Multifunctional Wastewater Treatment Landscapes

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ABSTRACT Environmental engineering research on decentralized, biological remediation of wastewater through the creation of treatment wetlands has advanced dramatically in the last decade. Treatment wetlands can effectively meet secondary treatment standards for total suspended solids and biological oxygen demand. Certain designs can achieve tertiary quality for ammonia, nitrates, and pathogenic bacteria. At costs equal to or lower than conventional systems, treatment wetlands can rejuvenate wastewater effluent generated by institutions, subdivisions, and small towns in diverse climates. In addition to providing ecosystem services relating to wastewater remediation, these site-based multifunctional landscapes also enhance biological diversity and provide open space values relating to scenic quality, recreation, and education. When aligned with ecosystem corridors, treatment wetlands become part of larger scale multifunctional landscapes that provide green infrastructure to guide development patterns at the regional scale. This paper examines the ability of a decentralized sequence of treatment wetlands located within public open space to improve ecosystem health and provide ecosystem service benefits to society at multiple geographic scales.

KEYWORDS Multifunctional landscape, treatment wetlands, constructed wetlands, green infrastructure, landscape infrastructure, wastewater.

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INTRODUCTION

Multifunctional landscapes systematically integrate a broad range of anthropogenic and naturally occurring patterns, functions, and values to support healthy ecosystems and provide goods and services that directly or indirectly benefit humans (Bomans et al. 2010). The Millennium Ecosystem Assessment organizes these goods and services into four categories: provisioning, regulating, cultural, and supporting (Hassan et al. 2005).

Wastewater treatment wetland systems are created wetlands designed for the express purpose of regulating hydrologic flows in surface drainage systems and providing water quality remediation services related principally to wastewater. They are spatially distributed in the landscape and can treat wastewater generated from institutional land uses, subdivisions, and small towns.

In that they deliver ecosystem services in addition to water quality remediation, treatment wetlands are examples of small-scale multifunctional landscapes. The fact that they can be deployed throughout the landscape in conjunction with various types of ecosystem networks suggests that they also contribute to the planning and design of multifunctional landscapes at the regional or watershed scale.

Wastewater treatment wetlands deliver provisioning services including purified water, infiltration of surface runoff to enhance base flow, and habitat enhancement. Regulating services provided include wastewater treatment as the primary function, and carbon sequestration and water cycling as secondary services. Cultural services provided include delivery of open space, as well as opportunities for trails, aesthetically appealing naturalistic vegetation, wildlife viewing, and education. Finally, supporting services provided include primary production as well as material (carbon, nitrogen, etc.) and energy cycling within the ecosystem

Table 1. Wastewater Treatment Levels (EPA 2010)

Treatment Level	Process	Indicators	Standard
Primary	Sedimentation	Particle size	< 30mg/L
Secondary	Filtration, Biological, Chemical	BOD	< 30mg/L
		TSS	< 30mg/L
		Fecal coliform bacteria	100cfu/100mL (primary contact)
		Fecal coliform bacteria	200cfu/100mL (secondary contact)
		E. coli bacteria	126cfu/100mL
Tertiary	Biological, Chemical	Ammonia	Based on receiving water
		Nitrate	Based on receiving water
		Phosphorus	Based on receiving water
		Pharmaceuticals	Based on receiving water

BOD	biological oxygen demand
TSS	total suspended solids
mg/L	milligrams per liter
cfu/100L	colony forming units per 100 milliliters.

Table 2. Nitrogen Transformations in Treatment Wetlands

Substance	Bacterial Environment	Transformation	Process
Organic Nitrogen	Aerobic	Ammonium ($NH^{4}+$)	Ammonification
Organic Nitrogen	Anaerobic	Ammonium ($NH^{4}+$)	Ammonification
Ammonium	Aerobic	Nitrite ($NO^{2}-$)	Nitrification
Nitrite	Anaerobic	Nitrate ($NO^{3}-$)	Nitrification
Nitrate	Anaerobic	Nitrogen Gas (N^{2})	Denitrification
Nitrogen Gas			Volatilization

After discussing characteristics of domestic wastewater quality, this paper examines the historical development, structure, function, and performance of treatment wetlands as well as the ecosystem services they provide in the planning and design of multifunctional landscapes at geographic scales ranging from the neighborhood to the region. Throughout this article, the term "urban areas" refers generally to land that has or will be developed for urban or suburban uses. Many of the concepts presented assume the availability of more undeveloped land area than is typically found in existing truly urbanized settings.

WASTEWATER CHARACTERISTICS

An understanding of domestic wastewater characteristics is important to evaluate the benefits of treatment wetland systems. Americans generate between 40 and 60 gallons of domestic sewage per person per day (Wallace and Knight 2006). Table 1 identifies the three levels of treatment needed to fully cleanse wastewater influent in constructed wetlands as well as sewage treatment plants. In primary treatment, large debris is trapped and removed from wastewater as influent flows into a treatment system. Smaller inorganic and organic solids drop out of the influent under the influence of gravity. A series of physical, biological, and chemical processes during secondary treatment provide further purification by filtering or digesting fine suspended and soluble organic materials in the wastewater. In tertiary treatment, additional physical, chemical, or biological processes remove substances such as dissolved metals, organic chemicals, and nutrients (for example, nitrogen and phosphorous). Water quality standards established by the US Environmental Protection Agency (EPA) for effluent that is discharged from each level of treatment are identified in Table 1. Most communities in the United States must meet secondary wastewater treatment standards. Tertiary treatment is often required when effluentpurif is discharged to watercourses or water bodies that are polluted and require remediation or those of high ecosystem value or sensitivity (EPA 2010).

Table 1 also indicates parameters or indicators of water quality that are used to measure water quality in effluent that is discharged by each treatment level. Biological oxygen demand (BOD) measures the oxygen required by microorganisms to consume organic material in water. Total suspended solids (TSS) are a measure of the organic and inorganic particles suspended in a water sample. Both parameters are indirect measures of water pollution. The concentration of various groups or species of bacteria in wastewater effluent indicates water quality. Total coliform bacteria (microorganisms that live in the intestines of humans and other animals), fecal coliform, and *Escherichia coli* are three common indicators of pathogens in wastewater.

Various genera of bacteria operating in oxygen-rich (aerobic) or oxygen-depleted (anaerobic) environments are the primary biological agents for removing nitrogen in treatment wetlands. These bacteria transform organic nitrogen into inorganic nitrogen and eventually into nitrogen gas, which is discharged into the atmosphere (Table 2). For example, ammonium is transformed by bacteria in an aerobic environment into nitrite in a process called nitrification. The design and sequence of wetland cells creates the bacterial environments to achieve the various transformations.

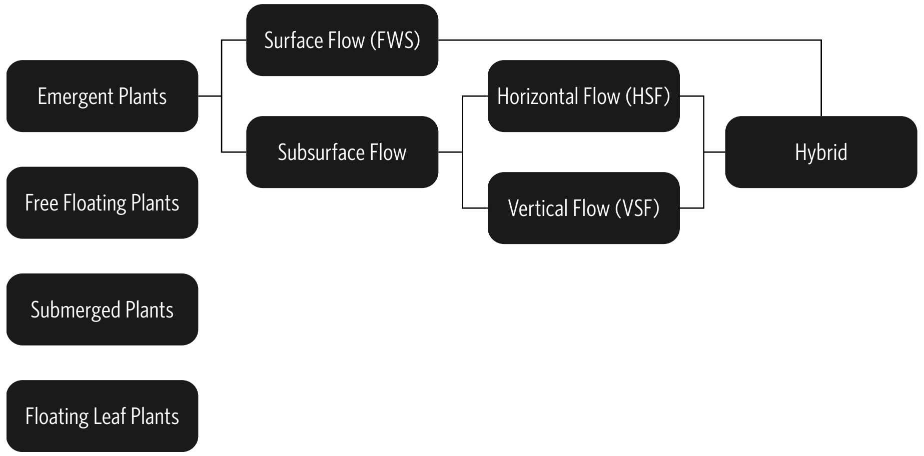

Figure 1
Constructed Wetland Types. Wetlands differentiated by vegetation type and flow regime. Adapted from Vymazal 2007.

DEVELOPMENT OF WASTEWATER TREATMENT WETLANDS

Residents of Lexington, Massachusetts began disposing of wastewater in a natural wetland over 100 years ago. Other communities around the world have also used natural wetlands with the single goal of wastewater disposal rather than water quality improvement. This practice degraded many natural wetlands as there was very little knowledge about or attention given to the capacity of these systems to assimilate the volume and nature of the wastewater they received (Vymazal 2011c).

Dr. Käthe Seidel began experimenting with constructed wetlands that include vegetation as subsurface wastewater treatment wetlands in the middle of the 20th century (1976). These systems contained no surface water, and they relied on water quality remediation associated with physical, chemical, and biological processes occurring in their substrate as well as emergent vegetation growing in the wetland. They became operational and widely applied throughout Europe in the 1960s. Water quality remediation occurred as a result of either the lateral flow of wastewater through substrate in horizontal subsurface flow (HSF) wetlands or vertical flow in vertical subsurface flow (VSF) wetlands. The need for tertiary treatment of wastewater to remove ammonia and nitrates inspired the development of hybrid systems that combined horizontal and vertical subsurface flow wetlands (Vymazal 2011c).

Development of this technology in the US focused on free water surface (FWS) wetlands for wastewater treatment (Vymazal 2011c). Unlike their European HSF and VSF system counterparts that relied on biogeochemical and phytoremediation processes occurring in the wetland substrate and emergent vegetation, FWS systems used processes occurring in bodies of open water to remediate water quality. They were widely used in the US to provide the tertiary treatment of municipal sewage.

WASTEWATER TREATMENT WETLAND TYPES

Based on vegetation type and hydrologic flow regime, wastewater treatment wetlands are classified into four categories (Figure 1 adapted from Vymazal 2007). The wetlands may treat wastewater in horizontal subsurface flow, vertical subsurface flow, free water (or surface) flow, or as hybrid systems.

All types of wetland treatment systems assume that wastewater entering a wetland system has been

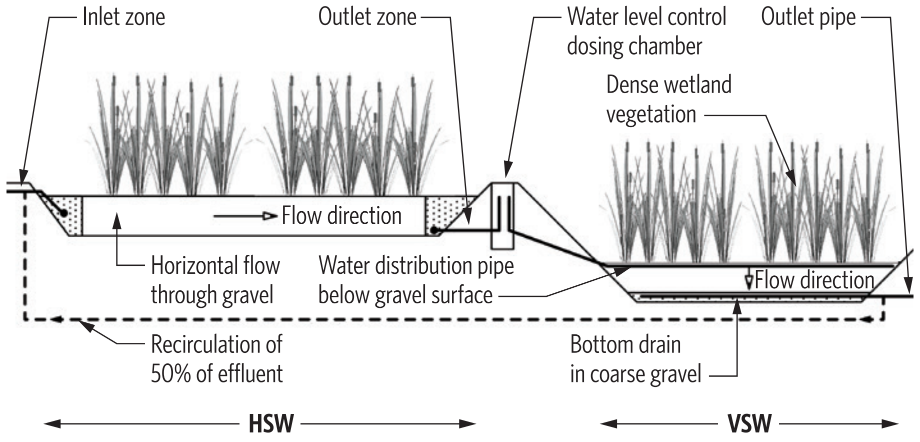

Figure 2
HSF wetland in the Czech Republic. Photo courtesy Jan Vymazal.

Figure 3
HSF Wetland (left), VSF Wetland (right). This section through a hybrid treatment wetland combines an anaerobic (HSF) and aerobic (VSF) treatment zone for outstanding contaminant removal. The recirculation feature increases system stability and nitrate removal (Austin 2012).

pre-treated in a septic tank. Typically, organic solids and suspended solids settle to the bottom of the tank. Anaerobic digestion transforms the organic solids into an inorganic substance. This process provides primary treatment of wastewater, which subsequently flows into treatment wetlands. As described below, additional levels (secondary and tertiary) of treatment occur within the wetland. Septic tank maintenance involves the periodic removal of accumulated solids.

Horizontal Subsurface Flow Wetlands

The rate at which biological and chemical processes transform organic and inorganic contaminants flowing out of a septic tank and treatment wetland into benign substances determines treatment wetland size requirements. Guidelines for determining HSF size requirements have evolved from monitoring system performance in treating domestic sewage. Approximately $4.5m^2$ of HSF wetland area per person served is required to meet domestic sewage effluent treatment standards in temperate climates (Vymazal 2005). Design criteria also exist to create systems that will meet EPA secondary treatment standards in cold weather conditions (Kadlec, Kuvellier, and Stober 2009).

In a HSF wetland (Figure 2, and Figure 3 left) there is no surface water. The wetland is densely planted helping to integrate the system into the surrounding landscape and to provide phytoremediation of contaminants. Density of plant coverage is one of several factors that determine the effectiveness of HSF wetlands. Other factors include gravel size used in constructing the wetland, and uniformity of water distribution throughout the gravel.

Septic tank effluent entering a HSF wetland flows out of a perforated pipe connecting the tank and the wetland and into a 1.8m wide gravel bed composed of coarse textured gravel (Figure 3 left). Large pore spaces in the coarsely textured gravel limit clogging of the drain system by fine-grained sediment and biofilm growth. After passing through this gravel cell, wastewater enters another treatment bed that is 0.6 to 0.8m deep (Figure 3 left) and contains finer textured gravel. The gravel provides a large surface area for the development of biofilm growth on gravel particles to promote contaminant removal. A longitudinal hydraulic gradient in the bed promotes continuous water flow (Wallace and Knight 2006; Cooper 2009). Wastewater reaching the lower end of the gradient flows through an outlet bed and into a perforated pipe which discharges into an adjacent VSF wetland. The outlet bed design is similar to that of the inlet bed. Even distribution of wastewater throughout the gravel bed enhances water quality remediation.

Beneficial bacteria growing on the gravel and roots transform organic matter into ammonium and nitrates to nitrogen gas. The plant roots must reach the bottom of the bed in order to maintain porosity of the bed and maximize nitrogen removal (Vymazal 2005). HSF wetlands effectively convert organic material to ammonium, and nitrates to nitrogen gas. However, they do not effectively convert ammonium to nitrate (Vohla et al. 2011).

A single-cell HSF wetland constructed in the Czech Republic (similar to Figure 2) that was monitored for 13 years achieved average effluent BOD measurements of 18.3mg/L and TSS of 8.3mg/L. Ammonia removal was 14.8 percent while nitrate removal was 41 percent (Vymazal 2011a).

An HSF treatment system built to serve 40 people in Little Stretton, UK, contained eight subsurface beds stepping down a slope. Although BOD and TSS concentrations were low in the outflow, there was a large reduction of ammonia (85.1 percent) as there was high oxygen transfer between the beds due to water aeration as it moved down slope between beds. However, the aerobic environment created by the inter-bed transfer of wastewater reduced nitrate and nitrite concentrations by only 16.4 percent (Cooper 2009).

Vertical Subsurface Flow Wetlands

There are two types of vertical subsurface flow wetlands: VSF with bottom drains and VSF with impoundments.

Vertical subsurface flow with bottom drain. As is true for HSF wetlands, pre-treated septic tank effluent entering vertical subsurface flow (VSF) wetlands is held below the surface. VSF wetlands are flooded periodically just below a surface layer of gravel or mulch (Figure 3 right). Water then flows down through a sand bed and exits the wetland through bottom drains (Figure 3 right). Water flowing through the pore spaces between the sand particles is replaced by air, creating an oxygen rich environment where BOD, TSS, and ammonia are effectively treated. While vertical subsurface flow wetlands may require energy from small pumps and more regular attention from an operator than the HSF system, they have low spatial extent requirements (2m2 per person) (Tunçsiper 2009). As with HSF wetlands, VSF wetlands are densely planted to preserve porosity of the filter media (Figure 4).

Vertical subsurface flow with impoundment. An alternative design (Figure 5) for a VSF wetland improves the removal of total nitrogen. This design is employed when the VSF wetland is not combined with HSF or FWS wetlands in a hybrid system. Two Austrian VSF wetlands operating in tandem demonstrated that VSF wetlands with an impoundment can achieve EPA secondary effluent standards for BOD and TSS, and advanced treatment for nitrogen removal. An impoundment is a layer of coarse gravel that is permanently saturated with water. This flooded basin below the filtration media creates an oxygen-depleted zone where different genera of beneficial bacteria can grow. Each VSF cell contained $10\,m^2$ planted with *Phragmites sp.* The first cell included a 50 cm deep bed of sand and an impoundment below the sand filtration bed (Figure 5). The second stage included a sand layer above a coarse aggregate drainage layer. Pretreated wastewater flooded the top of the wetland to a depth of 16.2mm every three hours. The wetland was monitored for 19 months. BOD levels in the VSF effluent ranged from 4mg/L in summer and 12mg/L in winter at the outlet (Langergraber et al. 2009).

The VSF wetland also provides advanced removal of ammonia. The effluent from the second wetland cell contained an average ammonia concentration of 0.3mg/L in summer (a 99.5 percent reduction) and 17.5mg/L in winter (a 64 percent reduction). This wetland removed 46 percent more of the ammonia than a single cell VSF wetland with no impoundment (Langergraber et al. 2009).

Figure 4
This vertical flow constructed wetland treats wastewater for 6,000 residents (Photo courtesy of Blumberg Engineering: www.blumberg-engineers.com).

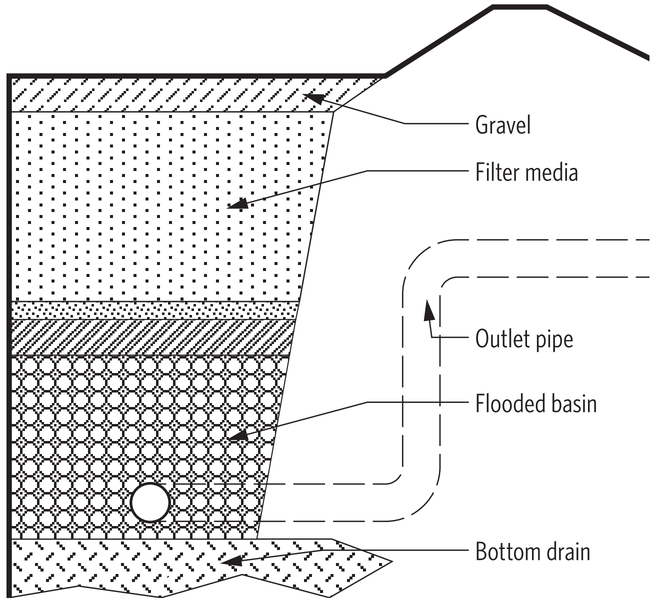

Figure 5
VSF Wetland, Section. The flooded basin is an oxygen-depleted zone for the conversion of nitrate to nitrogen gas (adapted from Brix 2005).

Nitrate levels in the two-stage VSF wetland increased over time. Wastewater entering the system in the winter contained an average nitrate concentration of 0.30 mg/L, while that leaving the system had a nitrate concentration of 21.1 mg/L. Summer performance indicated an increase of nitrate concentrations from 0.37 mg/L at the inlet to 30.9 mg/L at the outlet. This large increase in nitrate concentration indicates complete conversion of ammonia to nitrates (Langergraber et al. 2009) but insufficient denitrification of nitrates to nitrogen gas.

Elimination of total nitrogen was 53.2 percent in summer and 37.1 percent in winter. This high performance is attributed to the nitrification of approximately 80 percent of the ammonium in the first-stage wetland with the flooded sub-basin with some production of nitrogen gas (Langergraber et al. 2009).

While the two-stage VSF wetland removed approximately 99 percent of the pathogenic bacteria, residual counts of *E. coli* remained significantly higher than the EPA standard for primary contact (for example swimming) (Langergraber et al. 2009). Additional treatment in another wetland stage or ultraviolet light disinfection is required before this effluent can be used for primary recreation.

Free Water Wetlands

Free water wetland systems (FWS) are constructed wetlands containing open water bodies. Vegetation in FWS treatment wetlands includes emergent, free-floating, submerged, and floating (but rooted) plants. They are especially effective in obtaining tertiary treatment (removal of nutrients such as nitrogen and phosphorus within wastewater). As discussed in subsequent sections of this article, FWS also offer a wide range of ecosystem services in addition to wastewater remediation. A free water surface wetland in Columbia, Missouri provides multiple ecosystem services. In addition to delivering regulating services related to water quality mitigation, it also creates provisioning services related to habitat enhancement and water supply services for the nearby Eagle Bluffs Conservation area. The system also provides cultural services associated with an extensive recreational trail (Figure 6) that provides enjoyment of rural scenery and wildlife viewing opportunities (Kadlec, Cuvellier, and Stober 2010).

Figure 6
Free surface water wetlands in Columbia, Missouri treat municipal wastewater to meet secondary standards for advanced water quality (Photo by author 2012).

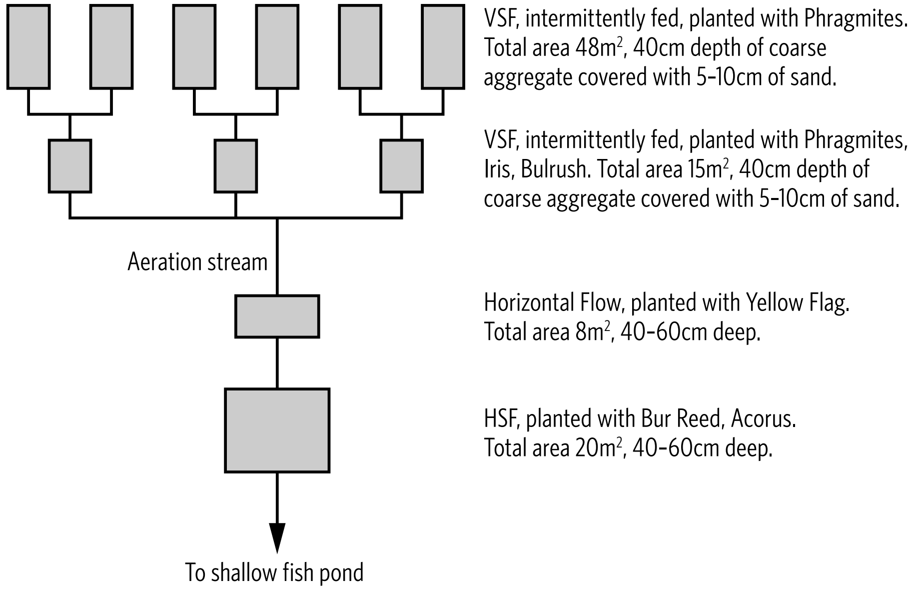

Figure 7
Plan view diagram of the hybrid wetland at Oaklands Park, UK for treatment of domestic sewage (adapted from Burka 1990).

Hybrid Treatment Wetlands

Hybrid wetlands combine at least two of the wetland types (HSF, VSF, FWS). Figure 3 illustrates hybridization of HSF and VSF used in sequence to achieve secondary effluent treatment and to reduce ammonia, nitrate, and phosphorus.

A hybrid treatment wetland constructed at the Oaklands Park (Figure 7), in the United Kingdom, exemplifies a hybrid system built to serve a population of 65 people. In this system, pre-treated wastewater from septic tanks enters six VSF wetland cells, only one of which is active at any time to avoid clogging the

Table 3. Oaklands Park Performance in the Four Subsurface Flow Cells (mg/L)

Flow Form	surface area m^2	Influent OD5	Effluent BOD5[a]	Influent TSS	Effluent TSS[a]	Influent NH^4+	Effluent NH^4+[b]	Influent NO^3	Effluent NO^3[c]
Vertical	8	285	57	213.3	38.5	50.5	29.2	1.7	10.2
Vertical	5	57	14	38.5	17.7	29.2	14	10.2	22.5
Horizontal	8	14	15	8	8.2	14	15.4	22.5	10
Horizontal	28	15	7	9.2	4	15.4	11.1	10	7.2

derived from Burka 1990; Gaboutloeloe et al. 2009

BOD biological oxygen demand

TSS total suspended solids

[a] EPA discharge requirement less than 30mg/L

[b] No EPA discharge requirement for ammonia. In streams, rainbow trout fry tolerate up to about 0.2mg/L; hybrid striped bass can handle 1.2mg/L

[c] No EPA discharge requirement for nitrate. In streams concentrations above 5mg/L inhibit growth in fish; salmon are much more sensitive.

sand media in the cell. The VSF cells can operate with intermittent periods of activity lasting a few hours. The VSF systems discharge into two stages of HSF wetlands. The system concludes with a fishpond for nutrient removal (Burka 1990; Gaboutloeloe et al. 2009).

Table 3 presents data that illustrate the performance of the Oaklands Park system. Outlet concentrations of BOD and TSS from the second stage HSF stage are 7.0 and 4.0 mg/L respectively. Ammonia and nitrate concentrations are reduced by 78 percent and 68 percent. The data for pond effluent is not shown in Table 3, but the free water stage further reduced ammonia, nitrate, and phosphorus levels. Phosphorus declined from 19.8 mg/L in the septic tank effluent to 8.2 mg/L (a 58.5 percent reduction) at the pond outlet. While this level of removal does not meet the EPA target of 1 mg/L, use of calcium rich gravel and sand in the subsurface wetlands would improve phosphorus removal (Vohla et al. 2011). Pathogenic bacteria were reduced to below the EPA standard for primary contact (Burka 1990; Gaboutloeloe et al. 2009).

While design of hybrid wetland system at Oaklands Park required no use of artificial energy, the hybrid system illustrated in Figure 3 includes a small pump to return wastewater to the HSF wetland to improve de-nitrification. In this design, placement of the HSF wetland (Figure 3) before the VSF wetland would result in incomplete de-nitrification without requiring recirculation (Brix 1998).

A recent demonstration project in the Czech Republic illustrates the benefit of hybrid wetlands. A three-stage wetland was constructed with a fully saturated VSF cell followed by a free draining VSF cell. The third cell was a HSF bed. Fifty percent of the effluent from stage two was pumped to stage one for denitrification. Average removal rates were 94.5 percent for BOD (10 mg/L); 88.5 percent for TSS (9.2 mg/L); 78.3 percent for Ammonia (6.5 mg/L); and 65.4 percent for Phosphorus (1.8 mg/L). The concentration of nitrates in the outflow was 1.1 mg/L. The combined ammonia and nitrate removal was 73.5 percent (Vymazal and Kröpfelová 2011).

Resilience of Wastewater Treatment Wetlands

Because wastewater treatment effectiveness in constructed wetlands depends on plants and a host of organisms, a concern is that the systems are too fragile. However, Zapater et al. demonstrate that biological treatment systems are both stable and resilient (2011). Shocks to an experimental wetland were induced by altering pH to high and low levels as well as adding high amounts of organic material, detergent content, bleach content, and *E. coli* bacteria contamination. The impact of pump failure (no recirculation for two days) was also tested. The system recovered from these impacts within 24 hours to perform at levels similar to a control wetland. The resilience is thought to be due primarily to the buffering capacity of the bed materials and the re-circulation feature of this wetland, which reduced clogging and mixed septic tank effluent with partially treated water (Zapater et al. 2011).

ECOSYSTEM SERVICES PROVIDED BY WASTEWATER TREATMENT WETLANDS

With the exception of Oaklands Park, the design of the treatment wetlands discussed above made no attempt to address ecosystem values beyond domestic wastewater remediation. However, the nature of treatment wetlands affords the opportunity for providing multiple ecosystem services. Provision of these services relates directly to the land cover and hydrologic manipulations that occur in the construction of treatment wetlands at specific sites. They also relate to the indirect benefits associated with introduction of treatment wetlands in multiple locations throughout the landscape. This section discusses the diversity of ecosystem services that can be provided at the site and landscape scale in the design, planning, and management of treatment wetland systems.

Site-based Ecosystem Service Benefits

Enhanced biological diversity. Most of the wetlands reviewed above used a single wetland plant species. However, a diverse planting plan, dominated by native species, significantly enhances biological diversity. HSF wetlands containing higher plant diversity produce more biomass compared with wetlands containing monocultures (Zhu et a. 2010). Enhanced plant diversity in FWS treatment wetlands often produces a richer mix of macroinvertebrates than naturally occurring wetland systems (Feest, Merrill, and Aukett 2012). Compared with wetland species monocultures of reed canary grass (*Phalaris arundinacea*) or cattail (*Typha sp.*), diverse plant communities contain a higher abundance of dragonflies, damselflies, and other Odonata species (Moore and Hunt 2011).

Optimizing the biodiversity benefits of FWS wetlands requires selection of plant species that meet habitat requirements of fauna whose presence is desired (Hsu et al. 2011). Vertical and horizontal vegetative structure also affects species presence. For example, the abundance of blackbirds, coots, dabbling ducks, and diving ducks is lower in wetlands containing continuous and dense stands of emergent vegetation and water depths from 0.3 to 1 m. Such wetland structure is frequently used in design of FWS wetlands. Higher species richness exists in FWS wetlands in which the extent of emergent vegetative cover equals the extent of open water (Fleming-Singer and Horne 2006).

Normally, plants in treatment wetlands are not harvested because they take up less than ten percent of the nitrates and other nutrients in wastewater. However, this reduction could be significant to increasing populations of amphibians that are sensitive to even low levels of ammonia and nitrate (Tunçsiper 2009).

Management of the vegetative structure and the hydrologic regime of treatment wetlands also affect habitat diversity. Planting practices that encourage maximum habitat improvements include phasing seeding over time and using container-grown plants. Weeding to remove invasive plants also helps establish species diversity (Moore and Hunt 2011). Hydrologic regime management strategies that enhance diversity include maintaining water depths, and flooding the surface during the wetland establishment period and before commencing wastewater treatment. Periodic draw-down of the water level in constructed marshes to expose mud also enhances habitat value (Murkin, Murkin, and Ball 1997).

Avian species are attracted to treatment wetlands by the presence of water, a range of food sources, and the inclusion of shrub vegetation in the planting design (McKinney, Raposa, and Cournoyer 2011). Construction of wetlands containing these elements enhances diversity for both migratory and resident avian species (Hickman and Mosca 2002). The benefits of including avian habitat diversity in the design, planning, and management of treatment wetlands are evidenced by the 1991 construction of four treatment wetlands on a 182ha site in Illinois. Within two years of construction, overall faunal species diversity on the site increased by 100 percent. Species diversity increased by 30 percent for nesting birds and 400 percent for waterfowl. Between 1993 and 2002, overall species increased from 167 to 195. Of these, 13 species were endangered and eight were considered threatened within the state, including the Sandhill Crane (*Grus canadensis*) (EPA 1993).

Enhanced water quality. Vegetative diversity in shallow FWS marshes and horizontal and vertical flow wetlands effectively improves water quality. Compared with the performance of monocultures of bulrush (*Scirpus spp.*) or cattail (*Typha spp.*), FWS marshes containing a mix of *Scirpus* and *Typha*, as well as grasses and smartweed (*Polygonum*) removed more than three times the nitrate as single-specie stands. A more even distribution of detritus (and thus carbon) in diverse wetlands results in higher levels of denitrification, producing enhanced removal of nitrate (Bachand and Horne 1999). Plant diversity also enhances retention of nitrogen and ammonia in the gravel substrate of HSF wetlands (Zhu et al. 2010). Shallow, clear, and open water in FWS wetlands allows greater penetration of solar-generated ultraviolet light that kills pathogenic bacteria.

Figure 8. Secondary effluent from a conventional treatment plant in Roseburg, Oregon is applied to slopes draining into a restored wetland to remove excess phosphorus. The 340-acre parcel also provides outstanding and diverse wildlife habitat. This project saved $90 million compared to an upgrade to the treatment plant.

Landscape-based Ecosystem Service Benefits

Diverse native species in urban areas. Rapidly increasing extirpation of fauna in urban settings (He and Hubbell 2011) is attributable to the loss of habitat (Hassan et al. 2005). Retaining and enhancing species diversity in urban areas requires use of ecological corridors that connect local habitat fragments with regional habitat systems. Connecting subsurface and FWS treatment wetlands with residual urban forest patches in a system of urban corridors provides more ecosystem benefits at lower cost than if the same elements exist as single use landscapes. Habitat is easier and less expensive to assemble if it serves multiple functions, more than one community interest group, or is subsidized because of diverse ecosystem service benefits.

The inclusion of buffer areas that separate corridors from adjacent urbanized land uses by at least 10m enables persistence of species that are moderately tolerant of human presence (Fernández-Juricic, Jimenez, and Lucas 2001; Duerksen et al. 1998; Kubes 1996), though the width and length of the corridors depends upon the needs of desired species. Corridor lengths of not more than 2,000 m between habitat patches enhances urban species diversity (Kubes 1996), as does patch areas of at least 5ha. Unless they are adjacent to special habitats or part of a system of ecological corridors, urban habitat patches containing less than 2 ha have species diversity equal to that of a typical suburban residential yard (Catterall 2009; McGuckin and Brown 1995).

Integrating forest and wetland habitat values. Assuming they meet EPA secondary wastewater treatment standards, integrating FWS marshes and ponds into a wetland network enhances the habitat diversity of urbanized corridors. Creating treatment wetlands in a pattern that coincides with the spatial alignment of urban forest corridors expands the diversity of habitat values in these ecosystem corridors.

Cultural ecosystem services. Treatment wetlands are attractive and interesting. The planning, design and management of treatment wetlands can therefore provide cultural benefits such as scenic beauty, recreation, and education. In a multifunctional landscape, wetlands can foster walking and other forms of health-related behaviors, nature study, social gathering, and retreat from the urbanized environment. The location of trails, wildlife viewing areas, and settings for educational programs often correlates spatially with the location of wetlands (Moore and Hunt 2011).

Treatment wetlands can be designed to provide a variety of cultural ecosystem services in addition to biodiversity and wastewater quality rejuvenation. While the provision of water quality services in HSF wetlands requires rectangular beds to achieve uniform water flow, the margins beyond the beds can be manipulated to provide diverse scenic, recreational, and educational values. The performance of VSF wetlands is independent of their shape, and they can be designed to provide a variety of cultural services. The shape requirements of FWS wetlands fall between the extremes of HSF and VSF beds. However, the aquatic as well as terrestrial components of FWS systems allow their design to contain an increased diversity of plants. Thus, FWS systems can provide an especially rich array of cultural services as design objectives expand beyond a focus on provision of only wastewater quality rejuvenation. When aligned with the location of amenity and cultural values such as recreation, aesthetics, and environmental education, corridors of treatment wetlands, forest habitat, and recreational/open space systems create urbanized multifunctional landscapes that provide a rich array of ecosystem services.

Remediation of wastewater from conventional sewage treatment systems. Treatment wetlands can be used to remediate wastewater quality in effluent from conventional treatment systems. The Eagle Bluffs Conservation Area in Missouri (Figure 6) exemplifies use of a FWS treatment wetland in a wildlife refuge to remediate effluent from a conventional treatment plant (Kadlec, Cuvellier, and Stober 2010). A second example is the Roseburg, OR treatment wetlands and land application of secondary effluent to remove phosphorus (Figure 8).

ECOSYSTEM DISSERVICE

Treatment wetlands sometimes produce ecosystem disservices. Mosquitos are a concern in constructing FWS containing surface water. However, high plant diversity in these systems, leads to greater abundance and diversity of predatory insects that reduce the number of mosquito larva in marsh wetlands when compared to open water ponds without vegetation (Moore and Hunt 2011).

Constructed wetlands contribute to anthropogenic greenhouse gas emissions through methane production. Sweden is creating 12,140 ha of constructed wetlands, which will increase the nation's methane emission by 0.04 percent. These systems will also remove nitrates from farm stormwater runoff. Planting dense emergent and floating leaf vegetation in wetlands limits the amount of methane produced (Thiere, Stadmark, and Weisner 2011).

Methane emissions by wetlands must also be evaluated in light of their carbon sequestration potential, especially when compared with other land uses in the landscape. The annual accumulation of carbon is higher in wetlands than for managed turf grass and regenerating forests (Moore and Hunt 2011). These examples demonstrate that the design, planning, and management of treatment wetlands often involve balancing the enhancement and degradation of competing ecosystem services.

Compared to hybrid treatment wetlands, employing only one treatment wetland type will not remove excess nutrients and pharmaceuticals from wastewater. These substances may compromise health of aquatic systems or organisms. Discharge of these substances in secondary treatment effluent from conventional treatment plants creates abnormalities in amphibians (Ruiz et al. 2010). However, hybrid treatment wetlands effectively remove a full range of contaminants, including excess nutrients and pharmaceuticals (Ávila et al. 2010; Matamoros et al. 2009).

ECONOMIC VALUATION OF ECOSYSTEM SERVICES ASSOCIATED WITH TREATMENT WETLAND

Assessing the economic value of ecosystem services provided by treatment wetlands.

Assessing the pecuniary value of ecosystem services provided by treatment wetlands uses methods originally developed to assess the economic value of city park systems (Trust for Public Land 2010). This process is exemplified in a Chinese case study. The 1,141 ha Sanyang wetland in Wenzhou, China was highly degraded by filling wetland edges and sedimentation from adjacent land uses. Most of the wetland vegetation was destroyed and edges between terrestrial and aquatic environments were straightened (Tong et al. 2007).

The analysis compared the economic value of goods, processes, and habitat provided by the existing landscape compared to those specified in a restoration plan. Proposed wetland ecosystem services in the restored wetland were valued at $8640 per ha while services provided by the degraded wetland amounted to the $907 per ha. Costs for wastewater quality remediation provided by the restored wetland were estimated to be 43 percent of the total potential value (Tong et al. 2007). This study demonstrates the economic potential of treatment wetlands within multifunctional landscapes.

Figure 9. Koh Phi Phi Multifunctional Community Garden. Collection and distribution building far left, VSF left, HSF center, FWS right, polishing pool center (Photo courtesy Hans Brix, Aarhus University, Denmark).

Capital And Operating Costs Of Treatment Wetlands Compared To Conventional Treatment Systems.

Costs of treatment wetlands are distributed differently than those of conventional treatment plants. Treatment wetlands require more land area to treat the same volume of water. The large expenditures for land acquisition and the availability of appropriately sized and located properties within existing urbanized settings often impede use of treatment wetlands. However, depending on the availability of local gravel and sand resources (a key component of subsurface treatment wetland construction), construction costs of treatment wetlands are comparable to or lower than construction costs of wastewater treatment plants.

Because they employ sunlight, gravity, and biological processes to rejuvenate wastewater quality, treatment wetlands have lower operating costs than conventional wastewater treatment plants (Vymazal 2011b). The primary operating cost in treatment wetlands is water quality testing, which is sometimes higher in a distributed wetland treatment system. Pumping and artificial aeration, which are required to accomplish effective wastewater mitigation in a conventional treatment plant, are rarely necessary in treatment wetlands, and exist at a smaller scale when required. While treatment wetlands have been constructed to serve as many as 6,000 residents living in a mixed-use district (Figure 4) (Blumberg Engineers 2003), most systems are considerably smaller.

The value of secondary benefits is often ignored in cost/benefit comparisons of treatment wetlands and conventional treatment plants. The provision of additional ecosystem services (biological diversity and cultural values) associated with multifunctional treatment wetlands would have to be provided (and purchased) in alternate locations with the use of conventional treatment plants for wastewater quality rejuvenation. The use of more holistic assessment methods of wastewater treatment costs would demonstrate the true value of treatment wetlands (Tong et al. 2007).

KOH PHI PHI ISLAND CASE STUDY

Koh Phi Phi Island, Thailand exemplifies the use of treatment wetlands in creating a multifunctional landscape design (Figure 9). This landscape incorporates wastewater treatment into a city park on a 0.6 km^2 parcel in the center of the town. The park amenities are fully integrated with the treatment wetlands. The park program features a pavilion, turf areas, large panels of flowering plants, seating and strolling areas, and a small sports field. In addition to these social, recreational, and aesthetic amenities, water from the treatment wetland system is captured in a reservoir for irrigation of the park (Brix et al. 2011).

The island's population is just 3,000, but more than 1 million tourists visit annually. The island was devastated by a tsunami in 2005, after which the Danish government provided funds to restore wastewater treatment services. Water, energy, and developable land are scarce on the island, necessitating the design of a multifunctional landscape. An extensive public process supported by the municipal government and major stakeholders, including restaurant and resort owners, generated the design concept. The design analogy was a blossom with a perching butterfly, which referenced the shape of the island and local symbols. The project cost $700,000 (2006 dollars). A local contractor constructed the project using island residents for labor (Brix et al. 2011).

The system was designed to treat 400,000 L of wastewater per day. The provision of septic tanks and sewer connections at the scale of individual residential and business sites enables the existence of a distributed pretreatment system. Solar-powered pumps deliver pretreated water to three parallel VSF wetland cells with a total area of 2428 m^2. The VSF wetlands are 0.70 m deep, with three layers of gravel. They are planted with *Canna* and *Heliconia* (lobster claw). Water from the VSF cells flows through three parallel cells of HSF wetland with a total area of 750 m^2). The HSF wetlands are 0.6 m deep and planted with *Canna* in 25mm deep gravel beds. The third stage of treatment includes three 0.6 m deep FWS pools with an area of 809 m^2 and planted with *Papyrus*. The treated water flows into a 0.71 m deep linear polishing pond containing 200 m^2 of open water to remove nutrients. The effluent is treated to tertiary standards and then flows into a closed reservoir for use in irrigation (Brix et al. 2011).

Monitoring of the system's performance over two years revealed that effluent from the system met EPA standards. However, wastewater remediation performance of the system declined after the first year. The declining effluent quality was attributed to illegal connections to the sewer system without installing the required septic tanks and grease traps for pre-treatment. Nevertheless, Koh Phi Phi Island case demonstrates that the pairing of recreation, aesthetic, and other cultural services and wastewater functions is viable where a wastewater authority enforces health codes and is held responsible for the small amount of maintenance and adjustment that the biological system requires.

APPLICATION OF TREATMENT WETLANDS IN NEW URBAN DEVELOPMENT

Treatment wetlands can be easily integrated into new residential and mixed-use development as they can be distributed at various elevations in the watershed and do not require large land areas. This provides opportunities for water reuse as treated water flows through the watershed. Coordinating the physical planning of these wetlands with development patterns and the spatial alignment of urban ecosystem corridors provides opportunity to create a multifunctional urban landscape.

The following example illustrates integration of treatment wetlands into a multifunctional landscape in the context of residential development. Assuming construction of a residential subdivision containing 380 dwelling units with 2.63 persons per unit (total population of 1000), a wetland treatment area of 0.2 ha using a VSF is required to produce effluent that meets secondary treatment standards. Adding an HSF wetland to accomplish tertiary treatment objectives requires an additional wetland area of 0.5 ha. Realization of minimum biodiversity benefits associated with the HSF and VSF wetlands would require an additional 1.3 ha of FWS wetlands for a total of 2 ha of wetlands within the subdivision. The National Recreation and Park Association (NAPA) recommends 2.6 to 4.2 ha of parkland per 1,000 people in residential areas (Lancaster 1983). Beyond the 0.7 ha dedicated to treatment wetlands, the additional 0.6 to 2.2 ha needed to meet the NAPA standard could include a variety of recreation amenities, trails, stormwater management, or other public uses to provide multiple ecosystem services. Recreational amenities such as a 0.5 km circuit path, fishing docks, and picnicking areas would provide additional ecosystem services in the open space area. If connected to an urban ecosystem corridor, a wetland treatment/recreational node could provide additional services in framing the pattern of larger scale urban development.

After accounting for evaporation and transpiration losses, about 303,000L of treated wastewater would be available each day to support parkland irrigation or other non-potable uses. Assuming an average gross density of 1.7 dwelling units per hectare, the area of the multifunctional treatment wetlands and recreational uses would represent only four to five percent of the total developed land.

CONCLUSION

Treatment wetlands have the potential to deliver ecosystem services at both the site and landscape scale. Individual HSF or VSF treatment wetlands of $2\,\mathrm{m}^2$ (VSF) to $4.5\,\mathrm{m}^2$ (HSF) of treatment area per person effectively meet secondary treatment standards. A sequence of the HSF and VSF wetlands achieves tertiary water quality. Distribution of treatment wetlands throughout a green infrastructure system allows treated effluent from subsurface treatment wetlands to be used to create FWS wetlands for habitat enhancement, irrigation, and open space uses. While the capital cost of large constructed wetland systems for wastewater treatment may equal the cost of conventional treatment systems, the operating costs and energy use are lower. The economic value of the ecosystem services provided by subsurface and FWS wetlands justifies their construction or restoration to realize a full range of provisioning, regulating, and cultural benefits. When connected to urban ecological corridors, the on-site ecosystem services provided by treatment wetlands effectively enhance the creation of larger scale multifunctional landscapes to guide overall patterns of urbanized development.

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