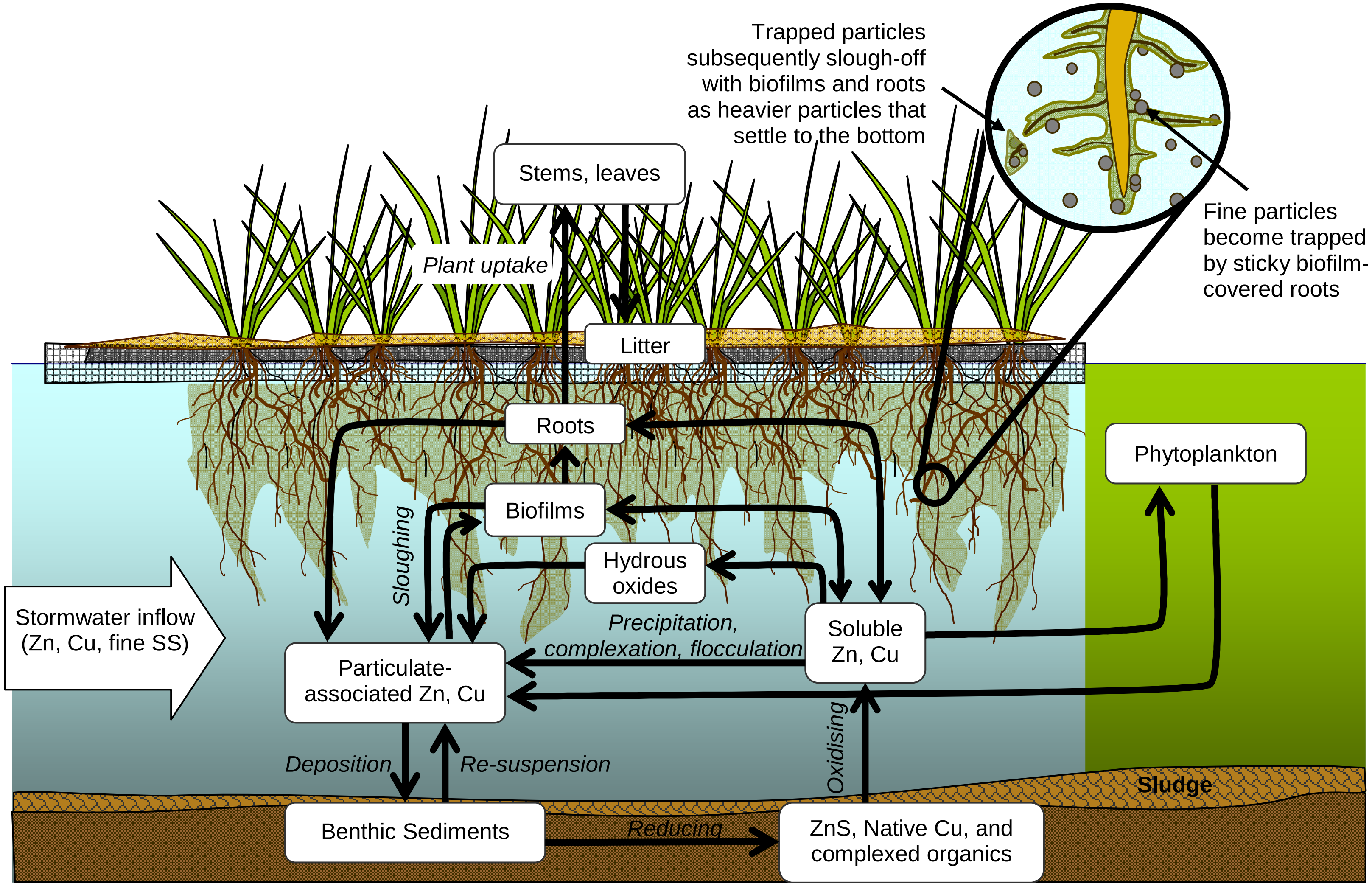
5.3.5 Conceptual model of copper and zinc processes and removal pathways in a stormwater floating treatment wetland system

The range of possible pathways and interactions involving copper and zinc likely to occur within a floating treatment wetland system are complex and inadequately defined within the literature. In order to summarise the various processes that may be involved with the cycling and removal of copper and zinc in a floating wetland system receiving stormwater, a conceptual model is proposed in Figure 39. It is suggested that this model form the basis of future experimental investigations aimed at quantifying the relative importance of the various sinks and fluxes identified under the range of conditions likely to be experienced within a stormwater treatment system.

It is proposed that one of the most important pathways for removal and immobilization of copper and zinc from stormwater within a FTW system will be the capture of fine suspended particulates and associated copper and zinc within the network of roots and biofilms beneath the floating wetland, followed by sloughing as heavier particles, deposition in anaerobic benthic sediments and subsequent immobilization under reducing conditions as organic complexes, zinc sulphide and native (elemental) copper.

Figure 39.

Conceptual model of copper and zinc pathways and interactions within a floating wetland stormwater treatment system.



6 Wetland Vegetation for Floating Treatment Wetlands

6.1 Plant species and growth habits

A broad range of emergent macrophyte species have been used in constructed wetlands world wide with success to date. The choice of species often comes down to selecting locally occurring native species that exhibit vigorous growth within polluted waters under the local climatic conditions. *Phragmites australis* (Common reed) has been very widely used throughout Europe, Asia, and Australia and is known to perform well in treatment wetlands. However, this species is not native to New Zealand and therefore considered highly inappropriate. Species that are commonly used in surface and subsurface flow treatment wetlands in New Zealand include those that tend be the larger and more vigorous plants, such as *Schoenplectus tabernaemontani*, *Typha orientalis*, *Baumea articulate*, *Eleocharis sphacelata* and *Carex secta*. Typha species have effectively been used in floating treatment wetlands in Canada and the USA.

Hubbard et al. (2004) compared three different species (*Typha latifolia*, *Juncus effuses*, and *Panicum hematomon*) grown on floating rafts for the purpose of treating swine lagoon wastewater in Georgia, USA. Both *T. latifolia* and *P. hematomon* grew well on the floating rafts (in terms of above-ground biomass). However, *Juncus* did not perform well and died off completely when grown on swine wastewater within one year and exhibited poor growth when grown on an quarter strength inorganic "Hoaglund solution". Given that *J. effuses* naturally grows in poorly drained soils, rather than fully saturated conditions, the authors concluded that this species was not suitable for growth as floating vegetation in wastewater.

As described previously, vetiver grass (*Vetiver zizanioides*) has been used in floating wetland application for treatment of sewage and piggery effluent and has been found to exhibit good growth characteristics in such situations. However, it originates from India and is therefore not naturally found in New Zealand. Thus, its introduction here may be questionable.

Floating treatment wetlands were trialed in Hungary for removal of nutrients from lake water (Gulyas and Mayer; 1993; Lakatos, 1998). Of the 67 species that were compared in an initial screening trial, the following were identified as suitable for floating meadows:

- Alisma plantago-aquatica
- Glyceria maxima
- Mentha aquatica

- ❑ Myosotis palustris
- ❑ Sagittaria sagittifolia
- ❑ Sium erectum
- ❑ Sium latifolium
- ❑ Sparganium erectum
- ❑ Symphytum officinale
- ❑ Thelypteris palustris
- ❑ Typha laxmannii
- ❑ Typhoides arundinacea

Although none of these are endemic to New Zealand, it can be assumed that locally occurring species of the genus Typha (e.g., *T. orientalis*) are likely to perform well in floating treatment wetlands and should even attain auto-buoyancy under favourable conditions.

Floating Islands International (FII) have been able to grow a wide range of aquatic, riparian and dryland species (including herbs, shrubs and trees) rooted in growth media contained in their buoyant island matrix (Figure 40). Obviously, getting the right mix of porosity, water retention and capillary action (to "wick" water up into the growth media) will be important for species not well adapted to surviving continuous water-logging. For stormwater and other water quality applications native plant species adapted to growth in wetland conditions are likely to be hardier, produce greater submerged root mass and have a more natural character.

Figure 40.
FII floating wetland vegetated with a range of ornamental herbs and shrubs.

6.1.1 Recommended species for New Zealand

A wide range of native emergent sedges (e.g., *Carex, Cyperus, Schoenoplectus* and *Baumea* species) and rushes (*Juncus* species) are expected to be able to grow well in suitable floating wetland systems. Taller-growing native species such as the larger sedges (e.g., *Baumea articulata* and *Schoenoplectus tabernaemontani*) and raupo (*Typha orientalis*) are likely to have greater wind resistance (windage), requiring greater anchorage and increasing susceptibly to overturning during high winds. Whilst this may be a problem in smaller floating wetland units, the risk of overturning will become diminished as the surface area of an individual floating wetland unit increases. As mentioned previously, *T. orientalis* is also likely to form self-buoyant floating mats under ideal conditions.

6.2 Effect of dissolved oxygen and nutrient concentrations on rooting depth

The depth of root penetration beneath the floating mat will be affected, at least in part, by the concentration of dissolved oxygen and nutrients within the stormwater. Plant root development is generally greatest under aerobic conditions, whereas reducing conditions can substantially inhibit root growth. Indications from other studies and the observations of the authors suggest that conditions tend to become anaerobic in the water column under a floating wetland, particularly if residence times, organic loadings and coverage of the water surface are high. However, it may be possible to manipulate the dissolved oxygen concentration in the water column by including open water zones that allow for re-aeration through algal photosynthesis and diffusion across the air-water interface. Further investigation is needed to determine the effectiveness of open water zones at re-aerating the water column, and the effect that this may have on plant root development in a stormwater FTW system.

The effect of nutrient concentration on root development may be less straight forward. On one hand, a ready availability of nutrients generally promotes good plant growth and vigor. On the other hand, plants growing in nutrient poor conditions will often develop more extensive root systems in order to increase the surface area available for nutrient uptake.

6.3 Growth media and plant establishment

Selection of an appropriate growth medium will be particularly important during the initial stages of plant establishment. In terms of the physical properties of the growth medium, a balance between available water and aeration is essential for the establishment of healthy plants. Materials must be used that provide adequate small pore spaces to hold water for plant uptake, whilst allowing enough large pores to allow exchange of air in the medium to maintain aerobic conditions. The wetted weight and relative buoyancy of the media can be important issues also. If the media is prone to becoming waterlogged and heavy, it may adversely affect the buoyancy of the floating wetland.

Care needs to be taken to select a media that provides suitable growth conditions, including porosity, water retention, capillarity, and fertility. Outside of applications where there is substantial nutrient concentrations in the water (e.g., wastewater treatment), care is required to provide sufficient nutrients to promote plant establishment and spread, but not cause nutrient losses to the surrounding waters which may cause eutrophication issues. The use of inorganic fertilizers can also cause a build-up of salts which can be detrimental to the growth of many freshwater wetland plants.

The materials used in the growth medium should provide a pH somewhere between 5.0 and 6.5. The pH of a newly formulated growth mix should be checked before use. pH adjustment can be made by mixing dolomite limestone or similar through the media.

Two of the most commonly used components in FTW growth media are coir (coconut fibre) and peat. During the early trials of Smith and Kalin (2000), commercially available shredded peat in the form of compressed bails was used as the growth media for establishing plants in their floating rafts, but with very limited success. They reported that this fine material rapidly waterlogged and settled as a dense layer over the raft area. The saturated peat layer did not lend much support to seedlings planted to the raft, while dissolved oxygen consumption by the decaying peat actually caused 100% mortality after one planting campaign of 5,000 seedlings. Furthermore, at those locations with adequate fetch to generate waves, peat commonly sifted out of the rafts, and physical support of seedlings during their early development was lost. An alternate substrate was identified, in the form of clods of live Sphagnum Moss collected from local wetland areas (Smith and Kalin, 2000). The authors report that this material has since proven to be an excellent substrate, providing good physical support of vascular wetland seedlings such as *Typha spp*. during the first growing seasons. In several cases, the Sphagnum continued to grow, and proliferate over the rafts, supporting the germination and growth of up to 25 other vascular and bryophyte species on the rafts.

FII have developed a proprietary soil-less, neutral to slightly buoyant plant propagation medium for use in their floating wetland systems, called "BioMix". BioMix incorporates an organic bedding mix and hydrophilic foam which acts to provide good capillary wicking of moisture up to the plants, whilst maintaining an open structure to prevent the media becoming anaerobic.

It is anticipated that a coarse peat-moss or coconut fibre material with an open structure will provide a suitable basis for floating wetland growth media. This may be amended with a small amount of organic-based fertilizer, such as worm casting (vermin-compost) or compost. Other additions, such as pumice, perlite or vermiculite may prove to be beneficial as light-weight bulking materials to provide additional air space without significantly increasing the weight of the mix.

Where the floating wetland is growing on high nutrient waters, such as sewage, it may be possible to plant directly into the floating mat without additional planting media, particularly where a structurally amenable material is used, such as the FII polyester matrix. Seedlings could be planted directly into openings that were cut into the floating matrix. The plants would then be forced to take up nutrients directly from the water column, which may enhance plant uptake processes.

6.4 Planting methods

There are three main techniques commonly employed for establishing plants in wetland situations:

- Direct seeding.
- Planting of cuttings.
- Use of seedlings

Direct seeding is often used as a rapid and cost effective method for plant establishment over large areas of newly created or restored wetland and can be effective under ideal conditions. Depending on the structure used for the creation of a floating wetland, direct seeding may be a suitable method of plant establishment, as it will be possible to provide a suitable level layer of clean purpose-made growth media that will be amenable to seed germination. The bottom-up, capillary based wetting experienced by a floating wetland may also improve the success of seed germination. Floating Islands International supply a range of seed mixes purposely developed for use with their floating wetland products that contain predominantly North American species.

One limitation of direct seeding is that some native New Zealand wetland plant species do not germinate readily from seed and viable seed can be difficult to find (e.g., *Baumea articulata*). In addition, exposed areas of growth media can succumb to weed establishment before the desired seeds germinate.

The direct planting of cuttings, particularly of rhizomes, is a particularly common approach for the establishment of some wetland plant species, such as *Typha spp*. and *Schoenoplectus tabernaemontani*. Division of larger clumping plants, such as some sedges, can also be successful.

In most cases, the planting of seedlings will be preferable. Although likely to be the most expensive approach in the sort-term, the planting of seedlings will generally yield the highest success rate and most rapid establishment and growth rates. Numerous plant nurseries now supply or specialize in wetland plant seedlings.

One option for optimizing plant establishment may be for the floating wetland units to be pre-planted and grown in the nursery prior to deployment. This approach is used effectively in Germany by Bestmann Green Systems who sell pre-planted floating wetland blankets and rafts. An issue that needs to be considered in this regard is how to manage, transport and deploy pre-planted floating wetlands, as they will be considerably heavier and more fragile that their unplanted counterparts.

6.5 Suitable planting time

Wetland planting in most areas of New Zealand is best carried out in spring or early summer; generally September to December inclusive and the earlier the better, to ensure a reasonable period of active growth before the following winter (Tanner et al. 2006). Plant growth and establishment is generally slow during winter, during which time poorly rooted seedlings or cuttings can be particularly susceptible to destruction by waterfowl.

6.6 Weed and pest management

Uncontrolled weeds can compete with and suppress establishment of the desirable plants in treatment wetlands. Plants are most vulnerable during initial establishment. Invasion by terrestrial weeds may be a problem in newly planted floating wetlands, particularly as the growth media is generally not completely inundated. Consequently, weed management is likely to be necessary during the plant establishment period. Floating treatment wetlands should be set-up in a way that enables easy access for weed management, such as being able to pull the floating mat to the edge of the pond to allow access. Large floating wetlands can be constructed in a way that will support the weight of an adult.

Waterfowl, particularly Pukeko, Canadian geese and ducks, can cause serious damage to new plantings if large populations are present or attracted to the area. They tend to pull out new plants before their root systems can gain good anchorage, either grazing on young shoots and underground rhizomes, or on "bugs" associated with their roots. They can almost completely destroy a wetland planting in a few days if bird numbers are high and left unchecked. There have been reports of this proving to be a significant impediment to the establishment of floating wetlands in Western Australia, particularly as the floating wetlands provide an ideal refuge for water birds when deployed in a pond or lake (B. Masters pers. comm., 2006). Thus, some sort of protection from waterfowl may be required during plant establishment. Floating wetlands may lend themselves to the use of cages or netting over the planted areas.

As well as suppressing plant establishment, grazing and nesting activities can sometimes damage established growths, creating and maintaining gaps in the plant cover. This highlights a paradox that exists with FTWs, in that they provide beneficial habitat and refugia for waterfowl, which may cause a reduction in plant cover and potential deterioration of other functions such as water treatment. Clearly, a balance needs to be found that may require some periodic management intervention when waterfowl populations start to become problematic.

7 Design, Implementation and Management of Floating Treatment Wetlands

7.1 Retro-fitting of Floating Treatment Wetlands within the Stormwater Treatment Train

The Auckland Regional Council Technical Publication pertaining to stormwater management (ARC TP#10) identifies ponds and wetlands as devices for managing stormwater quantity and quality issues. Both systems operate and function slightly differently with regard to stormwater quality improvement. In terms of upgrading existing stormwater management infrastructure using floating wetlands, it seems that the greatest scope will be within pond-based systems. However, there may also be some potential for utilizing floating wetland components to optimize the performance of existing stormwater treatment wetlands, particularly where they have suffered vegetative decline due to inappropriate water depths.

7.1.1 Pond-based Stormwater Treatment System

There are two main types of stormwater management pond: (1) dry ponds and (2) wet ponds. A dry pond is a basin that temporarily stores runoff, whereas a wet pond contains a permanent pool of water. Floating treatment wetlands generally require a minimum water depth of approximately 0.5 m to be maintained so that they do not dry out and to prevent them from becoming rooted in the benthic sediments. Thus, their application will be restricted to wet ponds.

The purpose of stormwater ponds are to attenuate the severity of peak flows during rainfall events, thereby reducing downstream flood and erosion risk, and provide some water quality improvement. The main water quality improvement mechanism is physical sedimentation of suspended solids and associated organic matter and nutrients as a result of the detention time in the basin and reduced flow velocities.

A typical configuration of a wet pond system for stormwater management is given in ARC TP10 and consists of two main ponds in series (Figure 41). The first pond is designed to act as a sediment trapping forebay that can be easily cleaned out. It is envisaged that the most appropriate location for a floating wetland component in the system would be within the second pond, providing it doesn't intermittently dry out. Alternatively, it may be possible to include a floating treatment wetland component in the sedimentation forebay of some pond systems to enhance and optimise the removal of suspended solids.

Figure 41.
Plan layout of a typical wet pond system as recommended in ARC TP10.

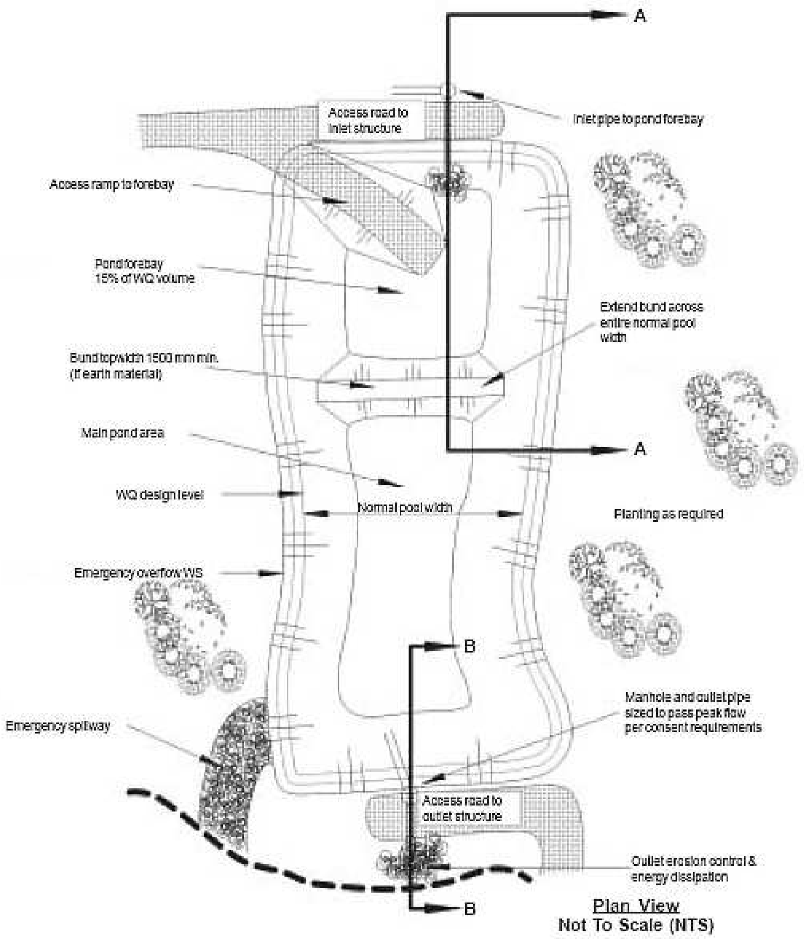
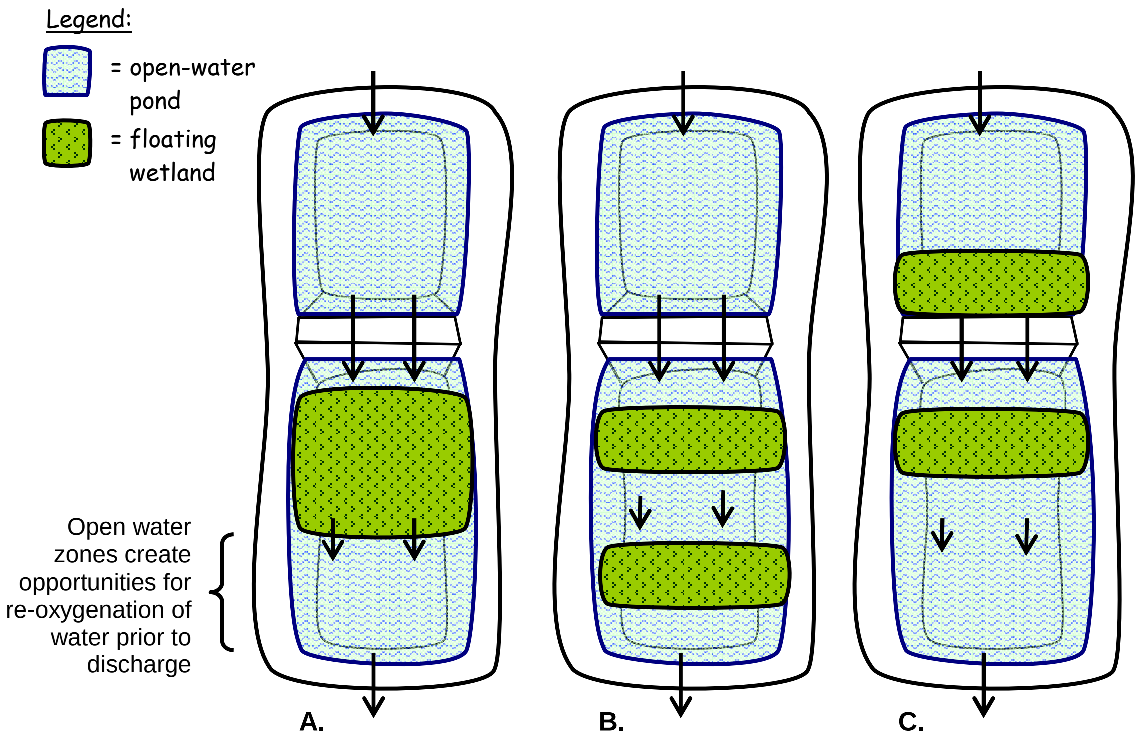


Figure 42.
Possible ways of retrofitting a given surface area of floating treatment wetland into the wet pond stormwater treatment system recommended in ARC TP10.



Each of the three floating wetland / pond configurations depicted in Figure 42 are likely to create slightly different physio-chemical conditions within the water column that will favour certain treatment processes, whilst discouraging others. The ideal conditions will depend on the treatment priorities and other objectives, such as aesthetics and habitat requirements. The floating wetland components of options A and B provide a mainly polishing function in the second pond, following the removal of coarse sediments within the forebay pond. Option A is likely to enhance the development of anaerobic conditions under the relatively large expanse of floating wetland which may enhance metal removal through sulphide formation. The approach depicted in option B would maintain more aerobic conditions and would therefore be likely to foster the development of more extensive roots beneath the floating wetlands and support a mixture of aerobic and anaerobic processes. Option C depicts an approach where the aim is to maximise the removal of fine particulates within the sedimentation forebay.

Regardless of the approach adopted, it is considered likely that an open water section or final pond will be necessary to facilitate the re-aeration of the water prior to discharge. This will be particularly important if the floating wetland system is designed in a way to optimize the creation of anaerobic or reducing conditions.

7.1.2 Wetland-based Stormwater Treatment System

The layout of a typical wetland-based stormwater treatment system, as recommended in ARC TP10, is depicted in Figure 43. The system consists of an alternating series of vegetated wetland zones and deeper water ponds. A floating wetland system could be retrofitted into one or more of the deep water zones within the middle section of such a system (Figure 44). The floating wetland zones would provide for enhanced fine particulate removal and create anaerobic zones conducive to denitrification, metal sulphide formation and sedimentation of metals in biofilm flocs.

Figure 43.
Plan view of a stormwater treatment wetland layout as recommended in ARC TP10.

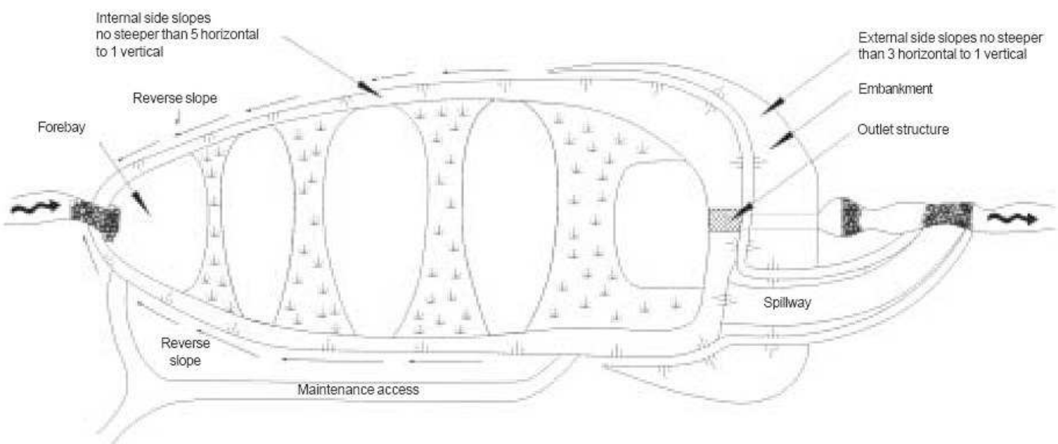
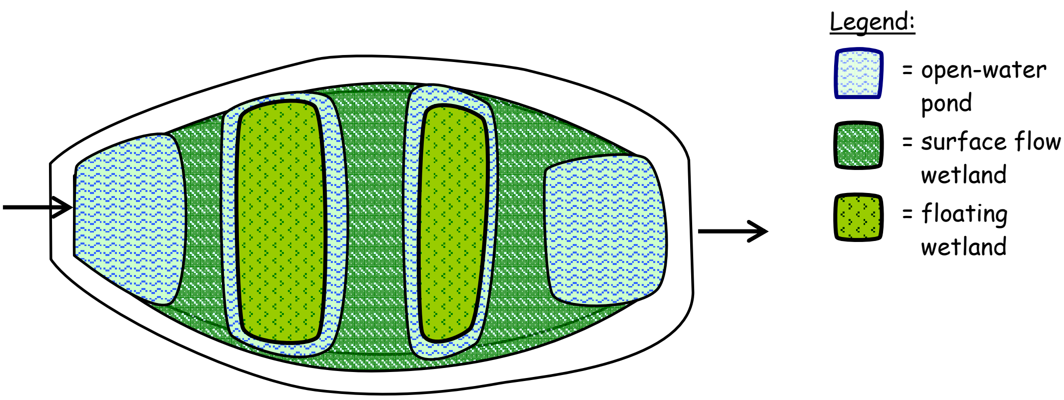


Figure 44.
Plan view of a stormwater treatment wetland layout with two floating wetland components retrofitted into deep water zones.



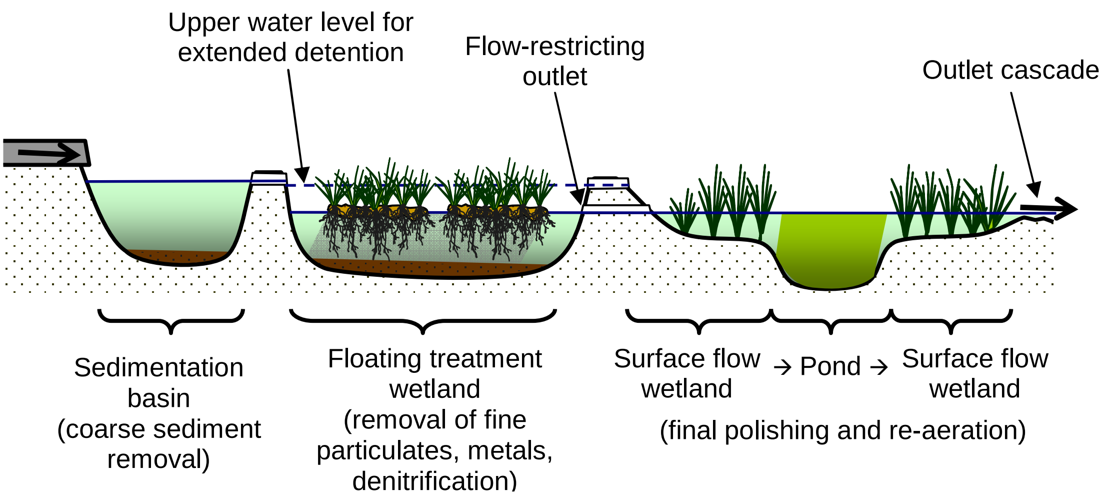
7.2 Newly Designed Systems- "starting from scratch"

The approaches discussed in the previous sections represent potentially suitable options for upgrading existing stormwater treatment ponds or wetlands by retro-fitting floating wetland components into such systems. However, the question arises as to what may be the ideal design for a new system incorporating floating wetlands that is unconstrained by pre-existing infrastructure?

Although there is currently not enough information known about the exact function, performance and operation of floating wetlands in a stormwater treatment context, a first attempt at a conceptual design has been made and is depicted in Figure 45. The proposed system utilizes a sedimentation basin/forebay up front for the settling of coarse sediments. Stormwater would then flow into a floating treatment wetland basin that would act to filter and trap fine particulates and associated metals. The sediments under the floating wetland would become reducing, providing conditions conducive to metal immobilisation through sulphide formation and nitrate removal via denitrification. The floating wetland component would be configured to operate as an extended detention basin, so that during storm events the water level would rise to an upper limit and then slowly decant over subsequent days. This would provide storage capacity for inter-event treatment of stormwater, as well as serving a flow-attenuation function to improve the function of downstream treatment devices.

Following the floating treatment wetland, stormwater would then flow into a surface flow wetland system incorporating deeper open water zones to provide additional polishing and re-aeration of the stormwater before it is discharged. A cascade structure could also be included at the outlet to entrain more oxygen into the water before it leaves the system.

Figure 45.
Conceptual longitudinal cross-section through a "newly designed" stormwater treatment system incorporating floating wetlands, ponds and surface flow wetlands (not to scale).



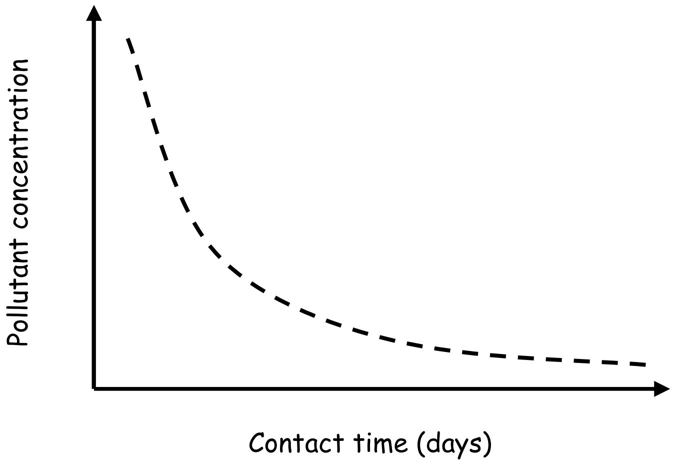
It should be noted that the conceptual design suggested in Figure 45 represents just one of a plethora of possible stormwater treatment configurations incorporating floating wetlands. The design is likely to evolve as more information comes to hand concerning how a floating stormwater treatment wetland might function and perform, the dominant processes occurring with a floating wetland, and how these processes may best be utilized within a treatment train in order to achieve certain water quality objectives.

7.3 Other Floating Wetland Design Considerations

7.3.1 A Sizing Approach

Currently, there are no guidelines available for the design of floating treatment wetlands. Consequently, the size of a floating treatment wetland required to achieve particular stormwater treatment goals can not be determined with any certainty. Based on the assumption that copper and zinc removal in a FTW will predominantly occur through entrapment of fine particles within the root zone and subsequent incorporation of sloughed material into the sediments, the hydraulic residence time (HRT) of the system is likely to be a key design factor (Figure 46). The HRT will directly affect the contact time that is possible between stormwater and the plant roots, and also the velocity of flow through the system which will impact on the efficiency of settling processes. Because the floating mat is buoyant and can tolerate variable water depths, FTWs can be designed to operate like an extended detention basin (i.e., temporary storage of stormwater at an elevated water depth). However, it is anticipated that there will be an upper limit to the water depth, above which the efficiency of fine particulates, copper and zinc removal will start to decline as the degree of contact between the hanging plant roots and the stormwater decreases. To determine what this maximum water depth is, information is needed on the rooting depth of different wetland plants growing in stormwater FTWs, and the relationship between treatment performance and the "rooting depth : FTW water depth" ratio (i.e., the proportion of the depth profile occupied by roots).

Figure 46.
Conceptual design curve illustrating relationship between contact time (HRT) and pollutant concentration. Such a curve could be derived by batch-loading a series of FTW mesocosms and sampling over time.



A first step in deriving a performance curve such as that depicted in Figure 46 would be to batch load a number of replicated floating wetland mesocosms with stormwater and sample the water quality over time (e.g., daily sampling).

A comparison of floating wetlands against, and in combination with, ponds and surface flow wetlands would also be useful for determining the relative efficiency of these three treatment options for various pollutants.

7.3.2 Proportion of surface coverage

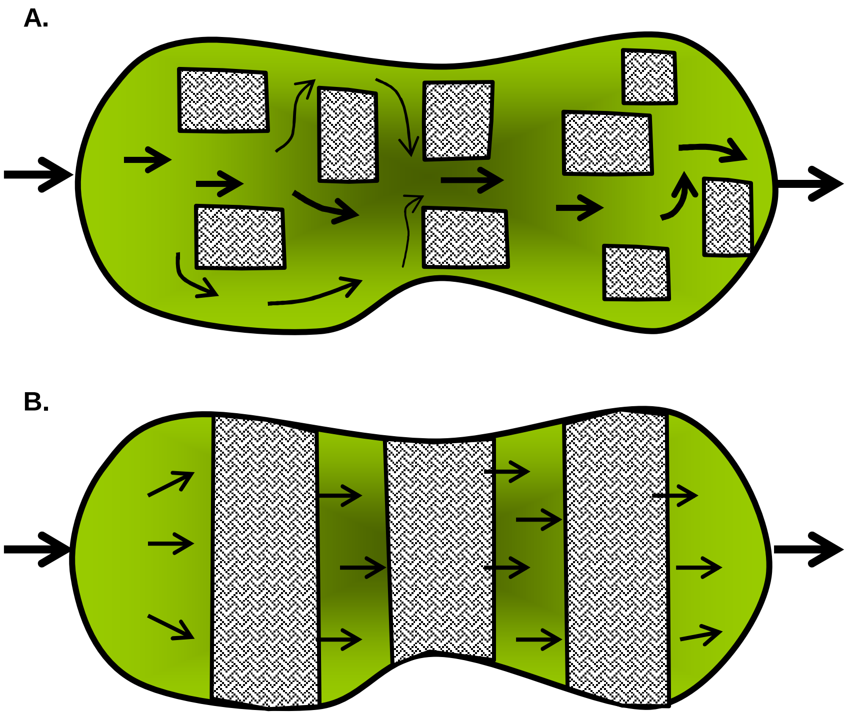
It is considered likely that the relative proportion of floating wetland coverage to open water areas will play an important role in manipulating the redox and dissolved oxygen status of the water column and underlying sediments in a floating wetland system. Large expansive areas completely covered with floating wetland are likely to become increasingly anaerobic, whereas areas of open water will provide opportunities for oxygen introduction into the water column via algal photosynthesis and diffusion. Thus, research is needed to uncover the relationship between the proportion of surface coverage, the redox status of the system, and the effect on contaminant removal.

7.3.3 Hydraulic Issues

Some serious consideration will need to be given to hydraulics during the design of a floating wetland treatment system. The risk of dead-zones and associated short-circuits developing in such a system seem just as high as with a conventional surface flow wetland system. For example, the monitoring of Sasser et al. (1991) in a large natural floating marsh suggested that there was minimal interaction between the water under the floating marsh and the adjacent open water lake system, except during times of high rainfall and peak flow through the system.

Depending on the arrangement of floating wetland elements, preferential flow paths will potentially develop through open water sections of a floating treatment wetland/pond system due to the increased resistance to flow caused by the floating mat and hanging roots (Figure 47). To avoid this, the floating wetland components of such a system should be designed to traverse the width of a stormwater pond perpendicular to the prevailing flow direction. It will also be important to ensure that plant establishment is successful and relatively uniform throughout the floating wetland area to ensure reasonably uniform root development beneath the floating mat.

Figure 47.
Stylised aerial view of two floating wetland configurations showing hydraulic flow paths. System A, consisting of numerous small floating islands may be prone to the development of dead zones and short-circuiting caused by preferential flow around the islands. Preferential flow paths are less likely to develop with configuration B because the lateral floating wetland bands that traverse the basin width provide a more uniform resistance to flow, whilst the intermediate bands of open water provide opportunities for redistribution of the flow.



It is likely that a certain amount of flow will short-circuit vertically underneath the root zone of the floating wetland, particularly during peak flows when increased water depths mean that the vertical distance between the floating mat and underlying substrate is greatest. At this stage, it is unclear, what effect such vertical short-circuiting will have on the overall treatment performance of the system.

As discussed previously under the section on plants, it will be important to ensure that the basin that is used to contain the floating wetland maintains an adequate depth of water year round to ensure that the roots of the floating wetland plants do not become attached to the benthic sediments. If the plant roots were given the opportunity to become firmly rooted in the bottom of the basin, the floating wetlands may become submerged once the water level rises during a rainfall event. It is recommended that a minimum water depth of 0.5 m should be maintained within the floating wetland basin. This can be achieved through the use of appropriate outlet structures. Floating wetlands may not be appropriate in locations that experience long periods of dry weather unless the water level is actively topped up from external sources.

7.4 Practical Issues

7.4.1 Securing and mooring the floating wetlands

Unsecured floating wetlands will be subject to movement and drift due to wind and wave action, which could cause all of the floating wetland units to accumulate at the leeward end of the pond. Thus, techniques for securely mooring the floating wetlands need to be considered before they are deployed in operational stormwater treatment ponds.

The common approach is to secure the floating wetlands to the side of the pond using synthetic ropes or chains which are fastened to three or four corners of the floating wetland. The materials and devices used will need to be strong and durable enough to withstand the likely extremes of flow rates, waves, wind and water depths during peak storm events.

In some applications, floating wetlands have been anchored to the bottom of the basin. Anchoring to the bottom of a stormwater pond would have to take into account the highest likely water depth in order to make sure that the wetlands do not sink or become submerged during peak flows.

Smaller floating wetland units can often be joined together to form larger floating wetlands using some sort of connecting device.

7.4.2 Wind and Wave Issues

Apart from causing unsecured floating wetlands to move around a pond, wind and waves can also cause small floating wetlands to over-turn. Thus, it is recommended that where relatively small floating wetlands are used in areas subject to high winds, that low-growing vegetation be used. As a rule of thumb, the vegetation planted to a floating wetland should have a maximum growth height that is less than the width of the floating mat in order to avoid tipping.

Floating wetlands have been used to moderate the impact of waves on pond or lake shorelines. Assuming they are stable enough to withstand the wave action, they can be effective at dissipating minor wave energy and reducing swash erosion.

7.4.3 Management Requirements

Assuming durable long-lasting structures are used for the creation and mooring of the floating wetlands, and consideration is given to the extreme conditions likely during intense storm events, floating treatment wetlands should require only minimal on-going maintenance.

Plant harvesting for contaminant removal is not likely to be worthwhile. However, if so desired, harvesting of above-ground biomass on a floating wetland is likely to be relatively easy compared to a surface flow wetland. The floating wetland could be pulled to the bank of the pond for ease of access. In most cases the floating wetland will also be able to support the weight of an adult person during harvesting.

As with any treatment wetland system, monitoring and maintenance may be required during the initial plant establishment period, particularly to control bird damage. There may be some on-going requirements for bird control in order to ensure good plant health. Plant species selection will play an important role in either encouraging or discouraging bird activity.

Given that one of the main treatment processes in a floating treatment wetland will be enhanced sediment accretion, dredging and removal of accumulated sediments from the basin bottom may be needed after a number of years. Removed sediments may contain elevated concentrations of metals and other contaminants and should therefore be managed appropriately. There is the potential for the metals that have been sequestered under reducing conditions in the sediments to become remobilized if the sediments are dredged and allowed to become oxidized.

8 Conclusions and Recommendations

Self-buoyant floating wetlands occur naturally in various parts of the world, although they represent a relatively uncommon type of wetland ecosystem. The concept of artificially creating floating wetlands for the purpose of water treatment has emerged over the past two decades as a variation on the conventional constructed wetland designs that typically involve sediment-rooted emergent macrophytes or smaller free-floating aquatic plants. To date, floating treatment wetlands (FTWs) have been used for the treatment of a range of polluted waters and effluents. However, there are no published reports of direct application of FTWs specifically for stormwater treatment.

Floating treatment wetlands offer great potential as a relatively simple, low-cost, passive option for the upgrading of existing stormwater ponds in order to enhance the removal of fine particles and associated metals. FTWs may also be suitable for incorporating into stormwater wetland systems, especially those suffering vegetation decline due to inappropriate water depths and excessive inundation. For new systems, a stormwater treatment train designed to optimize fine particulate and metal removal may consist of a coarse sediment removal forebay, surface flow wetland section, FTW zone followed by an open-water pond prior to discharge. However, substantial research is needed in order to identify the key treatment processes and expected treatment performance of FTWs for stormwater quality improvement.

The predominant pathways for the removal of copper and zinc from stormwater are expected to be via the entrapment of fine particulates and their adsorbed metals within the network of roots and biofilms that develops under the floating wetland mat and subsequent sloughing of this material as heavier particles that readily settles under the relatively quiescent conditions that develop under the protection of the floating mat. Once incorporated into the sediments beneath the FTW, the reducing conditions created by the limited oxygen exchange and input of plant derived organic matter is likely to contribute to the immobilization of copper and zinc in the form of organic complexes, zinc sulphide and insoluble native copper. Investigations are required to validate and quantify these processes.

A number of important areas for further research were identified during the compilation of this review in order to verify and realize the potential of FTWs for enhanced stormwater treatment within the Auckland region, including:

- Identification of the main removal processes and pathways for copper, zinc and other stormwater contaminants within FTWs.
- Determination of FTW design criteria based on the relationship between the stormwater loading rate (hydraulic and/or contaminant) and the removal rate for various contaminants of concern in order to enable the sizing of FTWs with a reasonable level of confidence.
- Examination of the redox conditions that develop within the water column and sediments underlying a FTW receiving stormwater, particularly with regard to how these conditions affect metal removal.

- Identification of the relationship between the ratio of open water to floating wetland cover and the redox status of the underlying water column and sediments within a FTW-pond system receiving stormwater.
- Identification of suitable native New Zealand wetland plant species and the extent of their root development beneath a FTW under varying redox and nutrient conditions.
- Quantification of the amount of fine sediments and associated metals captured within the root-biofilm network beneath a FTW and the rate at which this material may be sloughed off and deposited within the sediments.
- Investigation into the relationship between copper and zinc removal and the water depth, relative to the rooting depth of the FTW vegetation.
- Quantification of the significance of plant uptake as a removal pathway for copper and zinc and the ultimate fate of this plant material within a FTW system.

Before full-scale FTW applications are attempted, the following practical issues would need to be resolved at pilot and field scale:

- Determination of the most suitable and cost-effective materials and technique for constructing stormwater FTWs.
- Identification of suitable techniques for securely mooring and anchoring FTWs within stormwater ponds.
- Identification of techniques for successful plant establishment, particularly with regard to minimizing the impact of birdlife.

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9.1 Personal Communications

Bernie Masters of Floating Island Australasia, Capel, Western Australia, 14th July 2006.

Bestmann Green Systems Pty Ltd., Tangstedt, Germany, 2006 (various communications).

Anne Lamont-Low and Bruce Kania of Floating Island International Pty Ltd., Montana, USA, 2006 (various communications).

10 Appendix 1: Terminology used around the world to describe natural and artificial floating wetlands.

Natural:

- Floating Island: general term used to describe any floating piece of land, commonly consisting of peaty soil and/or buoyant aquatic vegetation. Does not necessarily imply an island dominated by wetland vegetation.
- "Flotant": natural floating marshes in Louisiana, USA.
- Floating Marsh: technical term used to describe "Flotants" listed above.
- Floating Typha Mats: floating wetland dominated by *Typha* spp. in Canada.
- "Tussocks": terminology used in Florida, USA, to describe, often undesirable, floating marsh islands.
- "Plav": extensive floating mats dominated by *Phragmites australis* covering approximately 100 000 ha of the Danube River Delta in Romania.
- "Sudd": floating wetlands in central and east Africa.
- "*Embalsados*" – (floating soils): floating peatlands in Argentina.
- Floating Peat- term used predominantly in the Netherlands in reference to peat that becomes buoyant when cut-over peat lands are rewetted. Typically dominated by growth of *Sphagnum* vegetation.

Artificial:

- Floating Vegetation Mat (FVM): constructed floating treatment wetlands in Canada, predominantly used for treatment of acid mine drainage (Smith and Kalin, 2000).
- Floating Reedbed Rafts (UK).
- Floating Meadows (Hungary).
- Vetiver Grass Pontoons (floating treatment wetlands specifically using vetiver grass).
- Floating Pond Restorer™ (floating wetland system developed by Ocean Arks International in the USA for upgrading the performance of wastewater treatment ponds).

- Floating Islands: BioHaven^{TM} artificial floating wetland systems developed and marketed by Floating Islands International (Montana, USA) utilising a specifically designed spun polyester matrix injected with patches of buoyant polystyrene foam.
- Floating Wetland Islands and Floating Wetland Blankets: Aquagreen^{TM} floating wetland systems developed and marketed by Bestmann Green Systems, BGS Ingenieurbiologie und –okologie GmbH (Tangstedt, Germany).