Reviving Urban Ecosystems with Constructed Floating Wetlands

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INTRODUCTION

Constructed floating wetlands (CFWs) are a highly efficient ecosystem restoration technology that can be used to improve stormwater quality and reclaim degraded urban shorelines to provide a wide variety of wetland ecosystem services. The concept of CFWs has its origins from naturally-occurring floating wetlands found around the world. They consist of a buoyant substrate that supports wetland plants growing hydroponically, with roots suspended below the water surface. They have the capacity to tolerate fluctuating water levels and variable nutrient loading and can be designed for a number of purposes including to improve water quality, provide bird and wildlife habitat, protect and beautify shorelines, reduce flood risk, sequester carbon and conserve economically important fisheries.

In the Pacific Northwest, coastal urbanization and stormwater runoff have been directly linked to the high mortality of returning spawning salmon (Feist 2011). Cities including Amsterdam, Baltimore, Chicago, London, Seattle, Singapore, and Washington are implementing shoreline projects that integrate floating wetlands into river restoration projects designed to revitalize ecologically degraded urban waterfronts. These projects have multiple ecological, economic and social objectives to increase water quality, wildlife and open space services in formerly degraded waterfront neighborhoods. For densely urbanized cities floating wetlands provide a cost-effective advantage over soil-based wetlands for retrofitting urban shorelines without the cost of cleaning up contaminated sediments and relocating waterfront buildings and infrastructure.

Constructed floating wetlands may be variously referred to as floating treatment wetlands, artificial floating islands, and floating ecosystems (Fonder 2010). They are most widely recognized for their capacity to improve stormwater quality and their proven capacity for reducing nitrogen, phosphorous and metals found in stormwater (Palvineri 2017; Tanner 2011). They are recognized as a water quality best management practice for providing sustained water quality treatment (https://chesapeakestormwater.net/bmp-resources/floating-treatment-wetlands, accessed 3/15/2018) and as the only recognized biological method for controlling harmful algal blooms (www.epa.gov/nutrient-policy-data/control-and-treatment, accessed 3/15/2018).

FLOATING WETLAND ANALOGS

Natural floating wetlands form in quiescent lakes and rivers when mats of wetland vegetation break loose from shorelines or organic sediments to become floating islands. Floating wetlands are found in both temperate to tropical mesotrophic-eutrophic ecosystems worldwide (Van Duzer 2004). Floating wetlands in the Danube River Delta, known as "plaur," consist of mats of common reed (*Phragmites communis*), cattail (*Typha* spp.), sedges (*Carex* spp.) and bulrush (*Scirpus* spp.) (Coops 1999).The largest wetland ecosystem in the world, the Pantanal of central Brazil, contains a variety of floating wetlands called ""baceiro" formed by communities of grasses including burhead sedge (*Oxycaryum cubense*) and *Eleocharis plicarhachis* (Pott 2011). In Louisiana the coastal floating wetlands of the Mississippi River Delta are called "flotants" (Sasser 1996). In freshwater marshes flotants are dominated by maidencane (*Panicum hemitomon*), while in in brackish marshes they are colonized by saltmeadow cordgrass (*Spartina patens*) and bulrush (*Scirpus* spp.) New forms of floating wetlands are still being described, such as the submerged and floating plant communities in floodplain wetlands of the Upper Columbia River (Rooney 2013).

PROCESS

Floating wetlands intercept sunlight, reducing photosynthesis, primary productivity and algal blooms. Overwater coverage affects dissolved oxygen concentrations with aerobic bacteria found along the perimeter, and anaerobic bacteria colonizing the interior of the floating wetland. Aerobic and anaerobic biofilm-producing microbes perform the biochemical work of processing nutrients, metals and other chemical compounds in floating wetlands. Their buoyancy is caused by both oxygen trapped in the plant rhizomes (i.e., aerenchymatous tissue), and from microbial (i.e., 'swamp') gases being trapped underneath organic substrates (histosols). These substrates consist of living rhizomes and organic litter, as well as inorganic sediments

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such as fine silts and clays. The substrates are about 50 cm thick but can exceed 1 meter (Tanner 2006). Wetland plants transport atmospheric oxygen into the rhizosphere via aerenchyma to form roots, rhizomes and stolons that quickly multiply in nutrient rich water. Through photosynthesis plant roots secrete sugar and oxygen that feed microbes, including both bacteria and fungi, which consume nitrogen, phosphorus and ammonia to feed the plants. Plant roots suspended in the water column capture nutrients that are both in solution and adsorbed to suspended sediments. Anaerobic bacteria metabolize these nutrients and produce lighter than air gases, mainly methane (CH4) as well as carbon dioxide ($C0_2$) and nitrogen (N) (Sasser 1991).

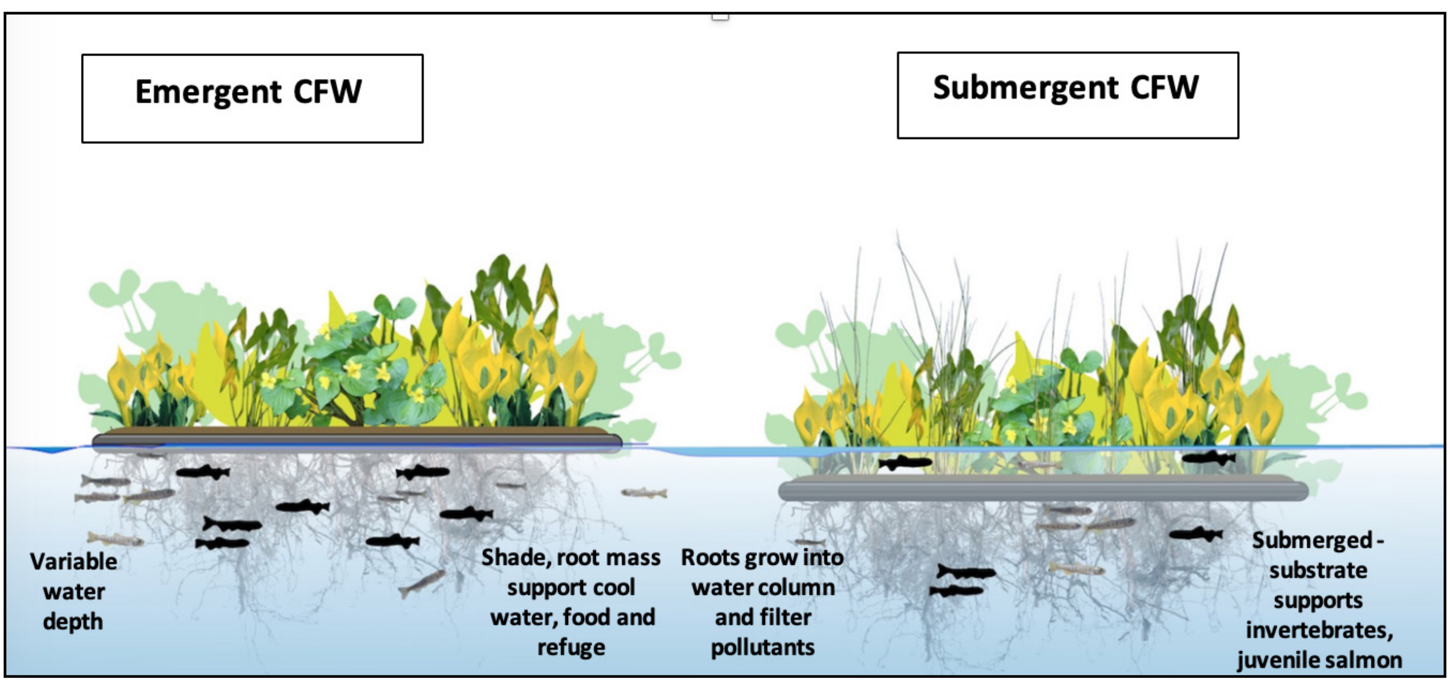
Constructed floating wetlands can be designed to perform both nitrification and denitrification (Rehman 2018). Bacteria can be inoculated into floating wetlands to remove organic and inorganic oil field wastewater and can provide a low cost, passive biological approach to effectively treating acid mine drainage (Kiskilia 2017). Increased removal of TN, TP and ammonium has been shown (Li 2009) to occur through the incorporation of biomedia such as clams and biofilm carriers along with wetland plants. White (2013) has demonstrated that floating wetlands can lead to increased reduction of nutrients from commercial greenhouse operations. Bourne (2013a, b, 2014, 2015) quantified water quality improvement induced by floating wetlands including the removal of metals (copper and zinc) and nutrients (nitrogen and phosphorous). Palvineri (2017) performed a meta-analysis of data from studies of floating wetlands and identified the pollutant removal processes as biosynthesis, settling and biofilm metabolism with pollutant accumulation in plant tissues, entrapment in roots, sedimentation, and physiochemical transformation.

DESIGN AND DEPLOYMENT

Floating wetland ecosystems are unique because they can function in waterbodies with fluctuating water levels and variable nutrient loads. They can be designed to float above or below the water surface to support a diverse assemblage of upland and wetland trees, shrubs, and herbs as well as submergent plant communities (Figure 1). They can be fabricated out of both bio-based materials, as well as inorganic plastic and metal materials. The water quality treatment performance of floating wetlands is affected by the size and depth of the parent water body, including depth and volume of water passing beneath the floating wetland. A review of stormwater CFWs experimental designs and installations by Lucke (2019) recommended the use of baseline monitoring, experimental controls, hydraulic conditions analysis and arranging CFWs to form baffles for optimal flow interception and performance.

Commercially-available floating wetlands are typically fabricated using plastic and metal components that are biologically inert, durable, and provide buoyancy. Two types of commercially-available floating wetlands are available. Mat-type designs consist of a non-woven polyester mat injected with urethane foam to provide buoyancy, e.g.: http://www.floatingislandinternational.com/. Wetland plants

FIGURE 1. Two conceptual designs for constructed floating wetlands (CFWs): one floating on the surface (emergent CFW) and the other slightly submerged.



grow in holes cut into the open cell foam mat, with roots colonizing the open cell foam and hanging below the mat substrate. A variant of this design consists of a buoyant polyvinyl chloride (PVC) mat with pre-cut holes that support cups in which plants grow: e.g.: http://www.beemats.com/home.html.

Pontoon frame floating wetlands, e.g.: http://www.biomatrixwater.com, http://terrapinwater.com, have high structural rigidity with a pontoon perimeter composed of high-density polyethylene (HDPE) pipe, inside of which plants are held in place in open cell foam mats or flexible plastic channels. Pontoon-style of floating wetlands is being used at the National Aquarium in Baltimore and includes complex microtopography to provide both emergent and submergent salt marsh habitats. These floating wetlands include air valves to regulate buoyancy (https://asg-architects.com/a-new-model-for-floating-wetlands/).

FIGURE 2. Floating wetland comprised of bio-based substrate with *Schoenoplectus acutus.*

Floating wetlands are also being developed using bio-based materials derived from biological products. Bio-based materials include natural organic matter, biocomposties and biopolymers. Gunther (2014) developed "reed-gabion" floating wetlands using natural organic matter consisting of dried common reed (*Phragmites communis*) encapsulated in untreated wire that achieved the "auto-buoyancy" of naturally-occurring floating wetlands after 1.5 years. The University of Washington is testing the use of the Mycoboard©, a biocomposite composed of wood chips fused with fungal mycelium, and Biofoam© a biopolymer similar in material properties to Airpop (expanded polystyrene). These materials are naturally hydrophobic and buoyant and are being using in floating wetlands designed to provide salmon feeding and refuge habitat in the Duwamish River in Seattle (Figures 2 and 3).

FIGURE 3. Floating wetland biofilter constructed of bio-based substrates protected by untreated gabion basket.

WATER QUALITY

Stormwater is a global ecological issue affecting water quality, water quantity, habitat and biological resources, public health, and the aesthetic appearance of urban waterways. Stormwater carries a soup of trash, bacteria, heavy metals, and other pollutants into local waterways. Floating wetlands have been most thoroughly researched for their ability to utilize the water quality improvement processes provided by wetlands to treat urban stormwater. A meta-analysis of research on floating wetlands by Palvineri (2017) provides removal rates, derived mainly from mesocosm design deployments (Table 1).

CFWs have demonstrated the capacity to control and prevent harmful algal blooms (HABS) or "red tides" which occur when toxin-producing algae grow excessively in a body of water. CFWs control algae blooms by shading water, preventing photosynthesis, reducing water temperatures and consuming nitrogen and phosphorous. HABS are a global phenomenon affecting virtually every country in the world, causing illness and death in humans, fish, seabirds, marine mammals, and other oceanic life, damaging ecosystems, fisheries resources, and recreational facilities, often due to the sheer biomass of the accumulated algae. HABS occur in response to a combination of increases in water temperatures, excessive nutrients, changes in salinity, increases in atmospheric carbon dioxide concentrations, and changes in rainfall patterns (https://oceanservice.noaa.gov/hazards/hab, accessed 3/15/2019). These algal blooms are predicted to occur more often, in more waterbodies, and to be more intense, threatening human health, the environment and economies across the world.

SEA LEVEL RISE

By 2100 coastal cities across the globe will be facing future sea-level rise of up to 2.0 meters/6.6 feet (Melillo 2014) resulting in widespread loss of coastal wetlands (IPCC 2013, Tiner 2013). Floating wetlands can be used to mitigate coastal wetland loss and help communities adapt to climate change. In Louisiana, for example, floating wetlands are being used as living breakwaters to reduce shoreline erosion, mitigate wetland loss, and sustain wetland fish and wildlife. In Seattle, Washington, floating wetlands are being developed as "salmon pocket parks" to provide food and refuge for threatened Chinook salmon (*Oncorhynchus tshawytscha*). These projects demonstrate some of the ecosystem services that floating wetlands may be capable of providing as a type of ecosystem-based adaptation that can help communities adjust and accommodate to climate change.

RIVER RESTORATION

Coastal and waterfront cities worldwide are undergoing shoreline revitalization with floating wetlands that can replace lost wetlands and shoreline habitats along rivers (Figure 4). Haynes (2014) developed a conceptual design for revitalizing the shorelines of San Francisco using a variety of floating wetland configurations. CFWs can be integrated into shoreline redevelopment projects to retrofit hardened riverbanks and restore wetland ecosystem services without the challenge and expense of buying and reconfiguring these lands and relocating transportation, industrial or commercial structures. Urban shorelines and estuaries often have legacies of industrial use, especially contaminated sediments and groundwater. In these landscapes floating wetlands may provide a cost-effective alternative to purchasing and remediating contaminated shoreline properties.

In Seattle, the University of Washington's Green Futures Research and Design Lab is researching the use of floating wetlands to provide habitat for Chinook salmon. In the Duwamish River over 97% of the historic wetlands have been lost to urbanization. These riverine and estuarine wetlands provided margin-habitat with slow and shallow water where thousands of ocean-bound smolts could quickly grow by feeding on a rich diet of aquatic and terrestrial invertebrates. The loss of these habitats has contributed to the ongoing decline of Chinook salmon populations and the Southern Puget Sound Orcas (*Orcinus orca*) that depend on Chinook salmon as their primary food prey. Efforts to restore these habitats using land-based wetland creation are ongoing but are limited by the cost of land and cleaning up historic contaminants. The Duwamish River is a federal superfund site with a legacy of industrial waste containing polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) having spoiled the river sediments. Floating wetlands may provide a cost-effective temporary alternative to retrofit these hardened, contaminated shorelines and provide substitute rearing habitat as clean-up efforts advance.

Retrofitting urban rivers and estuaries with floating wetlands is occurring in many cities. Washington, DC

TABLE 1. Floating wetland performance (Palmineri 2017).

Parameter	Average
Total nitrogen (N)	58.0%
Total phosphorous (TP)	48.75%
Amonium nitrogen (NH4-N)	72.8%
Chemical oxygen demand (COD)	57.8%

FIGURE 4. Biobarge providing near-shore wetland habitat.

has integrated 153-square meters of floating wetlands into the District Wharf Park to provide a variety of water quality, habitat, and open space services. In the French city of Rennes, Biomatrix Water Solutions Ltd. installed 620-square meters of floating wetlands along the historic stone walls that form the banks of the river Vilaine. These "floating ecosystems" are capable of supporting trees, as well as emergent plants, and include deflectors to protect the floating wetlands from boats and water-carried debris. A movement to retrofit the Chicago River with floating wetlands came out of research by Yellin (2014) who observed a 100% increase in fish species adjacent to a vegetated floating wetland. This research helped launch a new community group - Urban Rivers - and a community Kickstarter campaign to install 160 feet of floating wetlands that eventually obtained grants from a variety of sources. These floating wetlands are restoring fish, bird and wildlife habitat, beautifying the shoreline, and providing urban gardens for raising food. The project has helped to revitalize a degraded neighborhood and led to plans for creating a mile-long floating eco-park.

In Baltimore Harbor three floating wetland projects have been developed. In 2009 a pilot project was launched to study whether floating wetlands could contribute to the goal of restoring water quality and wildlife to Baltimore's Inner Harbor (Streb 2013). Biohabitats Inc. designed a series of floating wetlands that were fabricated using a mix of polymer, bio-based and recycled materials, with the participation of local schools. The project proved to be popular with the local community and ecologically successful, bringing back wildlife including mollusks, fish, crabs, otters and birds. In 2013 the Maryland Port Administration deployed 278-square meters of floating wetlands specifically targeted to improving water quality adjacent to commercial container port facilities. In 2017 a new generation of floating wetlands was designed and deployed to provide intertidal wetland habitats for the National Aquarium. These floating wetlands won the 2018 American Society of Landscape Architects research award for a design that allows the elevation and buoyancy of the floating wetlands to be adjustable.

REGULATION

In the U.S., structures planned for construction in waterways are subject to provisions of Section 404 of the Clean Water Act that require federal permits administered by district offices of the US Army Corps of Engineers in addition to state and local requirements. The regulatory view of floating wetlands may vary regionally, in large part due to the emerging technology and the lack of data on long-term performance, including operation and maintenance requirements. Floating wetlands are a non-traditional form of constructed wetland that are most often deployed to help stormwater facilities achieve compliance with National Pollutant Discharge Elimination System (NPDES) permits or other discharge targets. Outside of their use in stormwater facilities, most federal, state and local agencies are unfamiliar with the use of floating wetlands to enhance wetland ecosystem services or provide compensatory mitigation for wetland impacts. Typical regulatory concerns are expressed regarding floating wetlands durability, overwater coverage, and predator-prey interactions, among others. Permits for the Chicago River floating wetlands project took over three years to acquire and regulators required extensive monitoring to evaluate project performance. The National Aquarium floating wetland project was initially permitted as a research project, an interim approach favored by some regulators to corroborate claims that floating wetlands are capable of providing functions similar to soil-based wetlands.

THE FUTURE OF CONSTRUCTED FLOATING WETLANDS

Floating wetlands are a highly efficient ecosystem restoration technology that can provide wetland ecosystem services as a form of green infrastructure. They can be used to improve stormwater quality, provide fish, bird and wildlife habitat, and mitigate climate change impacts. They are cost-effective approach to retrofitting built-out urban shorelines and increasing ecosystem services along rivers and harbor waterfronts where land costs and contaminantion make land-based restoration extraordinarily expensive. Improved engineering has resulted in designs that can be configured to support a broad range of upland and wetland habitats with trees, shrubs, herbaceous and submergent plant communities.

A substantial body of research exists on the capacity of floating wetlands for improving water quality in mesocosm settings; however, additional research is needed to study the performance of field deployments. While the habitat benefits of floating wetlands have been widely promoted, very little research has specifically examined field-based deployments of floating wetlands and their impact on fish and wildlife populations. In order to advance the habitat benefits of floating wetlands design guidelines are needed to create habitat structures that can support invertebrates, amphibians, fish, birds and mammals.

Improved understanding is needed about the fate and transport of nutrients, metals, and contaminants of concern (COCs). If plant and root tissue uptake is a principal pathway for removing nutrients and COCs from these aquatic ecosystems, floating wetlands will need to incorporate design features that support periodic harvest and disposal of accumulated plant leaves, stems, rhizomes and root networks. This may lead to the development of buoyant, bio-based compostable substrates that can be rapidly colonized by wetland plants installed as plugs or sod. Such a biodegradable floating wetland system could theoretically be seasonally deployed and decommissioned to achieve specific water quality ecosystem services to reduce the impacts of stormwater and prevent HABS.

More information is needed on how to locate, size, arrnge, operate and manage floating wetlands to optimize water quality processes to reduce turbidity, reduce nutrients, remove metals, and degrade contaminants. The structure and material of floating mat, plant density, plants harvesting and disposal procedures. Further investigation is needed to identify the type of micro-organisms specific for various kinds of pollutants, their organic pollutants degradation capacity, plant growth-promoting activities, performance, and synergistic relations with plants. Integrating floating wetlands into stormwater infrastructure will require the development of specific water quality performance data for each proprietary product. ■

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