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Constructed Wetlands for Wastewater Treatment: A Review

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ABSTRACT

The first experiments on the use of wetland plants to treat wastewaters were carried out in the early 1950s by Dr. Käthe Seidel in Germany. The first full scale systems were put in operation during the late 1960s and since then constructed wetland systems have been spreading throughout the world. At present, there are several types of constructed wetlands used for wastewater treatment. Free water surface systems with various types of vegetation - free-floating, floating-leaved, submerged and emergent – are used in many countries. Subsurface flow systems are primarily built with horizontal flow, however the increased need for ammonia removal initiated a fast development and spread of vertical flow systems which are intermittently fed. This allows higher oxygenation of the bed and consequently higher nitrification. Also, various types on constructed wetlands may be combined in order to achieve higher treatment efficiency. Most constructed wetlands around the world are still primarily used to treat municipal and domestic wastewaters but treatment of many types of industrial and agricultural wastewaters, stormwater runoff and landfill leachate has recently become also common. Despite the mistrust of many civil engineers and water authorities constructed wetlands have been widely accepted around the world and have become a suitable solution for wastewater treatment.

Keywords: horizontal flow macrophytes, Phragmites australis, runoff, sewage, vertical flow

INTRODUCTION

In 1953, Dr. Käthe Seidel for the first time presented methods for improvement of inland waterways which suffered from over-fertilizaton, pollution from sewage and siltation by means of appropriate plant species (Seidel, 1953). However, at that time, views on wastewater treatment among experts were limited to physical, chemical and biological (bacterial) methods and the controlled use of macrophytes for water purification was not taken into consideration. In addition, it was believed that most macrophytes cannot grow well in polluted water and the ability of macrophytes to eliminate toxic substances in water was not recognized as well (Seidel, 1976).

Between 1952 and 1956, Seidel carried out numerous experiments on the use of wetland plants for treatment of various types of wastewater, including phenol wastewaters (Seidel, 1955, 1965a, 1966), dairy wastewaters (Seidel, 1976) or livestock wastewater (Seidel, 1961). In early 1960s, Seidel intensified her trials to grow macrophytes in wastewater and sludge of different origin and she tried to improve the performance of rural and decentralized wastewater treatment which was either septic tanks or pond systems with inefficient treatment. She planted macrophytes into the shallow embankment of tray-like ditches and created artificial trays and ditches grown with macrophytes. Seidel named this early system the hydrobotanical method. Then she improved her hydrobotanical system by using sandy soils with high hydraulic conductivity in sealed module type basins planted with various macrophyte species. To overcome the anaerobic septic tank systems she integrated a stage of primary sludge filtration in vertically percolated sandy soils planted with *Phragmites australis*. So the system consisted of an infiltration bed through which the sewage flowed vertically and an elimination bed with a horizontal flow (Seidel, 1965b). This system was the basis for hybrid systems which were revived at the end of the 20th century. However, Seidel´s concept to apply macrophytes to sewage treatment was difficult to understand for sewage engineers who had eradicated any visible plants on a treatment site for more than 50 years (Börner et al., 1998) and therefore, it was no surprise that the first full-scale constructed wetlands were built outside Germany.

Constructed wetlands have evolved during the last three decades of the 20th century in a viable treatment technology used for various types of wastewater around the world. There are several types of constructed wetlands which could be distinguished according to several criteria such as presence/absence of free water surface, macrophytes used or direction of flow (Table 1). Constructed wetlands are primarily used to treat domestic and municipal wastewaters but their use for other types of wastewater such as agricultural and industrial wastewaters, various runoff waters and landfill leachate have become more frequent, recently (Kadlec and Knight, 1996; Vymazal et al., 1998; Kadlec and Wallace, 2008).
Free water surface constructed wetlands

Table 1. Types of constructed wetlands for wastewater treatment

	Constructed wetlands						
Water level	Free water surface				Subsurface		
Plants	Free-floating	Floating-leaved	Submerged	Emergent	Emergent		
Flow	Horizontal				Horizontal	Vertical	
Direction						Downflow	Upflow

Systems with Emergent Macrophytes

In spite of many prejudices among civil engineers about odor nuisance, attraction of flies, poor performance in cold periods the IJssel Lake Polder Authority in Flevoland in The Netherlands constructed its first free water surface (FWS) constructed wetland in 1967 (Veenstra, 1998). The wetland had a design depth of 0.4m and the total area was 1 hectare. A star shape layout was chosen in order to obtain optimum utilization of the available area which, however, complicated macrophyte harvesting and maintenance in general (de Jong, 1976). Therefore, longitudinal channels were added to facilitate mechanical biomass harvesting and system maintenance. The new wetland design included channels of 3m wide and 200m long, separated by parallel stretches of 3 meters.

In 1968, FWS CW was created in Hungary near Keszthely in order to preserve the water quality of Lake Balaton and to treat wastewater of the town (Lakatos, 1998). The constructed wetland was established in place of an existing natural wetland in peat soil. The existing natural wetland consisted of six ponds 40-60 cm deep with a surface area of 10 ha and the ponds were fed with 8000 m^3 d^{-1} of mechanically pre-treated wastewater

The free water surface (FWS) wetland technology started in North America with the ecological engineering of natural wetlands for wastewater treatment at the end 1960s and beginning of the 1970s. Odum (1985) began a study using coastal lagoons for recycling and reuse of municipal wastewaters and Odum and Ewel started to study the effectiveness of natural cypress wetlands for municipal wastewater recycling (Odum et al., 1977, Ewel and Odum, 1984). About at the same time, researchers at the University of Michigan in Ann Arbor began the Houghton Lake project, the first in-depth study using engineered wetlands for wastewater treatment in a cold climate region (Kadlec et al., 1975, Kadlec and Tilton, 1979). Industrial stormwaters and process waters were also applied to constructed wetland/pond system in 1975 at Amoco Oil Company´s Mandan Refinery in North Dakota (Litchfield, 1989). The use of FWS constructed wetlands for urban stormwater treatment was pioneered in California in the early 1980s (Chan et al., 1982). At present, there are thousands of FWS constructed wetlands with emergent vegetation treating municipal and industrial wastewaters, agricultural runoff, mine drainage waters and stormwaters around the world (e.g., Wieder, 1989; Kadlec and Knight, 1996; Kadlec, 2003, Vymazal et al., 2006).

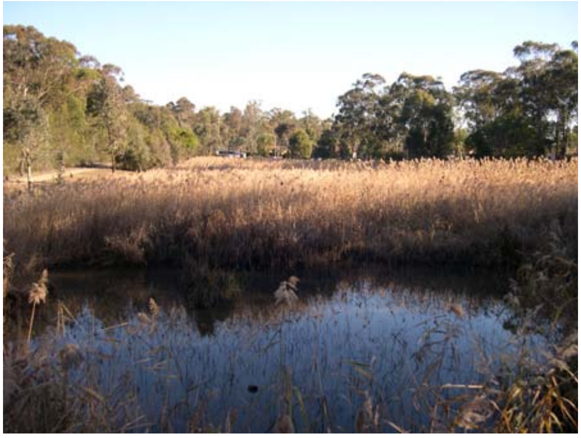

Figure 1. Free water surface constructed wetland for stormwater runoff treatment in Plumpton Park, NWS, Australia. Photo author.

A typical free water surface constructed wetland with emergent macrophytes (Figure 1) is a shallow sealed basin or sequence of basins, containing 20-30 cm of rooting soil, with a water depth of 20-40 cm. Dense emergent vegetation covers significant fraction of the surface, usually more than 50%. Besides planted macrophytes, naturally occurring species may be present (Kadlec, 1994). The most commonly used species for FWS constructed wetlands are in Europe: *Phragmites australis* (Common reed), *Scirpus (Schoenoplectus) lacustris ;* North America: *Typha* spp. (Cattail), *Scirpus* spp. (Bulrush), *Sagittaria latifolia* (Arrowhead); Australia and New Zealand: *Phragmites australis, Typha* spp., *Bolboschoenus (Scirpus) fluviatilis* (Marsh clubrush), *Eleocharis sphacelata (*Tall spikerush), *Scirpus tubernaemontani (= Scirpus validus,* Soft-stem bulrush). In the United States and New Zealand, *P. australis* is considered as invasive, non-native species and its use is either restricted or prohibited.

Flow is directed into a cell along a line comprising the inlet, upstream embankment, and is intended to proceed to all parts of the wetland to one or more outlet structures. The shallow water depth, low flow velocity, and presence of the plant stalks and litter regulate water flow and, especially in long, narrow channels, ensure plug-flow conditions (Reed et al., 1988). One of their primary design purposes is to contact wastewater with reactive biological surfaces (Kadlec and Knight, 1996).

Free water surface constructed wetlands with emergent macrophytes function as land-intensive biological treatment systems. Suspended solids removal is usually a fairly rapid physical process. The major removal mechanisms are sedimentation, aggregation and surface adhesion (QDNR, 2000). The largest and heaviest particles will predominantly settle out in the inlet open water zone while slightly smaller and lighter particles may only settle out after flowing into wetland vegetation. Wetland vegetation promotes this enhanced sedimentation by reducing water column mixing and resuspension of particles from the sediment surface.

Settleable organics are rapidly removed in FWS systems under quiescent conditions by deposition and filtration. Attached and suspended microbial growth is responsible for the removal of soluble organic compounds which are degraded aerobically as well as anaerobically. The decomposition pathway by which wetland carbon loads are processed is determined by a balance between the carbon load and the supply of oxygen. Oxygen is supplied to the wetland water column by diffusion through the air-water interface and via the photosynthetic activity of plants in the water column, namely periphyton and benthic algae (Kadlec et al., 2000; QDNR, 2000).

Nitrogen is most effectively removed in FWS constructed wetlands by nitrification/denitrification. FWS treatment wetlands typically have aerated zones, especially near the water surface because of atmospheric diffusion, and anoxic and anaerobic zones in and near the sediments. Biomass decay provides a carbon source for denitrification, but the same decay competes with nitrification for oxygen supply (Kadlec and Knight, 1996). Ammonia is oxidized by nitrifying bacteria in aerobic zones, and nitrate is converted to free nitrogen or nitrous oxide in the anoxic zones by denitrifying bacteria. Volatilization is likely as both plankton and periphyton algae grow in FWS CWs and higher pH values during the day may be favorable for ammonia loss. Nitrogen could also be removed via macrophyte harvesting but this amount is usually negligible as compared to inflow loadings (Vymazal, 2007).

FWS CWs provide sustainable removal of phosphorus, but at relatively slow rates. Phosphorus removal in FWS systems occurs from adsorption, absorption, complexation and precipitation. However, precipitation with Al, Fe and Ca ions - is limited by little contact between water column and the soil (Kadlec and Knight, 1996; Vymazal et al., 1998). Substantial amounts of phosphorus may be stored in the peat/litter compartment. Algal and microbial uptake may be high but this retention is a short-term process and nutrients are washed out from the detritus back to the water.

Wetlands are known to offer a suitable combination of physical, chemical and biological factors for the removal of pathogenic organisms. Physical factors include mechanical filtration, exposure to ultraviolet radiation, and sedimentation. Chemical factors include oxidation, exposure to biocides excreted by some wetland plants, and absorption by organic matter. Biological removal mechanisms include antibiosis, predation by nematodes and protists, attack by lytic bacteria and viruses, and natural die-off (Gersberg et al., 1989).

FWS constructed wetlands with emergent vegetation are used across the world for various types of wastewater (Table 2). The primary use is for secondary and tertiary treatment of municipal sewage but treatment of wastewater from agricultural and industrial facilities is becoming more important. In Europe and North America, the use of FWS systems for landfill leachte treatment is common and stormwater runoff .

Systems with Free-Floating and Submerged Vegetation

Free-floating macrophytes are highly diverse in form and habit, ranging from large plants with rosettes of aerial and/or floating leaves and well-developed submerged roots (*e.g., Eichhornia crassipes* - water hyacinth or *Pistia stratiotes* - water lettuce) to minute surface-floating plants with few or no roots (Lemnaceae - duckweed; *e.g., Lemna* spp., *Spirodela polyrhiza*, *Wolffia* spp. (Brix and Schierup, 1989c).

The traditional expertise of Asian farmers in recycling human and animal wastes through aquaculture and the practices intuitively developed by them for recovering nutrients from wastes by aquatic macrophytes propagated over waste-fed ponds gave a good basis for more engineered systems (Abassi, 1987). As early as in 1969, Sinha and Sinha reported on the use water hyacinth to treat digested sugar factory wastes. During the 1970s and 1980s numerous experiments with water hyacinth were conducted across Asia to treat various types of wastewater, e.g. from dairies, pal oil production, distillery, natural rubber production, tannery, textile, electroplating, pulp and paper production, pesticide production and heavy metals (Abassi, 1987).

Constructed wetlands with free floating macrophytes consist of one or more shallow ponds in which plants float on the surface (Figure 2). The shallower depth and the presence of aquatic macrophytes in place of algae are the major differences between constructed wetlands with free floating macrophytes and stabilization ponds (Kadlec et al., 2000).

Table 2. Examples of the use of free water surface constructed wetlands with emergent macrophytes for various types of wastewater

Type of Wastewater	Locality	References
Municipal/domestic	Worldwide	Kadlec and Knight (1996), Vymazal et al. (1998)
Agricultural	USA	McCaskey and Hannah (1997)
Swine	USA	Reaves and DuBowy (1997)
Dairy	Canada	Hermans and Pries (1997)
Stormwater runoff		
Dairy pasture	New Zealand	Tanner et al. (2005b)
Sugarcane fields	Zambia	Musiwa et al. (2002)
Residential area	Australia	Bavor et al. (2001)
Road runoff	UK	Pontier et al. (2004)
Airport de-icing	Sweden	Thorén et al. (2004)
Mine drainage		
Spoil heaps	UK	Batty et al. (2005)
Acid coal mine	USA	Brodie et al. (1988)
	Spain	De Matos and da Gama (2004)
Uranium mine	Australia	Overall and Parry (2004)
Copper mine	Canada	Sobolewski (1996)
Gold mine	Canada	Bishay and Kadlec (2005)
Industrial		
Refinery	China	Dong and Lin (1994)
	USA	Gillepsie et al. (2000)
Pulp and paper	USA	Hatano et al. (1993)
	China	Xianfa and Chuncai (1994)
Abattoir	Canada	Goulet and Sérodes (2000)
Tool industry	Argentina	Hadad et al. (2006)
Schrimp aquaculture	USA	Tiley et al. (2002)
Sugar factory	Kenya	Tonderski et al. (2005)
Food processing	Greece	Kapellakis et al. (2004)
Explosives	USA	Best et al. (2000)
Woodwaste leachate	Canada	Masbaugh et al. (2005)
Landfill leachate	Sweden	Benyamine et al. (2004)
	Norway	Mæhlum (1994)
	USA	Martin et al. (1993)

Organics are principally removed by bacterial metabolism of both attached and free living bacteria. The root system of the free-floating plants provides a large surface area for attached microorganisms, thus increasing the potential for decomposition of organic matter. The mass of plants on the surface minimizes wind-induced turbulence and mixing and the removal of suspended solids occurs through gravity sedimentation in the zone under the surface layer of floating plants. Nutrient removal in systems with free-floating plants is far more complicated that plant uptake alone. Nitrogen is potentially removed through plant uptake (with regular harvesting), ammonia volatilization, and nitrification-denitrification. The nitrifiers can flourish attached to the roots, which provide oxygen. Nitrification also occurs in the water column when dissolved oxygen levels of the water are adequate to support activity of nitrifying bacteria. These conditions are usually created at relatively low plant densities and a partial plant cover over the water surface. As the plant density increases, O_2 diffusion into the water is restricted, thus, decreasing the dissolved O_2 levels of the water (Rai and Munshi, 1979; Reddy, 1981).

Figure 2. Constructed wetland with water hyacinth (*Eichhornia crassipes*) as a part of a treatment system in Yantian Industry Area in Baoan District, Shengzhen City, south China. Photo author.

Also, dense plant cover on the water surface suppresses the growth of algae growth by preventing passage of sunlight to the water column. This results in anoxic zones and created favorable conditions for nitrate denitrification which may also proceed in benthic layer if sufficient sources of organic carbon are available.

Phosphorus can be removed from these systems by microbial assimilation, precipitation with divalent and trivalent cations, or adsorption onto clays or organic matter. However, most studies have shown that plant uptake and subsequent harvest is the only reliable long-term P-removal mechanism (DeBusk and Reddy, 1987). Harvesting is essential because detritus of plants tend to release P into water during decomposition, thus, decreasing the P removal efficiency of the system (Reddy and Sacco, 1981).

There was an explosion of research studies on the use of water hyacinth for wastewater treatment in the 1970s and early 1980s. However, after this period very few information appeared in the scientific literature mostly because these systems are not economic. Stewart et al. (1987) pointed out that while the concept of using water hyacinth for wastewater treatment had been extensively investigated and reviewed for nearly 20 years, there still remains little information regarding the operational needs associated with large scale applications. Also, the use of water hyacinth and water lettuce is strongly temperature-dependent and the use is restricted to subtropical and tropical regions.

Constructed wetlands with water hyacinth have been revived recently and attempts have been made to use these systems again. Maine et al. (2006) reported the use water hyacinth system for the treatment of wastewaters from a tool factory in Santo Tomé, Argentina. Tua et al. (2006) reported the use of water hyacinth-based constructed wetland for the treatment of fish processing wastewater in Vietnam. Perdomo et al. (2000) reported experimental use of water hyacinth for dairy wastewaters treatment in Uruguay. The system performed well but parallel system with *Typha* spp. exhibited better removal effect. Kalibbala et al. (2002) used ponds with *Eichhornia* for tertiary treatment of brewery wastewater in Uganda.

Submerged aquatic macrophytes have their photosynthetic tissue entirely submerged. Submerged plants, however, only grow well in oxygenated water and therefore cannot be used in wastewater with a high content of readily-biodegradable organic matter because the microbial decomposition of the organic matter will create anoxic conditions (Brix, 1993a). There is no direct evidence that short-term drops in oxygen concentration affect submerged plants distribution. However, longer exposure to low oxygen concentration may reduce growth of submerged macrophytes (Sahai and Sinha, 1976). Submerged macrophytes are often absent in anaerobic waters, but here also other factors like turbidity, sulfide and anaerobic sediments may play a major role (Best, 1982). In addition, the turbidity of the water must not be too high to prevent light transmission to the plants to support their photosynthetic activity (Reed et al., 1988).

Figure 3. Stormwater Treatment Area-1 Cell 4 (147 ha) in south Florida with Ceratophyllum demersum . Photo author.

The use of constructed wetlands with submerged macrophytes is still not fully developed. However, there are numerous examples of the operational systems. It is also important to realize that submerged vegetation may spontaneously develop in any free-water surface constructed wetland if the growth conditions are suitable. Gu et al. (2001) reported good phosphorus removal from Everglades Agricultural Area runoff in Stormwater Treatment Area Cells (Figure. 3) naturally colonized by submerged species Ceratophyllum demersum (Coontail) and *Najas guadalupensis* (Southern naiad). Hammer and Knight (1992) reported the use of constructed wetland with submerged vegetation (*Potamogeton pectinatus*- Sago pondweed) as a part of a constructed wetland that polishes effluents from primary and secondary lagoons for a 500-hog production facility at Pontotoc, Mississippi. Vincent (1992) reported the use of a treatment wetland system which purifies water from a swimming area of the Lac des Régates in Montréal, Canada. The wetland systems consist of four ponds with submerged species present in three of then. The submerged species were *Hydrocharis morsus-ranae* (Frog´s bit), *Myriophyllum spicatum* (European watermilfoil), *Elodea canadensis* (Common waterweed), *Potamogeton pectinatus* and *Vallisneria americana (eel-grass)*.

Table 3. Examples of the use of HF constructed wetlands for various types of wastewater.

Types of wastewater	Country	Reference
Municipal/domestic	Worldwide	Kadlec and Knight (1996), Vymazal et al. (1998), Kadlec et al. (2000)
Combined sewer overflows	UK	Cooper et al. (1996)
Linear alkylbenzene sulfonates (LAS)	India	Billore et al. (2002)
	Italy	Del Bubba et al. (2000)
Pharmaceuticals	Spain	Matamaros et al. (2005)
Industrial		
Petrochemical	USA	Wallace (2002a)
	China	Ji et al. (2002)
Chemical	UK	Sands et al. (2000)
	Portugal	Dias et al. (2006)
Pulp and paper	USA	Thut (1993)
	Kenya	Abira et al. (2005)
Tannery	Portugal	Calheiros et al. (2007)
	Turkey	Küçük et al. (2003)
Textile	Slovenia	Bulc et al. (2006)
	Australia	Davies and Cottingham (1992)
Abattoir	Mexico	Poggi-Veraldo et al. (2002)
	Ecuador	Lavigne and Jankiewicz (2003)
Food processing	Slovenia	Vrhovšek et al. (1996)
	USA	Wallace (2002b)
	France	Khalil et al. (2005)
	Italy	Mantovi et al. (2007)
	Lithuania	Gasiunas et al. (2005)
Distillery and winery	India	Billore et al. (2001)
	Italia	Masi et al. (2002)
	South Africa	Sheridan et al. (2006)
Lignite pyrolysis	Germany	Wiessner et al. (1999)
Mining waters	Germany	Gerth et al. (2005)
	USA	Pantano et al. (2000)
Laundry	Australia	Davison et al. (2005, 2006)
Agricultural wastewaters		
Pig farms	Australia	Finlayson et al. (1987, 1990)
	China	Wang et al. (1994)
	UK	Gray et al. (1990)
	Thailand	Kantawanichkul and Somprasert (2005)
	Lithuania	Strusevičius and Strusevičiéne (2003)
	Taiwan	Lee et al. (2004)
Fish farm effluent	USA	Zachritz and Jacquez (1993)
	Canada	Comeau et al. (2001)
	Germany	Schulz et al. (2003)
Dairy	Italy	Mantovi et al. (2002, 2003)
	Germany	Kern and Brettar (2002)
	USA	Hill et al. (2003)
	New Zealand	Tanner (1992)
	Denmark	Schierup et al. (1990)
Runoff waters		
Highway	UK	Shutes et al. (2001), Revitt et al. (2004)
	Italy	Bresciani et al. (2007)
Airport	UK	Worrall et al. (2002)
	USA	Karrh et al. (2002)
	Switzerland	Röthlisberger (1996)
	Canada	Higgins and Dechaine (2006)
Greenhouse and nursery	Canada	Prystay and Lo (1996)
	Australia	Headley et al. (2001)
	France	Merlin et al. (2002)
Agricultural	China	Zhou et al. (2004)
Urban	Australia	Geary et al. (2006)
Landfill leachate	Canada	Birkbeck et al. (1990)
	Norway	Mæhlum et al. (1999)
	Slovenia	Bulc (2006)
	UK	Robinson et al. (1999)
	Poland	Obarska-Pempkowiak et al. (2005)

SUB-SURFACE FLOW SYSTEMS

Horizontal flow constructed wetlands

In horizontal flow constructed wetlands (HF CWs) the wastewater is fed in at the inlet and flows slowly through the porous medium under the surface of the bed in a more or less horizontal path until it reaches the outlet zone where it is collected before leaving via level control arrangement at the outlet. During this passage the wastewater will come into contact with a network of aerobic, anoxic and anaerobic zones. The aerobic zones occur around roots and rhizomes that leak oxygen into the substrate (Cooper et al., 1996). In Europe, HF CWs are commonly called "Reed Beds", in the United Kingdom also "Reed Bed Treatment System" (RBTS) coming from the fact that the most frequently used plant is common reed (*Phragmites australis*). In the United States, the term "Vegetated Submerged Bed" (VSB) was also adopted. This term, however, is very unfortunate as it resembles systems with submerged plants.

Organic compounds are degraded aerobically as well as anaerobically by bacteria attached to the plant´s underground organs (i.e. roots and rhizomes) and media surface. Numerous investigations have shown that the oxygen transport capacity of the reeds is insufficient to ensure aerobic decomposition in the rhizosphere and that anoxic and anaerobic decomposition play an important role in HF constructed wetlands (Vymazal and Kröpfelová, 2006).

Removal of phosphorus in HF CWs is limited due to the fact that media used for HF wetlands (e.g., pea gravel, crushed stones) usually do not contain great quantities of Fe, Al or Ca to facilitate precipitation and/or sorption of phosphorus. It has been found that removal of nitrogen and phosphorus through plant harvesting is negligible and forms only a small fraction of the amount removed. In order to enhance phosphorus removal media with high sorption capacity such as blast and electric arc furnaces steel slags or light weigh clay aggregates have been used recently (Vymazal and Kröpfelová, 2008).

The major removal mechanisms for nitrogen in HF CWs are nitrification/denitrification reactions (Vymazal, 2007). However, the field measurements have shown that the oxygenation of the rhizosphere of HSF constructed wetlands is insufficient and, therefore, the incomplete nitrification is the major cause of limited nitrogen removal (Brix and Schierup, 1990; Vymazal 2007). Volatilization, adsorption and plant uptake play much less important role in nitrogen removal in HSF constructed wetlands (Cooper et al., 1996; Vymazal, 2007; Vymazal et al., 1998). Volatilization is limited by the fact that HF CWs do not have free water surface and algal activity is negligible in these systems. The fine-grained soils always show better nitrogen removal through adsorption than the coarse-grained soil (Geller et al., 1990). The higher elimination rate can be explained by the higher cation exchange capacity of the fine-grained soils. However, fine-grained soils are not used for HF systems, at present, because of poor hydraulic conductivity. Therefore, the adsorption capacity of the commonly used media (pea gravel, crushed rock) is very limited. Nitrogen removal via plant uptake and subsequent harvesting is usually low as compared to inflow loads (e.g. Vymazal, 2005).

Figure 4. HF constructed wetland for 5 PE in Kostelec nad Černými Lesy, Czech Republic planted with *Phragmites australis*. Photo author.

The technology of wastewater treatment by means of constructed wetlands with horizontal sub-surface flow was started in Germany based on research by Seidel commencing in the 1960s (e.g., Seidel, 1961, 1965 a,b, 1966) and by Kickuth in the 1970s (e.g., Kickuth, 1977, 1978, 1981). At present, HF CWs probably represent the most commonly used type of constructed wetlands around the world (Vymazal and Kröpfelová, 2008). They are frequently used to treat on-site domestic wastewater (Fig. 4), municipal sewage from small settlements and villages (Fig. 5), industrial (Fig. 6) and agricultural wastewaters. In addition, HF systems are used to treat landfill leachate.

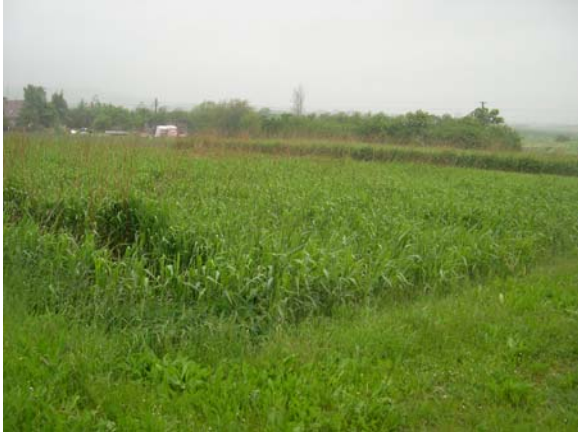

Figure 5. HF constructed wetland for municipal sewage treatment at Grønfeld, Denmark. Photo author.

Figure 6. HF constructed wetland at Estarreja, Portugal treating wastewaters from nitric acid production. Photo author.

Vertical flow constructed wetlands

Constructed wetlands with vertical flow (VF) were originally designed by Seidel (1965b) as pre-treatment units before wastewater treatment in horizontal flow beds. However, Seidel did not use VF wetlands as a single stage. VF CWs are fed intermittently with wastewater gradually percolating down through the bed. This kind of feeding provides good oxygen transfer and hence the ability to nitrify (Cooper et al., 1996). The early VF systems have usually been composed of several stages with 2-4 beds in the first stage which were fed with wastewater in rotation. The early VF systems were frequently the first stage of the hybrid systems (Burka and Lawrence, 1990; Liénard et al., 1990). Recently, VF systems with only one bed have been used (Fig. 7). These systems are called 2nd generation VF constructed wetlands or compact vertical flow beds (e.g., Weedon, 2003; Brix et al., 2002; Arias and Brix, 2005).

Figure 7. VF constructed wetland at Bojna, Slovakia. Photo courtesy F. Reffesberg.

VF CWs provide a good removal of organics, suspended solids and ammonia but on the other hand, they provide little room for denitrification, and therefore, ammonia-N is usually only converted to nitrate-N. VF CWs require less land (1-3 m^2 PE^{-1}, PE = population equivalent) as compared to HF systems (5-10 m^2 PE^{-1}) but require more maintenance and operation efforts because of the use of pumps, timers and other electric and mechanical devices. VF systems are very often used in European countries, such as Austria, Denmark, France, Germany and United Kingdom, especially for small sources of pollution but VF systems has already spread around the world (Table 4).

Cooper (2005) pointed out that the most important factors to achieve in the design of a VF are:

1. To produce a bed matrix that allows the passage of the wastewater through the bed before the next dose arrives whilst at the same time holding the liquid back long enough to allow the contact with the bacteria growing on the media and achieve the required treatment.
2. To provide sufficient surface area to allow the oxygen transfer to take place and sufficient becteria to grow.

Table 4. Examples of the use of VF constructed wetlands for various types of wastewater.

Waste type	Country	Referenece
Municipal/domestic	Worldwide	Cooper et al.(1996), Vymazal et al.(1998), Kadlec et al. (2000)
Special organics	Germany France Portugal	Machate et al. (1997) Cottin and Merlin (2006) Novais and Martins-Dias (2003)
Leachate Landfill Compost	 Australia Germany	 Headley et al (2004) Lindenblatt (2005)
Herbicides	UK	McKinlay and Kasperek (1999)
Airport runoff	Canada	McGill et al. (2000)
Dairy	The Netherlands	Veenstra (1998)
Cheese dairy	Germany	Kern and Idler (1999)
Abattoir	Canada	AQUA TT
Refinery wastewater	Pakistan	Aslam et al. (2007)

Table 5. Examples of hybrid constructed wetlands used for various types of wastewater. VF = vertical flow, HF = horizontal flow, FWS = free water surface, P = pond

Type of CW	Country	Type of (waste)water	Reference
VF-HF	UK	Sewage	Burka and Lawrence (1990)
VF-HF	USA	Sewage	House and Broome (2000)
VF-HF	Slovenia	Landfill leachate	Bulc (2006)
VF-HF	France	Cheese dairy	Reeb and Werckmann (2005)
VF-HF	Thailand	Pig farm wastewater	Kantawanichkul and Neamkam (2003)
HF-VF	Denmark	Sewage	Brix et al. (2003)
HF-VF	Poland	Sewage	Obarska-Pempkowiak et al. (2005)
HF-VF	Nepal	Hospital	Laber et al. (1999)
HF-VF	Mexico	Sewage	Belmont et al. (2004)
FWS-HF	Taiwan	Fish aquaculture	Lin et al. (2002)
FWS-HF	China	Industrial	Wang et al. (1994)
HF-FWS	Canada	Landfill leachate	Kinsley et al. (2006)
HF-FWS	Italy	Winery wastewater	Masi et al. (2002)
HF-FWS	Norway	Landfill leachate	Mæhlum et al. (1999)
HF-FWS	Kenya	Sewage	Nyakang´o and van Bruggen (1999)
HF-VF-HF	Poland	Sewage	Tuszyńska and Obarska-Pempkowiak (2006)
VF-HF-FWS-P	Italy	Winery wastewater	Masi et al. (2002)
VF-HF-FWS-P	Estonia	Sewage	Mander et al. (2003)

Hybrid constructed wetlands

Various types of constructed wetlands may be combined in order to achieve higher removal efficiency, especially for nitrogen. However, hybrid systems comprise most frequently VF and HF systems arranged in a staged manner. Many of these systems are derived from original hybrid systems developed by Seidel at the Max Planck Institute in Krefeld, Germany. The process is known as the Seidel system, the Krefeld system or the Max Planck Institute Process (MPIP) (Seidel, 1965b, 1976).

In the late 1970s and early 1980s, several hybrid systems of Seidel´s type were built in France (Liénard et al., 1990). Similar system was built in 1987 in U.K. at Oaklands Park (Burka and Lawrence, 1990). In 1990s and early 2000s, VF-HF systems were built in many European countries, e.g. in Slovenia (Urbanc-Berčič and Bulc, 1994), Norway (Mæhlum and Stålnacke, 1999) or Austria (Mitterer-Reichmann, 2002) and now this type is getting more attention not only in Europe but around the world because of more stringent requirements for ammonia discharge.

In mid-1990s, Johansen and Brix (1996) introduced a HF-VF hybrid system. The large HF bed is placed first to remove organics and suspended solids and to provide denitrification. An intermittently loaded small VF bed is designed for further removal of organics and SS and to nitrify ammonia to nitrate. However, in order to remove total nitrogen, the nitrified effluent from the VF bed must be recycled to the sedimentation tank Brix et al. (2003). A similar system was built in Poland at Sobiechy (Ciupa, 1996) or in Nepal at Dhulikhel in collaboration with Austrian researchers (Laber et al., 1999)

Recently, hybrid constructed wetlands comprise also more than two types of CWs and quite often include also FWS stage. Such example could be a system at Kõo in Estonia which consists of two VF beds, followed by HF bed and two FWS wetlands (Mander et al., 2003). In Italy, hybrid constructed wetlands are successfully used for treatment of concentrated winery wastewaters (Masi et al., 2002). For example, the system at Ornellaia consists of two VF beds, followed by HF bed and FWS wetland. System at Cecchi consists of HF bed followed by FWS wetland and the pond.
At present, many combinations of various types of constructed wetlands are in operation for various types of wastewater (Table 5).

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