The ability of vegetated floating Islands to improve water quality in natural and constructed wetlands: a review

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Abstract

Constructed and natural wetlands are widely used to improve many water quality parameters. Vegetated floating islands (VFIs) placed on the surface of these wetlands significantly enhance the efficiency of natural processes that reduce nutrients, suspended solids, heavy metals and other pollutants.

Pollutant reduction in VFIs, particularly nutrients such as nitrogen and phosphorous, occurs primarily through the actions of bacterial biofilms growing within the island matrix and on plant roots hanging below the islands. Direct uptake of nutrients by plants is minor, although plants are essential as they provide additional substrate for biofilm development while supplying oxygen and carbon for use by the bacteria.

Nitrogen-based nutrients are primarily removed from wetlands as nitrogen gas. Phosphorous is mostly deposited as organic-rich sediment which accumulates within or beneath the floating islands. This material can become anoxic and return its contained phosphorous to the water column, making it biologically available for algal or bacterial blooms that degrade water quality. Physical removal of this P-rich material is an essential wetland management action.

VFIs can remove phosphorous at up to $4.6 \, \text{g/m}^2/\text{day}$ and ammonia at up to $8.1 \, \text{g/m}^2/\text{day}$ with simultaneous denitrification of nitrate to nitrogen gas.

VFIs can significantly increase the efficiency of pollutant removal from natural and constructed wetlands.

Key words: bacteria, floating island, nitrogen, nutrient removal, phosphorous, wetland,

INTRODUCTION

The use of natural or constructed wetlands for water quality improvement began in the USA in the 1970s, with natural wetlands used to treat domestic sewage. The processes involved in this treatment process were largely unknown. Today, tens of thousands of constructed and natural wetlands around the world and scattered throughout all climatic zones remove or reduce a wide range of pollutants including heavy metals, biocides, nutrients such as phosphorous and nitrogen, petroleum-based chemicals and various human pathogens from water using natural processes.

Beginning in the mid-2000s, the use of vegetated floating structures to enhance the efficiency of constructed and natural wetlands to remove pollutants began to be applied to the open water sections of treatment wetlands. This paper reviews the history of vegetated floating islands (VFIs), outlines the natural processes at work within and beneath VFIs which cause them to significantly improve the efficiencies of treatment wetlands, and describes several of the different designs of VFIs currently available.

THE HISTORY OF NATURAL AND CONSTRUCTED WETLANDS FOR WATER QUALITY IMPROVEMENT

In the 11th century CE, rice farmers in Vietnam and China used the floating fern *Azolla* in their constructed wetlands or paddies to extract dissolved nutrients, after which the fern was collected and

used as a soil fertiliser or animal feed (Whitton & Potts 1999). Its symbiotic relationship with a cya-nobacterium *Anabaena* (Shi & Hall 1988) may be a recent scientific discovery but the functioning of this and other bacteria explains the ability of *Azolla*, like VFIs, to remove nitrogen and other pollutants.

The use of wetlands for water quality control appears to have been first formally used in 1971 when a large biological filtration system was constructed in south-east Missouri, USA, to treat acidic waste-water from a lead mine and mill operation (Erten *et al.* 1988). Throughout the 1970s and 1980s, researchers investigated the use of natural wetlands for domestic sewage wastewater treatment (Boyt *et al.* 1977; Tilton & Kadlec 1979; Deghi *et al.* 1980; Dierberg & Brezonik 1982).

However, it wasn't until 1988 when the First International Conference on Constructed Wetlands for Wastewater Treatment was held in Tennessee, USA (Hammer 1989), that the science underlying the use of wetlands for water quality improvement began to be accepted by regulatory authorities and water managers. Bacteria were considered to be important in removing nitrogen from polluted water, while algae and periphyton were considered to have a lesser role in the natural water cleaning processes that operated within wetlands.

THE HISTORY OF VEGETATED FLOATING ISLANDS FOR WATER QUALITY IMPROVEMENT

Floating islands are a natural feature of many wetlands around the world (Van Duzer 2004). However, the inspiration for using vegetated floating structures for water quality improvements appears to have arisen in South East Asia where floating plants such as *Azolla* and water hyacinth *Eichhornia crassipes* have been used to remove nutrients from water for centuries (Whitton & Potts *ibid.*).

Reports on the early use of floating plants to improve water quality are few. Water hyacinth was recommended for use to purify wastewater in Auckland, New Zealand, and Yorkshire, U.K., in the first half of the 20th Century (Dymond undated). In the 1970s, the US National Aeronautical and Space Administration fenced off part of a 16 ha sewage lagoon and used water hyacinth to turn a 'once-noxious test area' into 'a clean aquatic flower garden' (Anon. undated).

The concept of constructing a floating platform on which plants could be grown to improve water quality originated 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 control eutrophic water, with coverage of 20% recommended to significantly improve water quality (Bing & Chen 2001).

A VFI 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 *Hydroctyle umbellate* successfully improved domestic sewage water quality (DeBusk *et al.* 1989), although no larger scale evaluation of this concept followed. In 1984, Heathrow Airport in London, U.K., installed floating reed beds to remove glycol, used to de-ice runways and other surfaces, from stormwater (Revitt *et al.* 1997; Chong *et al.* 1999; Richter *et al.* 2003).

In 1998, VFIs were placed in Lake Mead, Nevada, to evaluate their nutrient removing ability while also assessing the structural durability of the islands and aspects of the plants growing on the islands (Boutell 2002).

Credit must go to Bruce Kania of Floating Island International LLC (FII) for the first commercialisation of VFIs. Starting in 2000, Kania began experimenting with different designs and construction materials for floating islands, initiating extensive laboratory research (Stewart 2005; Stewart *et al.* 2008), with commercial island production beginning in 2005. FII's VFIs consist of a spun polyester mesh within (and below) which plant roots and bacterial biofilm develop together.

Stewart (*ibid*.) 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 in … three studies.'

FII summarised the key findings of research funded by the Montana Board of Research and Commercialization Technology on FII's BioHaven floating islands (which are some 20 cm thick) as follows (see http://www.floatingislandinternational.com):

The best removal rates obtained by BioHaven floating islands in outdoor test ponds were:

- Ammonium 8.2 g/square metre/day (3.0 kg/year)
- Nitrate 8.2 g/square metre/day (3.0 kg/year)
- Phosphate 1.14 g/square metre/day (0.4 kg/year)
- Biological oxygen demand (BOD) 5.9 g/square metre/day (2.2 kg/year)

The best removal rates obtained by BioHaven floating islands in test tanks under laboratory conditions were:

- Ammonium 3.6 g/square metre/day (1.3 kg/year)
- Nitrate 114 g/square metre/day (41.6 kg/year)
- Phosphate 4.6 g/square metre/day (1.7 kg/year)

BioHaven floating islands achieved simultaneous aerobic and anoxic removal of ammonium, nitrate, phosphate, and organic carbon within a single island in a single impoundment.

WHAT MAKES CONSTRUCTED WETLANDS AND, BY DEFINITION, VEGETATED FLOATING ISLANDS WORK – 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). This was also well known to early researchers investigating the use of natural and constructed wetlands for treatment of wastewaters. Hammer (1990) 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 (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 …… Phosphorus transformations in artificial wetlands include chemical precipitation, adsorption onto sediments (particularly sediments containing clay or iron, aluminium or calcium salts), incorporation into microbial biomass, and plant uptake.'

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

Bishay & Kadlec (2005) state: '… 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 ecosystem, mass balances showed that bacteria removed 36% of the influent nitrogen, compared to algae and plants which removed just 5% (Kavanagh & 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 an

annual period, 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 types of wetland designs removed between 51.8 and 74% of phosphorous, with plants contributing between 3 and 12% of the total phosphorous removal (Yousefi & Mohseni-Bandpei 2010).

Clearly, bacteria undertake most nutrient removal within wetlands, forming biofilms on all available physical surfaces, including live plant stems and roots, as well as inanimate surfaces such as soil and dead timber. It is a crucially important step to accept that bacteria do most of the nutrient removal work within floating islands (as well as in natural and constructed wetlands) and that the use of well designed VFIs can significantly enhance overall nutrient removal efficiencies in wetlands.

TWO PROBLEMS WITH PHOSPHOROUS

Phosphorous removal from polluted water poses two serious problems. First, phosphorous is usually the limiting nutrient in fresh waterbodies (Schindler *et al.* 2008). If nitrogen is limiting, cyanobacteria can still extract atmospheric nitrogen and produce bacterial blooms which adversely impact upon water quality. 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 per litre (Anon. 2009).

Second, in most situations, phosphorous is removed from the water column and added to the basal sediments of lakes and other waterbodies. Changes in physio-chemical conditions within the wetland 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 vertically migrate, consume excess phosphorous at the sediment-water interface and then rise to the water surface to form blooms (Conley *et al.* 2009).

This bioavailability of organic-bound phosphorous within sediments has been repeatedly reported by laboratory and field researchers. A stormwater wetland constructed in North Carolina, U.S.A., showed that median reduction efficiencies for phosphorous ranged from −95% to +70%, meaning that one wetland was at times exporting almost double the amount of phosphorous it was receiving in influent water (Line *et al.* 2008).

In a study of phosphate distribution within an artificial wetland, there was a release of phosphorous from the organic-phosphorous fraction of the sediment, probably due to anoxic conditions (Maine *et al.* 2005).

Phosphorus is typically present in wastewater as orthophosphate and organic phosphorous. It accumulates in wetland sediments and plant litter which together are a major pool for phosphorous (more than 95%) in the cases of natural wetlands. Sedimentation is a physical process whereby particulate matter containing phosphorous settles and accumulates on the wetland floor. If the particulate materials are biodegradable organics, after degradation, phosphorous will be released back into the water column (Sundaravadivel & Vigneswaran 2001).

A detailed ecosystem model of phosphorous dynamics in a constructed riparian wetland showed via simulations that macrophytes pumped phosphorous out of deep sediments, causing an increase in total phosphorous in the water column mostly during the non-growing season (Wang & Mitsch 2000). While this is less of a problem in temperate and warm climates, the use of wetland plants which senesce over winter should be avoided.

In artificial wetlands, phosphorous 'transformations relocate phosphorus in the system and ultimate phosphorus removal from an artificial wetland is achieved by harvesting the plants or dredging the sediment' (Fisher, *ibid.*), although other researchers – see below – have shown that harvesting of plants removes only a small proportion of total stored nutrients.

A pilot-scale engineered ecosystem that operated for over two years showed that phosphorous was not removed by the system due to the lack of regular sludge removal (Yousefi and Mohseni-Bandpei, *ibid.*). The authors stated: 'Phosphorus can be regarded as a 'conserved' entity in this system since it cannot be removed atmospherically as can nitrogen, nor degraded into CO_2 and H_2O as can COD and organic solids, therefore all inputs and outputs can be directly measured and accounted for …. The balance 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. This fraction is often strongly overrated, but that may be affected by temporary phosphorus binding to the soil or substratum used in wetlands and the like.'

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, while some natural and constructed wetlands are able to reduce phosphorous from polluted water, many are ineffective in performing this essential task due to inappropriate physiochemical conditions prevailing within the wetlands, while other wetlands 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.

CURRENT SUPPLIERS OF FLOATING ISLANDS

World-wide, a number of companies and individuals supply a range of floating island products – see (Headley & Tanner 2006) for a review of technologies and designs. These products vary from islands whose buoyancy is derived from naturally buoyant bamboo onto which wetland plants are tied, through to sophisticated molded plastic designs which interlock together to create virtually unlimited island sizes and shapes.

In Australia, three companies are currently known to design, manufacture and/or install VFIs.

Aqua Biofilter has significant floating island trials in China (Duncan 2009) together with some smaller installations in Australia. The 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.

Water Restore manufactures and installs Rafted Reedbeds with installations at several sites in eastern Australia. Their system uses a buoyancy raft to support wetland plants whose roots penetrate and are suspended in the water to a depth of at least 600 mm, depending on plant species. The advantages are the physical, chemical and biological activity associated with the root zone.

The company's floating structure is somewhat similar to the design used by Aqua Filter in that it is based upon sealed plastic piping providing buoyancy, with wetland plants placed into coconut fibre (coir) matting.

FIA Technology Pty Ltd has designed and installed VFIs in several locations around Australia – see Figure 1. FIA's island design differs in two important ways from other manufacturers. First, buoyancy is provided via an external frame made from air blown recycled plastic with a density of about 0.7 g per cubic centimetre. Air bubbles created during the extrusion process are trapped within the plastic rods, ensuring that water cannot leak in. This inherent buoyancy is insurance against vandalism and protects against the possibility of leakage of water into sealed pipes, drums or other containers.

Figure 1 | FIA floating island installations at Mildura, Victoria, Australia. The two islands at rear were installed 15 months prior to the islands in foreground.

Second, FIA's design maximises development of bacterial biofilm within the matrix of the island. This is achieved by constructing a rectangular frame from which a pocket made from two layers of shade cloth is hung. Shredded plastic wastes such as nylon carpet (to increase the internal surface area on which biofilm can develop) and polystyrene packaging (to provide additional buoyancy as well as further internal surface area for biofilm) are placed into the pocket.

These two design innovations create islands that are virtually unsinkable and which have high internal surface area on which bacterial biofilm can develop. Wetland plants placed into the pocket create dense root mats. However, the use of non-biodegradable shredded plastic filling is superior to coconut fibre or coir matting which is consumed by bacteria over time.

To protect the small wetland plant seedlings from bird attack, all FIA islands are covered in bird netting which can be removed after 3–6 months. Alternatively, the netting can be left permanently in place in order to discourage waterbirds from nesting and roosting on the islands, thereby contributing a potentially large amount of nutrients to the waterbody from their droppings (Professor Jonathon Majer, Curtin University, *pers. comm.*, 2010).

IMPORTANCE OF PLANTS ON FLOATING ISLANDS

The critical importance of plants as part of the natural processes which remove nutrients and other pollutants from the water column cannot be overstated, even though plants remove only a small proportion of nutrients from the through-flowing water. Vegetation translocates oxygen into the underlying substrate thereby stimulating both nitrification of ammonia and the breakdown of BOD (Gersberg *et al.* 1986). Artificial wetland filters with plants had higher oxygen concentrations, pH, redox potential and metal retention than in systems without plants (Dunbabin *et al.* 1988).

Efficient nitrate removal from wetlands depends on denitrification which is supported by macrophytes supplying organic carbon (Weisner *et al.* 1994). Organic carbon available to denitrifying bacteria is released from plant litter and from living macrophytes which 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 the physical effects brought about by the presence of the plants: they provide good conditions for physical filtration and provide a huge surface area for attached microbial growth. Macrophtye-mediated transfer of oxygen to the rhizophere by leakage from roots increases aerobic degradation of organic matter and nitrification.

Vegetated floating structures have plant roots grow down into the water column while plant stems remain above water level (Headley & 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.

Overall, while plants remove only a small proportion of nutrients from wastewater, their presence are essential if maximum biofilm development within VFIs is to occur.

CONCLUSIONS

Thirty years ago, 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 operating within wetlands that were 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 pollutant removal from a multitude of different wastewaters.

Since the mid-2000s, the promotion of vegetated floating structures and VFIs of various designs to improve the 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 is an attempt to show that VFIs and other buoyant structures in wetlands are a logical and effective improvement to existing accepted practices which use wetlands to improve the quality of polluted wastewaters.

The key messages are:

- Bacterial biofilms develop on all physical surfaces within a wetland and it is bacteria, supplemented by oxygen and carbon from plants, which do the bulk of the work within wetlands including within and beneath floating islands.
- While nitrogen generally escapes to the atmosphere after bacterial degradation of ammonia, nitrite and nitrate compounds, phosphorous is taken up within bacterial and other biological matter, eventually falling to the bottom of the wetlands to create an organic-rich sediment.
- Because of the ability of phosphorous within wetland sediments to become biologically available under different physical and chemical conditions, physical removal and safe disposal of a wetland's sediments is essential if algal and cyanobacterial blooms together with other adverse consequences of nutrient-rich waterbodies is to be avoided.

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