Wetlands (2011) 31:805–814
DOI 10.1007/s13157-011-0186-3

REVIEW

Surface-Flow Constructed Treatment Wetlands for Pollutant Removal: Applications and Perspectives

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Received: 10 January 2011 / Accepted: 17 May 2011 / Published online: 31 May 2011

Abstract I review the technology and application of free-water surface flow (FWS), macrophyte-dominated constructed treatment wetlands (CTWs) for pollutant removal. FWS-CTWs are used to remove a wide range of pollutants from various wastewaters. In FWS-CTWs, hydrologic conditions have a key influence on the biotic community, biogeochemical processes, and the fate of pollutants. Therefore, understanding the interactive effects of hydrology and biotic communities is critical to pollutant removal. In the past two decades, studies and applications of FWS-CTWs have increasingly focused on four wetland technologies: 1) tertiary treatment wetlands, 2) submerged aquatic vegetation (SAV) dominated systems, 3) FWS constructed wetlands for watershed management, and 4) hybrid systems. Managing FWS-CTWs, including adjustment of flow and water depth is crucial to the sustainability of effective treatment. Multiple functions and services of FWS-CTWs such as biological conservation and other ancillary benefits can be added while FWS-CTWs are applied to wastewater treatment. To reduce the acreage necessary for pollutant removal, coupling FWS-CTWs with other technologies has an application perspective for water quality improvement. Using FWS-CTWs is cost effective and environmentally sound for water sanitation, reuse, and conservation and supports sustainable resource management.

Keywords Aquatic vegetation · Hydrology · Nutrient removal · Treatment wetland management and sustainability · Wastewaters

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Introduction

Constructed treatment wetlands (CTWs) are used to remove a wide range of pollutants such as organic compounds, suspended solids, pathogens, metals, and excess nutrients (e.g., N and P) from various wastewaters including storm-water runoff and municipal wastewater (Ghermandi et al. 2007; Vymazal 2007; Snow et al. 2008; Cooper 2009; Kadlec 2009). Because of high removal efficiency, low cost, water and nutrient reuse, and other ancillary benefits, CTWs have become a popular option for wastewater treatment (Ghermandi et al. 2007; Rousseau et al. 2008; Llorens et al. 2009; Kadlec 2009). The design for CTWs is based on free-water surface flow (FWS), horizontal subsurface flow (HF), or vertical subsurface flow (VF) (Kadlec 2009). Systems with aboveground flow are referred to as FWS-CTWs and those with belowground flow as subsurface flow CTWs can be further subdivided into HF- and VF-CTWs. Like natural marshes, FWS-CTWs exhibit a broad spectrum of biological characteristics that are capable of removing various constituents for water quality improvement (Ghermandi et al. 2007) and can be classified according to the dominant vegetation community: free-floating aquatic vegetation (FFAV), emergent aquatic vegetation (EAV), or submerged aquatic vegetation (SAV) dominated systems (Brix 1994; Vymazal 2007). FWS-CTWs typically consist of a sequence of treatment cells with water control structures that regulate flow and hydro-period to optimize the maintenance and functioning of vegetation communities. FWS-CTWs are often densely vegetated by a variety of wetland plant species such as *Typha* species and *Phragmites australis* and have a target water depth of 20–40 cm.

Much knowledge has been gained from studies on CTWs for wastewater treatment (Kadlec and Wallace 2009), but my review focuses only on FWS-CTWs. First, I examine important interactive factors influencing wetland functioning for pollutant removal. Second, I assess performance and applications of several typical FWS-CTW. Finally, I further examine the management, sustainability, and application perspective of FWS-CTWs. By reviewing pollutant removal performance and mechanisms of several types of FWS-CTWs, a better understanding of the effectiveness of macrophyte-dominated FWS-CTWs will be achieved, thus promoting wise application and management of treatment wetlands for pollutant removal.

Interaction of Hydrology and Biota for Pollutant Removal

In FWS-CTWs, removal efficiencies above 70% can be achieved for total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), and pathogens, primarily bacteria and viruses (Kadlec and Wallace 2009). Removal efficiencies for N and P are typically 40–50% and 40–90%, respectively (Andersson et al. 2005; Vymazal 2007; SFWMD 2011). FWS-CTWs have a variety of removal efficiencies for metals that are compound specific (Ghermandi et al. 2007; Arroyo et al. 2010). Pollutant removal efficiency in CTWs depends on a number of variables including pollutant loading, hydrologic regime, and vegetation type (Kadlec and Wallace 2009). Hydraulic and hydrologic conditions strongly influence biotic community composition, biogeochemical processes, and the fate of pollutants in natural marshes and FWS-CTWs (Reddy et al. 1999; Mitsch and Gosselink 2007; Kadlec and Wallace 2009). Therefore, pollutant removal often is accomplished by manipulating the system's hydraulic and hydrologic conditions and by selecting the type of dominant vegetation accordingly (Vymazal 2007; Kadlec and Wallace 2009). Water depth needs to be at a level that allows establishment and development of the desired vegetation type. Hydraulic retention time needs to be long enough to allow full utilization of wetlands to remove incoming pollutants. High runoff inflow velocities may scour sediments and resuspend nutrients and organic matter in the water column (Kadlec and Wallace 2009). Therefore, being unable to maintain an optimal hydraulic and hydrologic range and desired vegetation type often results in system failure.

Organic (C-, N-, P-, and S-containing compounds) removal processes are microorganism-mediated and controlled by oxygen availability and soil redox potential, both of which are governed by hydrology (Reddy and DeLaune 2008). However, the interactions between biota and hydrological regime are complex and need in-depth studies to be understood for pollutant removal. For example, anaerobic conditions caused by deep water favor N removal through denitrification, one of the major processes for N removal and peat accretion in FWS-CTWs, but it does not increase either the mineralization and nitrification of N or the adsorption and precipitation of P from the wastewater (Reddy et al. 1999; Vymazal 2007). Unlike N removal, the ultimate long-term removal mechanism for P is peat accumulation by which P is stored in organic matter and buried through sedimentation (Richardson 1985; Reddy et al. 1999). Chemical precipitation and adsorption of P to binding sites of sediments are also important removal mechanisms (Richardson 1985; Reddy et al. 1999; Ghermandi et al. 2007). However, due to the potential for efflux to the water column (Reddy et al. 1999), the fate of the precipitated and adsorbed P in sediments depends on the hydrologic regime or redox conditions in wetlands (Patrick and Khalid 1974). In addition, removal of most metals in FWS-CTWs depends on how metals transform and interact with other elements in the environment, which is affected by soil redox potential, pH, and the availability of relevant anions such as sulfide and carboxyl groups of organic matter in wetlands (Gambrell 1994; Odum et al. 2000). Besides biotic uptake, mechanisms for metal removal in FWS-CTWs include deposition, oxidation and reduction reactions, adsorption, and precipitation or co-precipitation as insoluble salts, particularly sulfides and oxyhydroxides (Odum et al. 2000; Sheoran and Sheoran 2006). The insoluble compounds or complexes of metals formed by these mechanisms are subject to removal from the water column via sedimentation and therefore sustainable metal retention occurs primarily in sediments (Vymazal et al. 2010). Theoretically, accumulated metals bound to sediments can reach saturation points or allowable or target concentrations that are the threshold of metal toxicity to biota, but the system's life can be decades or longer in terms of calculated metal loading rates (Beining and Otte 1997; Kadlec and Wallace 2009). Furthermore, actual burial of metals by newly accreting sediments may extend life expectancies of FWS-CTWs (Kadlec and Wallace 2009).

Wetland macrophytes play a role in pollutant removal through direct uptake, by mechanical resistance to flow that promotes settling of particles, and by providing a substrate for the attachment of algae and other microorganisms that sequester or break down pollutants (Brix 1994; Wetzel 2001). Wetland plants are often viewed as transient nutrient storage compartments because they absorb nutrients during the growing season and release nutrients at senescence. While this statement may be true for FFAV and SAV species due to their rapid turnover rates (Chimney and Pietro 2006), it underestimates the role of EAV species for nutrient removal. More than 50% of nutrient storage occurs in the belowground tissue of EAV species, as indicated by their high ratio of belowground to aboveground biomass (Reddy et al. 1999; Vymazal 2007). As EAV species mature and aboveground shoots senesce, a large proportion of critical nutrients in aboveground biomass are translocated to belowground tissues for storage and eventual reuse for new growth of shoots (Meuleman et al. 2002). Due to a lower turnover rate of the belowground tissue than shoots, when belowground tissues die, their nutrients are stored through burial by litter in a low oxygen environment where the rate of litter decomposition is slow (Wetzel 2001). FWS-CTWs, particularly systems designed for P removal are usually kept flooded throughout the year, which results in anaerobic conditions in soils. On the other hand, as EAV communities reach maximum plant density or 100% plant coverage in FWS-CTWs, N removal efficiency decreases, because the maximum plant density decreases microbial community diversity, results in lower dissolved oxygen levels as algal and autotrophic microbial communities are shaded, and contributes to the internal loading of nutrients as plants decompose (Ibekwe et al. 2007). Thullen et al. (2002) have observed that maintaining 50% plant coverage is the most effective way of keeping high efficiency of nutrient (particularly N) removal in constructed wetlands.

In addition, the role of algae and other microbes for nutrient removal has not often quantitatively been evaluated (McCormick et al. 2006; Ibekwe et al. 2007), although their importance in assimilation, transformation, and recycling of chemical constituents in CTWs is widely recognized (Kadlec and Wallace 2009). The mass of microbiota, with high reproductive and growth rates, on the enormous surface areas of plant litter and detritus is large. Under anaerobic conditions, much of the microbial biomass decomposes at an extremely low rate. Therefore, algae and other microbial communities effectively retain organic carbon and critical nutrients such as P (Wetzel 1993), which is sometimes misunderstood in the literature.

Applications of FWS-CTWs

Recently, much attention has been directed to FWS-CTWs to treat wastewater and enable sustainable resource management or ecosystem restoration (Ghermandi et al. 2007; Harrington et al. 2007; Scholz et al. 2007; Vymazal 2007; Rousseau et al. 2008; Snow et al. 2008; Kadlec 2009; Li et al. 2009). FWS-CTWs have been applied at different stages of treatment of wastewater from different sources with varying pollution characteristics and are suitable in all climates (Kadlec and Wallace 2009). When wastewater contains concentrated pollutants, some form of pretreatment (e.g., settling basins or anaerobic lagoons) is applied. Therefore, FWS-CTWs for treating municipal wastewater usually follow a primary or secondary pretreatment (Ghermandi et al. 2007; Kadlec 2009). Post-treatment for disinfection through chlorination or exposure to ultraviolet radiation may be needed for pathogen removal. FWS-CTWs can be used as a part of an integrated wastewater treatment train and as a "stand-alone" wastewater treatment technology. Examples of the use of FWS-CTWs for various types of wastewater are presented in Table 1. Although the primary applications of FWS-CTWs are for treating municipal and domestic wastewater, animal wastewater, and agricultural and urban runoff, other applications for treating food-processing wastewater and industrial wastewater are currently increasing due to the ability to removal of almost all organics tested in treatment wetlands (Kadlec and Wallace 2009; Vymazal 2011). These organics include petroleum hydrocarbons, chlorinated hydrocarbons, and other chemicals such as pesticides and fertilizers. FWS-CTWs are also an option for treating a variety of inorganic contaminants including halogens, sulfur, metals, and metalloids from industrial wastewater (Kadlec and Wallace 2009; Batty et al. 2008). FWS-CTWs designed for metal removal are limited but they are often applied to treatment of acid mine drainage that contains various metal compounds. In addition, FWS-CTWs can yield an effluent suitable for reuse, i.e., irrigation of agricultural crops, toilet flushing, cooling water, and cleaning purposes, and concurrently provide some opportunities to recycle nutrients and to accommodate wildlife (Rousseau et al. 2008; Ghermandi et al. 2007). Current applications of several typical FWS-CTWs are discussed in the following sections.

Tertiary Treatment Wetlands

Tertiary treatment wetlands (Table 2) are intended to polish the final effluent from conventional wastewater treatment plants (WWTP) before this water is discharged to natural areas such as rivers and lakes (Toet et al. 2005; Siracusa and La Rosa 2006; Wang et al. 2006; Ghermandi et al. 2007; Rousseau et al. 2008). The effluent from a WWTP is characterized by relatively low BOD (20–40 mg/l) and moderate N and P concentrations, which may still be too high for discharge to surface waters sensitive to eutrophication (Kadlec 2003; Toet et al. 2005). This effluent can be polished in FWS wetlands for water reclamation and reuse (Kadlec 2003; Ghermandi et al. 2007). Ghermandi et al. (2007) have assessed the performance of 38 tertiary treatment wetlands worldwide and found that the wetlands, on average, removed approximately 50% of BOD, 23% of TSS, and 89% of fecal coliforms. Toet et al. (2005) report a 26% reduction of N (126 gN $m^{-2}yr^{-1}$) and less than 5% reduction of P (5 gPm^{-2} yr^{-1}) in a wetland system in The Netherlands. Phosphorus removal in tertiary treatment wetlands varies (Vymazal 2007; Rousseau et al. 2008; Cooper 2009), dependent on both P loads and sizes of

Table 1 The use of FWS-CTWs for various types of wastewaters

Application	Primary pollutant	Objective and applicability	Effluent reuse
Treatment of primarily settled and secondarily treated sewage[a]	Particulate, dissolved organics, and pathogens	For small, rural communities particularly in developing countries	Agricultural irrigation
Tertiary effluent polishing[b]	Moderate nutrients	Most commonly applied; reduce N and P eutrophication	Discharge to surface waters; irrigation
Stormwater runoff management[c]	Suspended solids and low nutrients	Most commonly applied; reduce turbidity and eutrophication	Discharge to surface waters; irrigation
Treatment of animal wastes[d]	Organics, suspended solids, high nutrients, and pathogens	Commonly applied; may need pre-treatment	Recycle as flushing water, agricultural use, or discharge to surface waters
Landfill leachate treatment[e]	Nutrient (particularly N), metals, volatile and toxic organics	Reduce surface and subsurface water pollution; need pre-treatment	Irrigate the landfill mound and/or cover plants growing on it; discharge to surface waters; discharge limitation and regulation may need
Acid mine drainage treatment[f]	Metals and metalliods	Remove metals and rise pH; may need pre-treatment	Discharge to surface waters; discharge limitation and regulation may need
Food-processing wastewater treatment[g]	Source-specific; often dissolved, N- and P-containing organics	Reduce source pollution; need pre-treatment	Discharge to surface waters; irrigation
Industrial effluent treatment[h]	Source-specific; often containing organics and toxic chemicals	Reduce source pollution; need pre-treatment	Discharge to surface waters; discharge limitation and regulation may need

Note: [a] Kivaisi 2001; [b] Graczyk et al. 2009; Llorens et al. 2009; Ghermandi et al. 2007; Ibekwe et al. 2007; Wang et al. 2006; Toet et al. 2005; Greenway 2005; Thullen et al. 2005; [c] Kadlec 2006; Mustafa et al. 2009, SFWMD 2011; Revitt et al. 2001; [d] Meers et al. 2008; Dunne et al. 2005; Tilley et al. 2002; Stone et al. 2004; [e] Snow et al. 2008; Kadlec and Wallace 2009; [f] Batty et al. 2008; Sheoran and Sheoran 2006; Younger et al. 2002; [g] Vymazal 2011; Masi et al. 2002; Gambrell et al. 1987; Van Oostrom (1995); [h] Kadlec and Wallace 2009.

systems. Unlike organically bound N compounds, metallic compounds are difficult to remove from wastewater directly by biological processes; some metals are poorly removed or not removed at all (Ghermandi et al. 2007). Also, wetland effluents may contain human pathogens and represent a health threat to the public and wildlife (Graczyk et al. 2009). Therefore, the long-term ecological risk to wildlife exposed to heavy metals and pathogens needs to be monitored and assessed.

Submerged Aquatic Vegetation Dominated Wetlands

Large-scale SAV-dominated systems as a “stand-alone” technology (Table 2) do not have widespread use for primary or secondary wastewater treatment (Gumbricht 1993; Andersson et al. 2005; Kadlec 2006). Submerged aquatic vegetation species, such as *Ceratophyllum demersum*, *Elodea nuttallii*, *Potamogeton pusillus*, and *Najas guadalupensis* are present in many natural and constructed wetlands (e.g., Toet et al. 2005; Chimney and Goforth 2006) and often include associated periphyton, an assemblage of algae, bacteria, and other microorganisms (Vymazal 1995). However, SAV species only grow well in oxygenated waters with high-light conditions, and thus cannot be used for treating wastewater with a high content of readily biodegradable organic matter because of the anoxic, low-light conditions created by the microbial decomposition of organic matter (Brix 1994).

The SAV/periphyton assemblage effectively removes P from the water column directly by assimilating P through the shoots and leaves of plants and through a Ca-P co-precipitation mechanism (McCormick et al. 2006; Pietro et al. 2006). A 917-ha SAV-dominated FWS-CTW (STA-2 Cell 3) has been used successfully to remove P from agricultural runoff as a primary treatment in south Florida since 1999 (SFWMD 2011). This FWS-CTW achieved 79% of yearly total P removal, comparable to two parallel EAV-dominated FWS-CTWs (STA-2 Cells 1 and 2). Andersson et al. (2005) reported that the removal rates for total N and P were 24–33% and 30–53%, respectively, in two SAV-dominated marshes in southern Sweden, compared to removal rates of 41–69% and 71–90% for total N and P in two EAV-dominated marshes. In contrast, SAV communities assimilate and deposit much less carbon than EAV communities; the biomass turnover rate of SAV communities is on average 10 times faster than that of *Typha* communities (Chimney and Pietro 2006). Because of the combination of low carbon contribution to the sediment (Brenner et al. 2006) and high biomass turnover rate, a SAV/periphyton assemblage is unlikely to build peat as effectively as an EAV community. Submerged aquatic vegetation also accumulates large quantities of loose flocculent material that may be readily re-suspended and increase overlying water turbidity, thus impacting the sustainability of SAV communities and P removal performance.

Table 2 System characteristics and processes and mechanisms of pollutant removal for selected FWS-CTWs

FWS-CTWs	System characteristic	Process and mechanism
Stormwater Treatment Areas (STA-1E, STA-1 W, STA-3/4, and STA-5) (SFWMD 2011)	Consist of a *T. domingensis* and/or *T. latifolia* dominated marsh with FFAV (frond-end cell) and a *C. demersom, N. guadalupensis,Chara* sp., and/or *Hydrilla verticillata* co-dominated marsh (downstream cell) for P removal.	Sedimentation Biotic uptake Soil adsorption Peat accretion
Marsh-pond-marsh systems (Reddy et al. 2001; Llorens et al. 2009)	A sequence of marsh, lagoon/pond, and marsh treatment cells with both shallow and deepwater zones; EAV-dominated marshes; treat animal wastes and municipal wastewater.	Sedimentation Biological uptake Peat accretion Denitrification UV radiation disinfection and degradation
Tertiary treatment wetlands (Ghermandi et al. 2007)	A marsh consisting of with EAV and/or FFAV dominated treatment cells for treating effluent of the WWTP.	Sedimentation Biological uptake Denitrification Soil adsorption Peat accretion
SAV dominated treatment wetlands (Andersson et al. 2005; SFWMD 2011)	SAV dominated marshes for treating stormwater and effluent of the WWTP.	Sedimentation Biological uptake Soil adsorption Peat accretion Chemical precipitation
Multi-pond system (Yan et al. 1998; Yin and Shan 2001)	A network of shallow-water detention ponds connected by ditches in an agricultural watershed; allow *P. crispus, Myriophyllum vertilla, Alternanthera philoxeroides,* and *P. communis* to grow.	Sedimentation Soil adsorption Biological uptake Nutrient recycling through irrigation and harvesting
Integrated Constructed Wetlands (Scholz et al. 2007)	A network of shallow-water marshes with mixed EAV for cleansing farmyard wastewater and enhancing biological diversity.	Sedimentation Biological uptake Denitrification Soil adsorption Peat accretion

Use of FWS Wetlands for Watershed Management

Multi-pond systems (Table 2) are traditional agricultural hydraulic systems designed for water retention, flood control, and the irrigation of agricultural fields that have existed in south and southeastern China for thousands of years (Yin and Shan 2001). The multi-pond system is composed of many small, scattered, ditch-connected shallow (usually 1.5-m water depth) ponds that are vegetated by a variety of aquatic plants (Yan et al. 1998; Yin and Shan 2001). During a rainfall event, surface runoff from agricultural fields flows into adjacent ditches and passes through a series of small ponds before it reaches the river downstream. Similar systems exist in India, Europe, and other countries (Yin et al. 2006). The multi-pond system can recycle 50% of agricultural runoff and retain more than 80% of nutrients (total N and P), 85% of total dissolved P, and 51% of suspended solids in the watershed (Yin and Shan 2001; Shan et al. 2002). The retention and removal mechanisms for P in multipond systems are sedimentation, soil adsorption, P recycling through irrigation, and P uptake by aquatic plants (Table 2; Yin and Shan 2001). Farmers routinely harvest aquatic plants in ditches and ponds to feed livestock and poultry and every 3–4 years dig out accumulated sediments in early spring and apply them to adjacent agricultural fields as anameliorant. The multi-pond system is a sustainable way to control pollution, to recycle nutrients, and to reuse water within agricultural areas (Yin and Shan 2001). In Anhui, China, the multi-pond system has been encouraged by the government to store stormwater and retain suspended sediments and transported nutrients from agricultural fields (Yin et al. 2006).

The ancient multi-pond system shares similar ecological principles with the Integrated Constructed Wetlands (ICW) that have recently been developed for farmland management in Ireland and the UK (Scholz et al. 2007; Carty et al. 2008; Table 2). An ICW is defined as an unlined EAV dominated FWS-CTW with the objectives of cleansing and managing runoff flow from farmyards and other wastewater sources, integrating the wetland infrastructure into the local landscape, and enhancing the site's ancillary values and biological diversity (Scholz et al. 2007). The ICW usually requires a relatively large land area and has long hydraulic residence time, which is largely self-managing, biologically self-designing, and of social and economic coherence (Carty et al. 2008). The ICWs are capable of treating polluted water from farmyards and provide a sustainable management option that will effectively reduce nutrient and contaminant runoff into water resources (Scholz et al. 2007). Significant concentration reductions in BOD, COD, TSS, SRP, ammonia N, and fecal bacteria were observed from the ICW effluents but reduction of nitrate N varied (Table 3). The ICW system does not pollute the receiving waters (Mustafa et al. 2009; Kayranli et al. 2010).

Hybrid Wetlands

A hybrid wetland incorporates two or more different types of wetlands, frequently being comprised of VF and HF beds that are arranged in a two-stage pattern to achieve higher treatment efficiency and is most widely used in Europe (Vymazal 2005; Kadlec and Wallace 2009). First, FWS wetlands have recently been hybridized with other VF and/or HF wetlands to improve nutrient and bacteria removal efficiency, to reduce the acreage necessary for target pollutant removal, and/or to enhance habitat quality and ancillary benefits such as wildlife conservation and recreation (Vymazal 2005; Fleming-Singer and Horne 2006; Rousseau et al. 2008). In nine hybrid systems worldwide, the removal performance of COD (98%), TSS (99%), and BOD (98%) is generally high, but removal varies for both total N (31–99%) and P (14–98%), depending on system configuration, wastewater loading, treatment area, and climatic zones (Table 4).

A hybrid wetland also incorporates FWS wetlands dominated by EAV, FFAV, and SAV communities to achieve higher treatment efficiency, particularly for P removal. For example, the large-scale treatment wetlands in south Florida, collectively known as the Stormwater Treatment Areas (STA, Table 2), have been constructed to reduce P levels in agricultural runoff (Chimney and Goforth 2006; Kadlec 2006; SFWMD 2011). A front-end treatment cell (dominated by *T. domingensis* and/or *T. latifolia* with other EAV and FFAV species) is used initially to treat runoff and a back-end treatment cell (dominated by *C. demersom, N. guadalupensis,Chara* sp., and/or *Hydrilla verticillata*) is expected to reduce further P concentration of the effluent from the front-end cell (SFWMD 2011). In 1994–2010, the STAs removed 74% of the inflow total P load and retained more than 1,403 metric tons of total P that would have otherwise entered the Everglades (SFWMD 2011). Besides high total P removal, the STA has an 80% removal rate for nitrate and nitrite, but the removal efficiency of total N and sulfate was relatively low (SFWMD 2011).

Marsh-pond-marsh CTW (Table 2) is the third example of a hybrid wetland system (Reddy et al. 2001; Llorens et al. 2009). Llorens et al. (2009) reported that combining zones of open water with belts of *P. australis* and *T. latifolia* in a WWTP in Spain reduced effluent NH_4^+ concentrations from 31 mg N/L to 4 mg N/L with 55% of the effluent samples meeting the required standard of 2 mg N/L. There was also a notable decrease in fecal coliform concentration and a decrease in concentration of pharmaceuticals and personal care products through these wetlands. In a marsh-pond-marsh system for treating swine wastewater (Reddy et al. 2001; Stone et al. 2004), N removal had a seasonal pattern, lower in cold months (37–51%) than in warm months (often >70%), while P removal was low, varying from 30–45%. Compared to EAV dominated wetlands, the marsh-pond-marsh system has a higher removal rate of pathogens because they are exposed to ultra-violet radiation in the open-water areas (Ghermandi et al. 2007). Therefore, a system comprised of densely vegetated marshes with interspersed open-water zones is recommended to maximize pathogen removal (Greenway 2005).

Sustainability and Management of Treatment Wetlands

While a debate on the sustainability of FWS wetlands for wastewater treatment is still ongoing, particularly for P removal, long-term records provide evidence of the longevity of treatment wetlands (Kadlec and Wallace 2009). Two FWS wetlands, the Brillion Marsh in Wisconsin and Great Meadows Marsh in Massachusetts operated for over 70 years and retained their treatment efficiency (Kadlec and Wallace 2009). In contrast, a tertiary treatment wetland, the Easterly Wetland in Orlando, Florida, has reduced 70–80% of the nutrient load, but has showed a slight decline in nutrient removal efficiency over time, possibly due to an increase in flow and variation in P loading (Wang et al. 2006). Determining the longevity of treatment wetlands is complicated by various factors including inflow hydraulic and pollutant loading rates, natural factors such as extreme weather conditions, and the type of pollutants for which the wetlands are designed. However, newly accreting sediment in treatment wetlands may become an issue after a decade or two of operation because it can alter the hydrological regime (Kadlec and Wallace 2009). Others indicate that treatment

Table 3 Pollutant concentrations of inflow and outflow and removal efficiencies for Integrated Constructed Wetlands

ICW	Years of data collection	BOD (mg/l)			COD (mg/l)			TSS (mg/l)			*Escherichia coli* (CFU/100 ml)		
		Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal
Glaslough	1	768	4	99	1,279	39	97	2,184	12	99			
Dunhill	5	358	17	95	554	61	89	304	9	97			
Waterford	6	540	13	98	1,502	76	95	261	16	94	960,000	30	100
ICW (*N*=13)	5	775	16	92	1,563	58	91	338	19	91	910,233	415	99
(mean ± SD)		±1,593	±5	±9	±2,121	±21	±8	±316	±9	±6	±2,114,503	±556	±1
		SRP (PO_4^{-3}-P, mg/l)			Ammonia N (mg/l)			Nitrate N (mg/l)			Reference		
		Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal			
Glaslough	1	3.7	0	99	32	0.3	99	5	0.3	94	Kayranli et al. 2010		
Dunhill	5	7.8	5.2	34	53	22	58	0.6	0.7	−12	Kayranli et al. 2010		
Waterford	6	12	0.9	92	40	0.4	99	3.8	1.0	74	Mustafa et al. 2009		
ICW (*N*=13)	5	18	1	90	64	2	96	1	2	−158	Scholz et al. 2007		
(±1sd)		±20	±1.58	±19	±43	±6	±12	±1	±1	±215			

wetlands can be expected to sustain their performance as long as appropriate hydrology and vegetation are maintained and detritus removal occurs regularly (Scholz et al. 2007; Carty et al. 2008).

Proper management is crucial to the sustainability of an effective FWS system (Carty et al. 2008; Rousseau et al. 2008). Although the design of constructed wetlands as self-sustaining systems without intervention often is a useful goal, a self-sustaining system may not be possible for FWS-CTWs where nutrient loading and/or sedimentation rates are high and system hydrology is altered seasonally or for operational and maintenance purposes. Maintaining healthy vegetation is also imperative to sustaining both effective water quality treatment and habitat value (Thullen et al. 2005; Ibekwe et al. 2007). Minimum maintenance, including adjustment of flows and water levels is required to achieve successful performance in FWS systems (Carty et al. 2008; Rousseau et al. 2008; Kadlec and Wallace 2009). Adaptive management strategies should be used to enhance the long-term success of treatment wetlands by allowing modifications and enhancements in response to changes in natural conditions and the biotic uncertainties inherent in natural systems. For example, the performance of STA-1W began to decline in 2004 due to nutrient and hydraulic overloading and was aggravated by severe hurricanes. Rehabilitation efforts were made to enhance and optimize performance through revegetation and removal of accrued soil layers with high total P concentrations. Because the STA provides useful habitat for migratory waterfowl, some enhancement programs such as bird-watching have been added to the facility for environmental, educational, and recreational purposes. In addition, wetland design criteria often are not reflective of extreme environmental conditions such as weather and hydrologic fluctuations (Thullen et al. 2005; Mitsch and Gosselink 2007) that can negatively impact wetland functioning and decrease wetland sustainability.

Future Application Perspectives

FWS-CTWs can be used for many purposes other than water quality improvement. A number of ancillary benefits such as the creation of wetland habitat and biodiversity conservation that FWS-CTWs provide are important for sustainable resource management (Rousseau et al. 2008; Carty et al. 2008). Conserving biodiversity is essential to many ecosystem services (e.g., biotic regulation and aesthetic values) in both the wetland and the surrounding landscape (Siracusa and La Rosa 2006). Design features of the San Joaquin Wildlife Sanctuary that provide for the dual purposes of N removal and the creation of avian habitat do not inhibit removal of total N (Fleming-Singer and Horne

Table 4 Pollutant concentrations of inflow and outflow and pollutant removal for selected hybrid wetlands

Hybrid wetland	Country	Total N (mg/l)			Total P (mg/l)			COD (mg O_2/l)		
		Inflow	Outflow	% removal	Inflow	Outflow	% removal	Inflow	Outflow	% removal
[a]Greenway 2005	Australia	25	6	76	0.2	0.05	75			
[b]Greenway 2005	Australia	50	5	90	12	9	25			
[c]Stone et al. 2004	USA	116	70	40	56	48	14			
[d]Meers et al. 2008	Belgium	364	3.7	99	58	<0.3	97	1739	69	98
[e]Liu et al. 2007	China	16	6	59	1.2	0.1	92	17	5	67
[f]Wang et al. 1994	China	22	16	31	4.7	1.8	62	463	88	81
[g]Laouali et al. 1996	Canada	53	10	81	7.1	0.2	98	283	39	86
[h]Masi et al. 2002	Italy	15		82	4.9		73	4045		98
[h]Masi et al. 2002	Italy	27		90	1.9		94	1003		93
		TSS (mg/l)			BOD (mg O_2/l)					
		Inflow	Outflow	% removal	Inflow	Outflow	% removal			
[e]Liu et al. 2007	China	1367	12	99	26	6	77			
[f]Wang et al. 1994	China	320	3	99	138	58	69			
[g]Laouali et al. 1996	Canada	67	19	72	130	6	96			
[h]Masi et al. 2002	Italy	222		89	1793		98			
[i]Masi et al. 2002	Italy	103		75	425		93			

[a] A lagoon and a series of shallow, densely vegetated marshes and small deep-water ponds; [b] A lagoon, two FWS wetlands, and a HF wetland; [c] A marsh-pond-marsh system; [d] A multi-bed system consisting of eight beds/lagoons with VF and HF helophyte beds, pleustophyte ponds, and hydrophyte lagoons; [e] A series of FWS wetlands/ponds and subsurface flow beds; [f] An anaerobic lagoon, three water hyacinth ponds, and two HF beds;[g] A combination of HF and FWS wetlands; [h] HF and FWS wetlands; [i] VF, HF, and FWS wetlands with a pond.

2006). Also, harvesting aboveground biomass of plants from treatment wetlands not only improves nutrient removal efficiency (Meuleman et al. 2002; Thullen et al. 2005), but nutrients accumulating in plants may also be used for composting or energy generation as additional benefits (Cicek et al. 2006). Harvested plants can be used for biogas production through fermentation, a practice widely used in developing countries and Europe (Deublein and Steinhauser 2010).

In addition, coupling FWS-CTWs with other technologies can be used to achieve high treatment efficiency. For example, coupling passive, low-energy FWS-CTWs with high-energy engineered lagoons can increase the capacity of both treatment wetlands and lagoons (Kadlec 2003). Introducing engineered lagoons can reduce the size of the treatment area required for FWS-CTWs and shorten treatment time compared with conventional systems. This technical combination for wastewater treatment is becoming increasingly popular in small rural communities of developing countries such as China (Kivaisi 2001; Liu et al. 2009).

A floating mat-based system (also called floating treatment wetlands) has been developed and used in the UK, Belgium, China, and other countries (Revitt et al. 2001; Headley and Tanner 2006). The floating mat-based system is a variant of the conventional FWS design that employs EAV species growing as a floating mat or raft on the water surface instead of rooted plants in the sediments. Because of this feature, floating treatment wetlands offer a promise for rainfall-driven stormwater treatment systems because they are less affected by water level fluctuations. The engineered floating mat-based systems, therefore, incorporate EAV species growing in a hydroponic manner on floating rafts and enable the incorporation of treatment wetland elements into deep pond-like systems. On a relatively large scale, this approach (called the "Restorer") has been used for treating wastewater in lagoons (Headley and Tanner 2006). The multiple linear floating wetlands with synthetic textile curtains hanging beneath are used to provide additional substrate for biofilm attachment and to create a lengthy flow path (Todd et al. 2003). Introducing this floating mat-based system into a pond-marsh system or a degraded shallow lake has a number of advantages that may enhance pollutant removal processes or lake restoration.

Like any constructed wetland, FWS-CTWs have limitations. In many cases, overloading or uncontrolled discharging of wastewater may result in an irreversible degradation or failure of the system. The buildup of sediment from wastewater and the accretion of peat from decomposed vegetation affect the operation of the CTWs, and thus eventually they need rehabilitation. After approximately 15 years of operation and extreme weather conditions, the SAV cell of STA-1 W failed and accreted sediment in that cell was removed to restore wetland functioning.

Over the past several decades, FWS-CTWs have been used extensively throughout North America and many are in operation in Australia, Asian, and European countries (Ghermandi et al. 2007; Kadlec and Wallace 2009). Using FWS-CTWs for water quality improvement is cost effective and environmentally sound. The capabilities of the FWS-CTWs in water pollutant removal, together with other ecological services, provide a nature-based technology that supports sustainable resource management.

Acknowledgments I thank Michael Chimney and two anonymous reviewers for critical comments that greatly improved the manuscript and Delia Ivanoff, Tracey Piccone, Kathleen Pietro, and Lou Toth for reviewing the early version of it. The views presented in this paper are those of the author and the interpretation and conclusions do not necessarily reflect the views of the South Florida Water Management District.

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