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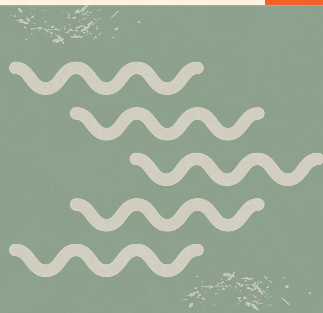
Finding the Balance:



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Vegetated Floating Islands Enhance the Ability of Wetlands to Reduce Nutrients and Other Pollutants

PRESENTER



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Bernie Masters holds a science degree majoring in geology and zoology from the University of WA. He has worked as a geologist, wildlife conservation officer, member of Parliament and environmental consultant. In 2007, he co-founded FIA Technology Pty Ltd to make and install vegetated floating islands. He is a member of the board of the South West Catchments Council and a former member of the Geographe Catchment Council.

Summary

Natural and constructed wetlands have been used to improve water quality in urban, industrial and agricultural environments for more than 40 years. Initially, pollutant uptake by wetland plants was assumed to be the primary removal mechanism but research now shows that bacterial/algal biofilms growing on all solid surfaces within the water column remove more than 80% of pollutants, although plants are needed to transfer oxygen and carbon to biofilms to maximise their pollutant-removal capacity.

Vegetated floating islands designed to maximise biofilm development were commercialised in the USA in the mid-2000s. Their placement on the surface of wetlands and other waterbodies significantly increases the area of biofilm capable of removing nutrients and other pollutants, while also shading the water column, reducing water temperature and creating useful wildlife habitat. This paper summarises the science which underpins their pollutant-reduction abilities and lists the current suppliers of floating islands in Australia.

Introduction

In the 1980s, when natural or constructed wetlands were first used in Australia to improve water quality, doubts were expressed about the ability of wetlands to reduce nutrients, heavy metals and other pollutants. Since then, research on the use of wetlands for water quality improvement has been extensive, with different constructed wetland designs now available to treat different pollutants. Published literature on constructed wetlands is widely available; conferences on their use are regularly held; and regulatory authorities now accept that well-designed wetlands have an important role to play in helping to overcome some of the adverse impacts of urbanisation, industry and agriculture.

Vegetated floating islands were first used for water quality improvement in the late 1990s. The scientific understanding of the biological processes involved in their ability to remove pollutants is slowly but steadily improving but academic and regulatory acceptance of their use remains modest. This paper is designed to show that, like wetlands, the use of floating islands is on a similar pathway of understanding and acceptance.

History of Wetlands and Water Quality Improvement

Wetlands for water quality improvement appear to have been first formally used in 1971 when a large biological filtration system was constructed in Missouri, USA, to treat acidic wastewater from a lead mine and mill (Erten *et al.*, 1988). Through the 1970s and 1980s, researchers investigated the use of natural wetlands for domestic sewage wastewater treatment (e.g., Boyt *et al.* 1977, Tilton and Kadlec 1979, Deghi *et al.* 1980, Dierberg and Brezonik 1982). While bacteria, algae and periphyton were considered to be important in removing nitrogen from polluted water, quantification of their role in removing pollutants was largely absent from the scientific literature, with the focus generally placed on plants which were assumed to take up most pollutants. It wasn't until 1988 at the First International Conference on Constructed Wetlands for Wastewater Treatment held in Tennessee, USA that the science underlying the use of wetlands for water quality improvement began to be accepted by regulatory authorities and water managers (Hammer 1989).

History of Vegetated Floating Islands and Water Quality Improvement

The idea of constructing a floating platform on which plants could be grown to improve water quality was first assessed in China, Japan and Taiwan in the 1990s. Floating beds of *Canna Cana generalis* were placed on fish ponds and their biomass production was measured (Wu, *et al.* 2000). Similar soil-less floating beds planted with *Canna* were also used to improve eutrophic water quality, with coverage of 20% recommended to achieve significant improvements (Bing and Chen 2001).

A vegetated floating island made from lightweight concrete was used in Kasumigaura Lake, Japan, in 1998 to create fish and water bird habitat while improving water quality and landscape (Noriyoshi *et al.* 1999) and to reduce shoreline erosion (Keigo *et al.* 1999). Trials in the USA in 1987 using the floating plant pennywort *Hydrocotyle umbellata* improved domestic sewage water quality (DeBusk *et al.* 1989). Managers of Heathrow Airport in London, U.K., then trialed in 1994 and installed floating reed beds to remove glycol from stormwater (Revitt *et al.* 1997, Chong *et al.* 1999, Revitt *et al.* 2001, Richter *et al.* 2003).

Credit must go to Bruce Kania of Floating Island International LLC (FII)—see www.floatingislandinternational.com—for the first commercialisation of vegetated floating islands. In 2000, Kania began experimenting with different designs and construction materials for floating islands, initiating extensive laboratory research (Stewart 2005, Stewart *et al.* 2008). Commercial production started in 2005, with the company understanding the important role of microbes in nutrient removal, while also recognising that ‘microbial removal rates were three times greater in the presence of plant roots’ (Hammer 1990). FII researcher Frank Stewart (2008) concluded: ‘it appears that each square foot of floating island was about 8 times more effective than each square foot of wetland for removing nitrate.’

After extensive studies, FII’s research on their 20 cm thick floating islands gave removal rates in outdoor and laboratory test ponds of:

- ammonium—1.3 to 3.0 kg/square metre/year.
- nitrate—3.0 to 41.6 kg/square metre/year.
- phosphate—0.4 to 1.7 kg/square metre/year.
- BOD—2.2 kg/square metre/year.

In a review article, Dodkins and Mendzil (2014) concluded that vegetated floating islands have many benefits over free water surface wetlands:

1. Plant roots assist in filtering and settling processes for sediment bound P and metals.
2. Plant roots act as a large surface area for micro-organism activity in: decomposition, nitrification, and denitrification (removal of BOD and N).
3. Mild acidification of water due to release of humic acids; and a C input from senescent vegetation, assist denitrification.
4. Floating islands can adjust to varying water levels.
5. A higher retention time is possible as ponds on which islands are placed can be made deeper without submerging the vegetation.

The percentage removal of nutrients and metals from effluent is 20–40% higher in wetlands with floating islands than in conventional free surface water wetlands. 20% coverage of islands is optimal for aerobic basins. 100% cover is optimal for anaerobic basins or aerobic basins where there is artificial aeration. The design of floating islands and control of basin water chemistry are essential for optimising treatment efficiencies.

Borne (2014) compared the fate and removal performance of phosphorus (P) in two parallel stormwater retention ponds, one retrofitted with a vegetated floating island and one without any vegetation, in a field trial near Auckland, New Zealand. Results suggested that inclusion of a vegetated floating island would significantly improve P removal efficiency, showing a 27% lower Total P outlet event mean concentration than from a conventional retention pond. Inlet particulate-bound P is thought to have been associated with particulate copper on fine particles like colloidal organic matter and/or clay and to be trapped in the sticky biofilm of the roots, followed by sloughing of biofilm which then settled on the bottom of the pond. The pond with the floating island induced a more neutral pH within and higher organic release into the water column, likely promoting dissolved P sorption onto particles. Interestingly, the reduced (low redox potential) sediment observed below the floating island did not induce P release probably due to the more neutral pH conditions which allowed re-adsorption onto organics and/or clay minerals (e.g. Al-OH). This resulted in higher P sediment accumulation in the treatment pond. P uptake by plants was not thought to be a significant removal pathway. Sorption of dissolved P, physical entrapment of particulate P in roots and then its settlement onto the floor of the wetland were thought to be the main P removal pathways for ponds equipped with floating islands.

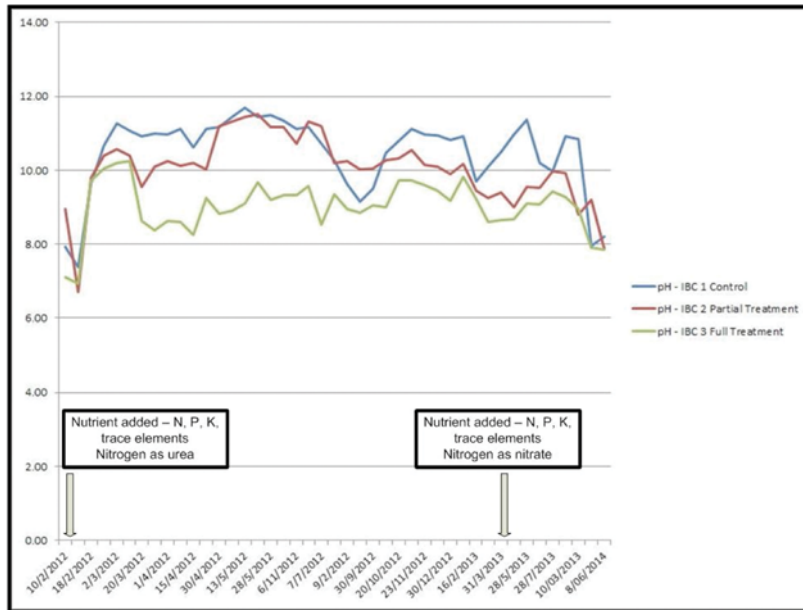
FIA Technology Pty Ltd conducted a microcosm trial using one cubic metre intermediate bulk containers (IBCs) (Masters, unpublished). Over the 30 months of this trial which began in February 2012, IBC 3 containing the vegetated floating island developed into a stable, complex ecosystem with excellent water clarity. In contrast, water in the Control and Partial

Treatment IBCs remained green with high levels of planktonic algae. Conclusions from the trial were that vegetated floating islands improve water quality in the following ways:

- Lower pH—see figure 1.
- Rapid removal of NH_4 which remains at sustained low levels—see figure 2
- Rapid removal of NO_3
- High water clarity in spite of elevated nutrient levels—see figure 3.

Figure 1. pH variation over 30 months in a microcosm trial involving one cubic metre international bulk containers:

- IBC 1 control—no floating island or vegetation
- IBC 2 partial treatment—an unvegetated floating island
- IBC 3 full treatment—a vegetated floating island



Research by Vázquez-Burney (2015) on vegetated floating islands in Florida, USA, used 149 m² of islands on a 1,122 m² pond (7% of pond area) over a 17 month period with a hydraulic residence time averaging 15.7 days. The islands were found to enhance pond nitrogen removal capacity by 32%. By evaluating the difference between the treatment and control periods, an incremental total nitrogen removal rate for the islands was calculated to be 4.2 kg N/m²/year.

Figure 2. NH_4 variation over 30 months of microcosm trial

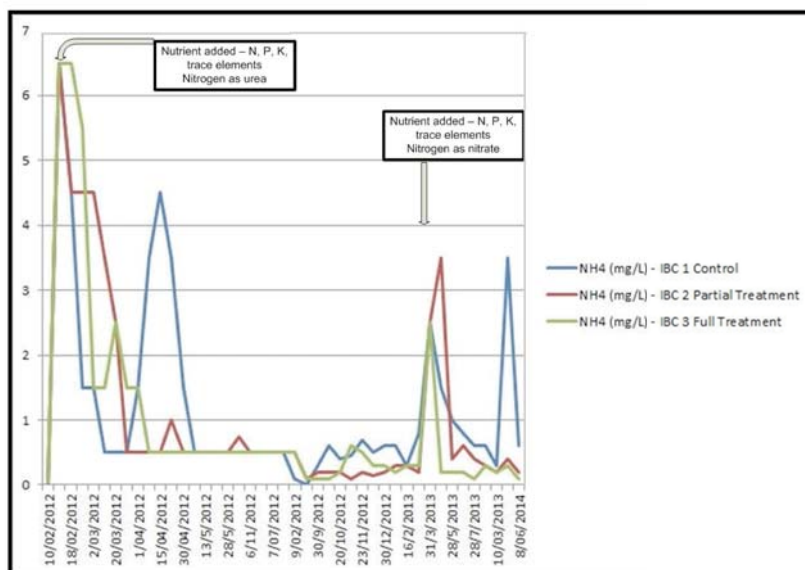
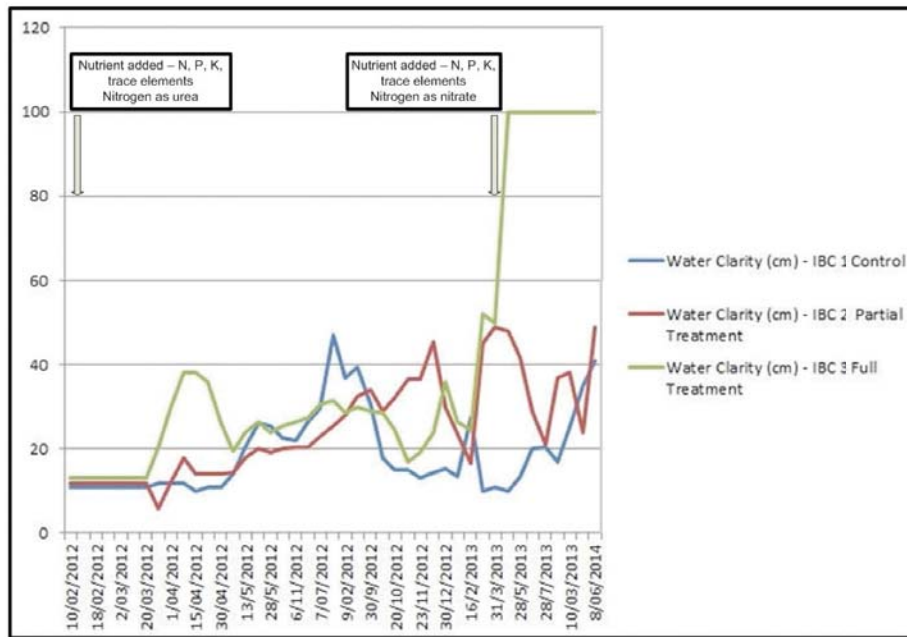


Figure 3. water clarity variation over 30 months of microcosm trial



What Causes Constructed Wetlands and, by Definition, Vegetated Floating Islands To Remove Nutrients—Plants or Bacteria?

For over 150 years, sewage engineers have known that “in the biological filter the purifying agencies are micro-organisms living in a gelatinous film on the filter medium” (Anon, 1987). Researchers investigating the use of natural and constructed wetlands for treatment of wastewaters found evidence in 1978 that nitrogen fixation is carried out in Western Australian wetlands by organisms related to those known to fix nitrogen in other regions (Finlayson and McComb 1978), with the presence of plant rhizomes greatly enhancing the rate of bacterial fixation, “presumably because the higher plant releases exudates which provide substrates for bacteria in the rhizosphere”.

In 1990, Hammer stated that “Water purification functions of wetlands are dependent upon four principle components—vegetation, water column, substrates and microbial populations”.

The multi-phase involvement of bacteria in nutrient removal was recognised by Fisher in 1990: “Biological nitrification-denitrification and plant uptake are usually the two most significant nitrogen removal mechanisms in artificial wetlands. Micro-organisms which proliferate in the aerobic root zone in an artificial wetland can stabilise organics and nitrify ammonium to nitrate. As the wastewater then flows into anoxic zones within the wetland, microbially mediated denitrification can convert nitrate to nitrogen gas which is then released to the atmosphere.”

Sinke *et al.* 1993 showed that bacteria play a considerable role in phosphate uptake by aerobic sediments. Uptake depends on the supply of organic carbon and removal was found to vary between 12 and 63% of the total phosphate held in the studied sediments. They concluded that bacterial processes have the potential to largely regulate the seasonal dynamics of phosphate concentration in the overlying water.

According to Bishay *et al.* 2005, “...it is clear that such processes (ammonia-processing stoichiometries) require oxygen, and are microbially mediated. In turn, the microbes involved are situated almost exclusively in biofilms on solid surfaces in the wetland water column”.

In a pilot-scale engineered wetland ecosystem, mass balances showed that bacteria removed 36% of the influent nitrogen, compared to algae and plants which removed just 5% (Kavanagh and Keller 2007). In subsurface-flow treatment wetlands, direct nutrient uptake by plants was insufficient to account for more than a fraction of the improved removal shown by planted systems (Tanner 2001): over a year, net storage in live plant tissues only accounted for 2–8% of total nitrogen removal and 1.9–5.3% of total phosphorous removal.

In subsurface constructed wetlands treating wastewater, nutrient removal efficiencies in two different wetlands removed between 51.8 and 74% of phosphorous, with plants contributing between 3 and 12% of the total phosphorous removal (Yousefi and Mohseni-Bandpei 2010).

The Two Major Problems with Phosphorous

Phosphorous removal from polluted water poses two problems. First, phosphorous is usually the limiting nutrient in fresh waterbodies (Schindler 2008). If nitrogen is limiting, cyanobacteria can extract atmospheric nitrogen and produce bacterial blooms. Accordingly, phosphorous reduction should be the primary goal of wastewater treatment systems, even when inflowing or ambient phosphorous levels are very low, for example, 0.1 mg/L (Anon. 2009).

Second, in most situations, organically-bound phosphorous is removed from the water column and added to the wetland sediments. Changes in physio-chemical conditions can then allow the stored phosphorous to again become biologically available. In field situations, phosphorous “is rapidly recycled between sediments and water”, with cyanobacteria such as *Microcystis* able to consume excess phosphorous at the sediment-water interface and then rise to the water surface to form blooms (Conley *et al.* 2009).

Phosphorus accumulates in wetland sediments and plant litter which together are a major pool for phosphorous (more than 95%) in natural wetlands, with phosphorous able to be released back into the water column (Main *et al.* 2005). Adsorption of phosphorous by iron, calcium, magnesium and aluminium minerals in the sediment is considered the most significant mechanism for more permanent phosphorous removal.

A detailed ecosystem model of phosphorous dynamics in a constructed riparian wetland showed that macrophytes pumped phosphorous out of deep sediments, causing an increase in total phosphorous in the water column mostly during the non-growing season (Belmont *et al.* 2009). The use of wetland plants which senesce over winter should therefore be avoided.

A pilot-scale engineered ecosystem showed that phosphorous was not removed by the system due to the lack of regular sludge removal (Kavanagh and Keller 2007). The authors stated: “Phosphorus can be regarded as a “conserved” entity in this system since it cannot be removed atmospherically ... (this) suggests that over 90% of the influent phosphorus passes through the (system) and is discharged with the effluent as expected. The actual phosphorus removal by plant growth is clearly shown to be very small, accounting for about 6% of total incoming phosphorus.”

Even where lake sediments have high phosphorous sorption capacities, they may release phosphorous into the water column by desorption under aerobic conditions if water-column phosphorous concentrations are low enough (Belmont *et al.* 2009). Hence, reducing the phosphorous concentrations in inflowing waters may not be sufficient to prevent adverse algal and cyanobacterial blooms from developing.

Overall, many wetlands are ineffective in removing phosphorous due to unsuitable physiochemical conditions at the water/basal sediment interface. Other wetlands can remove phosphorous initially but then begin to export this nutrient. Physical removal of the materials within which phosphorous is stored within the wetland—primarily within basal organic-rich sediments—is essential if medium- to long-term phosphorous reduction from through-flowing water is to occur.

Clearly, while plants play an important role in nutrient removal from wetlands (and hence from vegetated floating islands), bacterial biofilms are far more important.

Current Suppliers Of Floating Islands

In Australia, three companies currently design, manufacture and install (as required) vegetated floating islands.

Aqua Biofilter—www.aquabiofilter.com—has floating island trials in China (Duncan 2009) together with some smaller installations in Australia. According to the company’s website, the Aqua Biofilter floating island is “an advanced Floating Wetland Treatment Technology that can be utilised within a Wetland Treatment Train either retro-fitting or designed into future wetlands. Detention basins can be designed larger and deeper, effectively providing more storage and hydraulic retention times. Wetlands can also be sized smaller as a result, bringing down costs, achieving best practice and effectively treating Total Nitrogen, Total Phosphorous, Total Suspended Solids and reducing heavy metals.”

Aqua Biofilter islands installed in China are made from low density buoyant bamboo. In Australia, sealed plastic piping provides buoyancy, with wetland plant species planted into a layer of coconut fibre matting.

Spel Environmental—see spel.com.au/products/spel-wetlands. Spel’s Floating Treatment Media are made from recycled PET as used in plastic drink bottles. This plastic is made into a non-woven, non-toxic durable matrix of fibres. Dense and porous, it is inert and has been coated in a UV-resistant resin to US EPA irradiation accelerated degradation standards. Sheets of fibre matrix are bonded together with foam to provide buoyancy. Plants are inserted into the material and grow down into the water hydroponically. The biological processes occurring within the biomass of their islands are the same as in activated sludge but have the added advantage of increased microbial activity. Microbes and bacteria adhere to the roots of the plants and within the fibrous structure of the media themselves, secreting sticky extracellular proteins. Within these biofilms, microbes and bacteria trap and digest organic matter and nutrients in wastewater, including total suspended solids, biochemical oxygen demand, nitrogen and phosphorus.

The principal of surface area is: the more underwater surface area that is available for microbes and bacteria to stick to, the cleaner the water. This surface area is called the Bio-Mediation Quotient (BMQ): Spel’s floating media and root structure

combination has a BMQ in excess of 1,000m² per 1 m² of island which means 100 m² of planted active suspended media has more than 10ha of surface area.

FIA Technology Pty Ltd—www.floatingislands.com.au—(Australia-wide agent is www.clearwaterlakesandponds.com.au)—has its vegetated floating islands installed in many locations throughout Australia. FIA's island design has two key features. Buoyancy and strength are provided via an external frame made from air blown recycled plastic rods having a density of about 0.7 g/cc. Air bubbles are trapped within the plastic rods during the extrusion process, ensuring that water cannot leak in. This inherent buoyancy is insurance against vandalism and protects against the possibility of leakage of water into (and air out of) sealed pipes, drums or other containers.

FIA's design maximises the development of bacterial biofilm within the bed of each island by placing shredded plastic wastes (nylon carpet, polystyrene packaging, and polyurethane mattresses) between two layers of UV-resistant shade cloth, thereby increasing the internal surface area on which biofilm can develop. Wetland plants placed onto the pocket create a dense root mat which provides further surface area for biofilm development. FIA's first floating island installation was in 2008 at the Etiwanda stormwater detention pond, Mildura, Victoria, where it has survived flood conditions unscathed.

Importance Of Plants On Floating Islands

Plants are critically important, even though they remove only a small proportion of nutrients from the water column. Plants translocate oxygen into the underlying substrate, stimulating both nitrification of ammonia and the breakdown of biological oxygen demand (Gersberg 1986). Artificial vegetated wetland filters had higher oxygen concentrations, pH, redox potential and metal retention than in systems without plants (Dunbabin 1988). Efficient nitrate removal from wetlands depends on denitrification which is supported by macrophytes which supply organic carbon (Weisner 1994) to denitrifying bacteria via plant litter. In turn, plants also offer attachment surfaces for epiphytes which produce additional organic matter.

Macrophytes have several intrinsic properties that make them an indispensable component of constructed wetlands (Brix 1994): their most important functions are their physical effects: they provide good conditions for physical filtration and provide a huge surface area for attached microbial growth. Macrophyte-mediated transfer of oxygen to the rhizosphere by leakage from roots increases aerobic degradation of organic matter and nitrification.

The major roles of macrophytes in constructed wetlands as determined by Sundaravadivel and Vigneswaran (2001) are:

Wetland plant part	Wetland Plant Role
Aerial plant tissues	Light attenuation → reduced growth of phytoplankton Influence on microclimate → insulation during winter Reduced wind velocity → reduced risk of resuspension of solids Aesthetic appearance Nutrient storage
Plant tissue in water	Filtering effect → filter out large debris Reduced current velocity → increase rate of sedimentation, reduced risk of resuspension Surface area for attached microorganisms Excretion of photosynthetic oxygen increased → aerobic degradation Nutrient uptake
Roots and rhizomes	Stabilising the sediment surface → less soil erosion Release of oxygen increases organic degradation and nitrification Nutrient uptake Secretion of antibiotics for detoxification of root zone → pathogen removal

Macrophytes assimilate and store nutrient elements such as nitrogen and phosphorous, transport oxygen to the root zone, provide substrates for microbes and inhibit growth of algae (Chong 2003).

Vegetated floating structures have plant roots growing down into the water column while plant stems remain above water level (Hedley and Tanner 2008). The plants grow in a hydroponic manner, taking their nutrition directly from the water column in the absence of soil. Beneath the floating structure, a hanging network of roots, rhizomes and attached biofilms is formed, providing a biologically active surface area for biochemical processes as well as physical processes such as filtering and entrapment.

Conclusions

In the 1970s and 1980s, the use of natural and constructed wetlands for water quality improvement was a new field of science. Water managers were uncertain of the design parameters required to maximise pollutant removal. Researchers were uncertain of the processes responsible for pollutant removal. Regulators were uncertain of the efficiency with which wetlands removed pollutants. Yet 30 years later, tens of thousands of constructed wetlands operate around the world, with bacteria—supported by plants—responsible for most of the pollutants being removed from a multitude of different wastewaters.

Since the mid-2000s, the promotion of floating islands to improve pollutant removal efficiencies of constructed and natural wetlands has seen water managers, researchers and regulators show understandable caution in the uptake of this new natural technology. This paper shows that vegetated floating islands are a highly effective supplement to wetlands designed to improve water quality in polluted urban, agricultural and industrial environments.

The key messages are:

- Bacterial biofilms develop on all physical surfaces within a wetland and these bacteria within and beneath floating islands, supplemented by oxygen and carbon from plants, do the bulk of the pollution-reduction work.
- While nitrogen generally escapes to the atmosphere after bacterial degradation of ammonia, nitrite and nitrate compounds, phosphorous is taken up within bacterial and other organic matter, eventually falling to the bottom of the wetlands where it can become biologically available under altered physical and chemical conditions. Physical removal of this material at appropriate intervals is essential.
- Vegetated floating islands massively increase the surface area of bacterial/ algal biofilm within a wetland, enhancing the wetland's ability to reduce the levels of nutrients and other pollutants within inflowing water.

References

A list of the 42 references quoted in this paper is available on request to the author at bmasters@iinet.net.au