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Review

Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment

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Abstract

The first experiments using wetland macrophytes for wastewater treatment were carried by out by Käthe Seidel in Germany in early 1950s. The horizontal sub-surface flow constructed wetlands (HF CWs) were initiated by Seidel in the early 1960s and improved by Reinhold Kickuth under the name Root Zone Method in late 1960s and early 1970s and spread throughout Europe in 1980s and 1990s. However, cohesive soils proposed by Kickuth got clogged very quickly because of low hydraulic permeability and were replaced by more porous media such as gravel in late 1980s in the United Kingdom and this design feature is still used. In fact, the use of porous media with high hydraulic conductivity was originally proposed by Seidel. HF CWs provide high removal of organics and suspended solids but removal of nutrients is low. Removal of nitrogen is limited by anoxic/anaerobic conditions in filtration beds which do not allow for ammonia nitrification. Phosphorus removal is restricted by the use of filter materials (pea gravel, crushed rock) with low sorption capacity. Various types of constructed wetlands may be combined in order to achieve higher treatment effect, especially for nitrogen. However, hybrid systems are comprised most frequently of vertical flow (VF) and HF systems arranged in a staged manner. HF systems cannot provide nitrification because of their limited oxygen transfer capacity. VF systems, on the other hand, do provide a good conditions for nitrification but no denitrification occurs in these systems. In hybrid systems (also sometimes called combined systems) the advantages of the HF and VF systems can be combined to complement processes in each system to produce an effluent low in BOD, which is fully nitrified and partly denitrified and hence has a much lower total-N outflow concentrations.

Keywords: Germany; Horizontal sub-surface flow; Hybrid systems; Macrophytes; Nutrients; Organics; Sewage; Constructed wetlands

1. Introduction

Constructed wetlands (CWs) are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and the associated microbial assemblages to assist in treating wastewaters. They are designed to take advantage of many of the same processes that occur in natural wetlands, but do so within a more controlled environment. CWs for wastewater treatment may be classified according to the life form of the dominating macrophyte into systems with free-floating,

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rooted emergent and submerged macrophytes (Brix and Schierup, 1989). Most constructed wetlands for wastewater treatment are planted with emergent macrophytes but the design of the systems in terms of media as well as the flow regime varies. The most common systems are designed with horizontal sub-surface flow (HF CWs) but vertical flow (VF CWs) systems are getting more popular at present. Constructed wetlands with free water surface (FWS CWs) are not used as much as the HF or VF systems despite being one of the oldest designs in Europe (Brix, 1994; Vymazal et al., 1998; Vymazal, 2001a). Constructed wetlands have been used for decades mostly for the treatment of domestic or municipal sewage. However, recently CWs have been used for many other types of wastewater including industrial and agricultural wastewaters, landfill leachate or stromwater runoff. As many of these wastewaters are difficult to treat in a single stage system, hybrid systems which consist of various types of constructed wetlands staged in series have been introduced.

The first experiments aimed at the possibility of wastewater treatment by wetland plants were undertaken by Käthe Seidel in Germany in early 1950s at the Max Planck Institute in Plön (Seidel, 1955). 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.

2. Constructed wetlands with horizontal sub-surface flow

The most widely used concept of constructed wetlands in Europe is that with horizontal sub-surface flow (Fig. 1). The design typically consisted of a rectangular bed planted with the common reed (*P. australis*) and lined with an impermeable membrane. Mechanically pre-treated wastewater is fed in at the inlet and passes slowly through the filtration medium under the surface of the bed in a more or less horizontal path until it reached the outlet zone where it is collected before discharge via level control arrangement at the outlet. During the passage of wastewater through the reed bed the wastewater makes contact with a network of aerobic, anoxic and anaerobic zones.

This concept was developed in the late1960s in Germany by Käthe Seidel in Plön (Seidel, 1965a,b). Seidel designed the system with filtration material with high hydraulic conductivity. However, Reinhold Kickuth from Göttingen University developed another system under the name Root Zone Method (Kickuth, 1969, 1977). Kickuth's system differed from Seidel's system in the use of cohesive soils with high clay content. The first full-scale HF Kickuth's type CW for treatment of municipal sewage was put in operation in 1974 in the community Liebenburg-Othfresen (Kickuth, 1977, 1978, 1981; Brix, 1987a). The area of about 22 ha was originally used to dump waste material (silt, clay and dross) derived from mining of iron ore. It contained settlement ponds for separation of silt and clay which were filled with clay, gravel and chalk when mining ceased in 1962. In 1969, the local authority proposed to use part of the area for sewage treatment. The anaerobic maturation ponds were rejected and R. Kickuth recommended the RZM to be constructed on higher ground of the area (Boon, 1986).

Kickuth's concept was closer to the traditional understanding of a soil treatment of sewage but his statement that root and rhizome growth would improve hydraulic conductivity of heavy soils failed on several early construction sites and it gave a harsh setback to the scientific and official acknowledgement of HF CWs as sewage treatment systems. The problem in

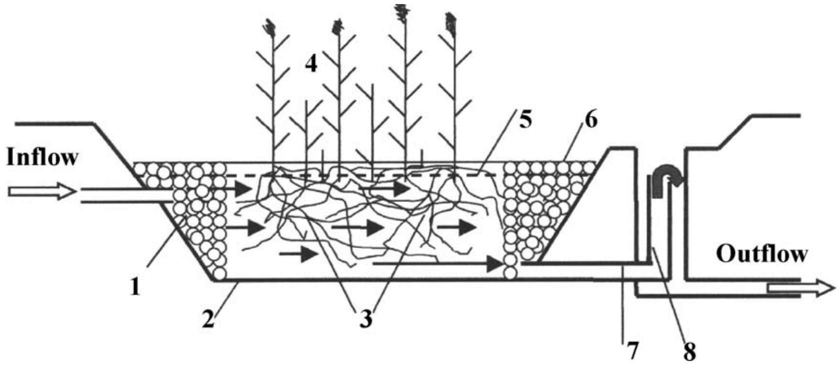

Fig. 1. Schematic representation of a constructed wetland with horizontal sub-surface flow. 1, distribution zone filled with large stones; 2, impermeable liner; 3, filtration medium (gravel, crushed rock); 4, vegetation; 5, water level in the bed; 6, collection zone filled with large stones; 7, collection drainage pipe; 8, outlet structure for maintaining of water level in the bed. The arrows indicate only a general flow pattern (modified from Vymazal, 2001a).

constructed beds where soil is used as medium is the low hydraulic conductivity which results in surface flow and thereby a short retention time within the system. Kickuth (1977) also proposed a size of vegetated beds of only $2\,m^2\,PE^{-1}$. It proved to be too small to achieve a satisfactory treatment effect. In 1983, German ideas were introduced in Denmark (Brix, 1987b). Despite problems with surface flow the soil-based systems exhibited high treatment effect for most parameters if a reed bed area $3–5\,m^2\,PE^{-1}$ was used. In order to overcome the overland flow Danish systems were designed with a low aspect ratio (length:width ratio). It resulted in a very wide beds and short passage length (Brix, 1998). However, the design with a very long inlet trenches caused problems with water distribution and, therefore, the inlet trench was subdivided into two or more separate units that could be loaded separately in order to get better control on the distribution of water (Brix, 1998). In early 1980s a few HF CWs were also built in other European countries, e.g. in Austria or Switzerland (Vymazal et al., 1998a).

In 1985, following visits to existing German and Danish systems, the first two HF CWs were built in the United Kingdom (here called Reed Bed Treatment Systems) and by the end of 1986 more than 20 HF CWs were designed (Cooper and Boon, 1987). The major change in the design was the use of very coarse filtration material which ensured sub-surface flow similarly to former design by Seidel (1965a,b). Also a specific area of $5\,m^2\,PE^{-1}$ was used in the United Kingdom. In the late 1980s, the first HF CWs were built in many European countries and HF CWs became the most widely used concept in Europe at 1990s. The exchange of design and operational experience among nine European countries resulted in the European Design and Operations Guidelines for Reed Bed Treatment Systems which were presented at the second Constructed Wetlands Conference at Cambridge (Cooper, 1990). In late 1980s, HF CWs were also introduced in North America (Watson et al., 1990) and Australia (Bavor et al., 1997). At present, HF CWs are used throughout the world. The most HF CWs are in operation in Germany where the number of these systems may exceed 50,000 (Wissing, personal communication). Other countries with a high number of HF systems in Europe are Austria (ca. 1000), United Kingdom (ca. 800), Italy (ca. 300), Denmark (ca 200), Czech Republic (ca 160), Poland, Portugal (ca. 120), Slovenia, France, Estonia, Norway or Switzerland. In North America, the number of HF CWs is estimated to be about 8000 (Kadlec, 2003).

The following equation, first proposed by Kickuth (1977), has been widely used for sizing of HSF systems for domestic sewage treatment:

$$A_h = \frac{Q_d(\ln C_{in} - \ln C_{out})}{K_{BOD}}$$

where A_h is the surface flow of bed (m^2), Q_d the average flow ($m^3\,day^{-1}$), C_{in} the influent BOD_5 ($mg\,l^{-1}$), C_{out} the effluent BOD_5 ($mg\,l^{-1}$) and K_{BOD} is the rate constant ($m\,day^{-1}$).

There were a lot of discussion on the K_{BOD} value. Formerly proposed value of $0.19\,m\,day^{-1}$ by Kickuth results in too small area of the bed and consequently lower treatment effect. The field measurements showed that the value of K_{BOD} is usually lower. Schierup et al. (1990) reported an average value of 0.083 m day^{-1} for 49 systems in Denmark and Cooper (1990) reported values between 0.067 and 0.1 m day^{-1} in the United Kingdom. Brix (1998) pointed out that in theory, the rate constant should be a constant, and therefore ideally independent of inlet concentration and loading rate. However, it has been found that rate constants generally increase with hydraulic loading rate and BOD_5 mass loading rate. In addition, in systems which have been in operation for at least 10 years a steady increase in K_{BOD} value was observed. The average K_{BOD} value for 66 village systems after 2 years of operation was 0.118 ± 0.022 m day^{-1}. At present, using field measurements from many operational systems, the value of 0.1 m day^{-1} (36.5 m year^{-1}) (Cooper et al., 1996) is considered as sufficient. This generally means that the value of A_h is about 5 m^2 PE^{-1}. However, this sizing is suitable for BOD_5 and SS removal but for removal of nitrogen and phosphorus is not appropriate. Based on North American experience Kadlec and Knight (1996) developed the following values of areal rate constant K adjusted to 20 °C: total-N: 27 m year^{-1}, organic-N: 35 m year^{-1}, ammonium-N: 34 m year^{-1}, nitrate-N: 50 m year^{-1} and total-P: 12 m year^{-1}. Brix (1998) reported K-values based on the Danish experience as follows: total-N: 12 m year^{-1} and total-P: 9 m year^{-1}.

2.1. Removal mechanisms

Typical arrangement of HF constructed wetland (Fig. 1) has the depth of filtration bed usually 0.6–0.8 m in order to allow roots of wetland plants and namely *Phragmites* to penetrate the whole bed and ensure oxygenation of the whole bed through oxygen release from roots. Roots and rhizomes of reeds and all other wetland plants are hollow and contain air-filled channels that are connected to the atmosphere for the purpose of transporting oxygen to the root system. The majority of this oxygen is used by the roots and rhizomes themselves for respiration, but as the roots are not completely gastight, some oxygen is lost to the rhizosphere (Brix, 1994, 1997). According to the working principle of HF CWs, the amount of oxygen released from roots and rhizomes should be sufficient to meet the demand for aerobic degradation of oxygen consuming substances in the wastewater as well as for nitrification of the ammonia. However, many studies have shown that the oxygen release from roots of different macrophytes is far less than the amount needed for aerobic degradation of the oxygen consuming substances delivered with sewage and that anoxic and anaerobic decomposition play an important role in HSF constructed wetlands (Brix, 1990; Brix and Schierup, 1990). As a results organic compounds are degraded aerobically as well as anaerobically by bacteria attached to plant underground organs (i.e. roots and rhizomes) and media surface and the removal of organics is generally very high in HF CWs (Table 1).

Table 1
Treatment efficiency of vegetated beds of HF CWs—world wide experience (data from Australia, Austria, Brazil, Canada, Czech Republic, Denmark, Germany, India, Mexico, New Zealand, Poland, Slovenia, Sweden, USA and UK)

Parameter	Inflow (mg l^{-1})	Outflow (mg l^{-1})	Efficiency (%)	*N*
BOD_5	108	16.0	85	164
COD	284	72	75	131
TSS	107	18.1	83	158
TP	8.74	5.15	41	149
TN	46.6	26.9	42	137
NH_4^+-N	38.9	20.1	48	151
NO_3^--N	4.38	2.87	35	79
FC (CFU/100 ml)	1.27×10^7	9.96×10^5	92	51

Modified from Vymazal (2001a).

Aerobic degradation of soluble organic matter is governed by the aerobic heterotrophic bacteria. Cooper et al. (1996) pointed out that also ammonifying bacteria degrade organic compounds containing nitrogen under aerobic conditions. Both bacterial groups consume organics but the faster metabolic rate of the heterotrophs means that they are mainly responsible for the reduction in the BOD_5 of the system. Insufficient supply of oxygen to this group will greatly reduce the performance of aerobic biological oxidation. However, if the oxygen supply is not limited, aerobic degradation will be governed by the amount of organic matter available to the organisms. In most systems designed for the treatment of domestic or municipal sewage the supply of dissolved organic matter is sufficient and aerobic degradation is limited by oxygen availability. In addition to hetrotrophic and ammonifying bacteria also nitrifying bacteria utilize oxygen to cover their physiological needs. However, it is generally agreed that heterotrophic bacteria outcompete nitrifying bacteria for oxygen (e.g. Brix, 1998).

Anaerobic respiration occurs in the soil zone below the Fe^{3+} reduction zone and the process can be carried out by either facultative or obligate anaerobes. It represents one of the major ways in which high molecular weight carbohydrates are broken down to low molecular weight organic compounds, usually as dissolved organic carbon, which are, in turn, available to microbes (Valiela, 1984). Anaerobic degradation is a multi-step process. In the first step the primary end-products of fermentation are fatty acids, such as acetic, butyric and lactic acids, alcohols and the gases CO_2 and H_2 (Mitsch and Gosselink, 2000; Vymazal, 1995; Vymazal et al., 1998b).

Acetic acid is the primary acid formed in most flooded soils and sediments. Strictly anaerobic sulfate-reducing bacteria and methane-forming bacteria then utilize the end-products of fermentation and, in fact, depend on the complex community of fermentative bacteria to supply substrate for their metabolic activities. Both groups play an important role in organic matter decomposition (Valiela, 1984; Grant and Long, 1981; Vymazal, 1995). The acid-forming bacteria are fairly adaptable but the methane-formers are more sensitive and will only operate in the pH range 6.5–7.5. Over-production of acid by the acid-formers can rapidly result in a low pH value. This stops the action of the methane-forming bacteria and will result in production of odorous compounds from the constructed wetland. Anaerobic degradation of organic compounds is much slower than aerobic degradation. However, when oxygen is limiting at high organic loadings, anaerobic degradation will predominate (Cooper et al., 1996).

Suspended solids that are not removed in pre-treatment system are effectively removed by filtration and settlement (Cooper et al., 1996; Vymazal et al., 1998b). Most of the suspended solids are filtered out and settled within the first few meters beyond the inlet zone. The accumulation of trapped solids is a major threat for good performance of HF systems as the solids may clogg the bed. Therefore, the effective pre-treatment is necessary for HF systems.

The major removal mechanism of nitrogen in HF constructed wetlands is nitrification/denitrification (Vymazal, 1999). Field measurements have shown that the oxygenation of the rhizosphere of HF constructed wetlands is insufficient and, therefore, incomplete nitrification (i.e. oxidation of ammonia to nitrate) is the major cause of limited nitrogen removal. Zhu and Sikora (1994) pointed out that no obvious nitrification could be observed when dissolved oxygen concentration is lower than 0.5 mg l^{-1}. Platzer (1998) suggested that good nitrification in HF constructed wetlands is possible but the bed area necessary is usually extremely large as the maximum load in order to achieve nitrification should not exceed 73 g TKN m^{-2} $year^{-1}$. However, this loading rate is very low (Table 2) and for systems which are usually designed for BOD and SS removal (resulting in approximately 5 m^2 l^{-1} PE) nitrification is hardly achievable. In general, nitrification which is performed by strictly aerobic bacteria is mostly restricted to areas adjacent to roots and rhizomes where oxygen leaks to the filtration media. On the other hand, prevailing anoxic and anaerobic conditions offer suitable conditions for denitrification but the supply of nitrate is limited as the major portion of nitrogen in sewage is in the form of ammonia. In addition, mineralization of organic nitrogen (ammonification) which proceeds both under aerobic and anaerobic conditions actually adds ammonia to the system.

Volatilization, adsorption and plant uptake play much less important role in nitrogen removal in HF CWs (Cooper et al., 1996; Vymazal, 1999; Vymazal et al., 1998a). Volatilization is limited by the fact that HF CWs do not have free water surface. Hence, algal activity is negligible in these systems and, therefore, pH values do not increase. The fine-grained soils always show better nitrogen removal through adsorption

Table 2
Loading of constructed wetlands with horizontal sub-surface flow

Parameter	Inflow	Outflow	Removed	Efficiency (%)	*N*
BOD_5	39.2[a]	7.6[a]	31.6[a]	81	131
COD	120[a]	34.6[a]	85.4[a]	71	110
TSS	53.6[a]	11.6[a]	42.0[a]	78	130
TP	141[b]	96[b]	45[b]	32	104
TN	644[b]	394[b]	250[b]	39	113
NH_4^+-N	388[b]	255[b]	133[b]	34	90
NO_3^--N	98[b]	67[b]	31[b]	32	66

For details see Table 1. (Modified from Vymazal (2001a,b)).
[a] Values in kg ha^{-1} day^{-1}.
[b] Values in g m^{-2} $year^{-1}$.

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 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.

Phosphorus is removed primarily by ligand exchange reactions, where phosphate displaces water or hydroxyls from the surface of Fe and Al hydrous oxides. However, media used for HSF wetlands (e.g. pea gravel, crushed stones) usually do not contain great quantities of Fe, Al or Ca and therefore, removal of phosphorus is generally low. Tanner et al. (1997) showed that in planted wetlands the surface layers (10 cm) are more aerobic ($E_h = 367$ mV) than equivalent unplanted wetlands ($E_h = 8$ mV). It is generally accepted that aerobic conditions are more favorable for P sorption and co-precipitation (Boström et al., 1982; Faulkner and Richardson, 1989).

It has been found that removal of nitrogen and phosphorus through plant harvesting is negligible and forms only a small fraction of the removed amount. Plant uptake removal mechanisms are limited in temperate and colder regions because harvesting regimes do not allow the harvesting of macrophytes, and especially *P. australis*, during the peak nutrient standing stock in the late summer. However, this mechanism may play more significant role in nutrient removal in tropical and subtropical regions where the plants grow year-round and nutrient translocations between above- and below-ground parts are minimal. The nutrient standing stock, i.e. the amount of N and P sequestered in aboveground biomass can reach the values of 40–50 g N m^{-2} and 5–10 g P m^{-2} and therefore, the amount of nitrogen and phosphorus that could be removed by plant harvesting form less than 10% of the total removed nutrients (Table 2). However, for tertiary treatment systems with low nutrient loading rates, the harvest may form a substantially larger portion of removed nutrients (Vymazal, 2001a, 2004, 2005).

2.2. Two case studies from the Czech Republic

In Table 3, performance of the on-site HF CW at Žitenice, Czech Republic, is presented. The system was built in 1993 for four PE and the major design parameters are:

- pretreatment: advanced septic tank with a long retention time (up to 12 h) and in-built vertical baffles which prevent the release of settled material;
- bed area: 18 m^2;
- filtration material: coarse sand (1–4 mm);
- vegetation: common reed (*P. australis*) and common cattail (*Typha latifolia*) were replaced by yellow flag (*Iris pseudacorus*) and blue flag (*Iris sibirica*) in 2002.

Table 3
Performance of on-site HF CW at Žitenice, Czech Republic during the period January 2003–September 2004

Parameter	Inflow ($mg\,l^{-1}$)	After pre-treatment ($mg\,l^{-1}$)	Outflow ($mg\,l^{-1}$)	Efficiency (%)
BOD_5	373	73	9.7	97
COD	1118	182	37	97
TSS	639	44	9.1	99
TP	17.1	10.6	10.6	38
NH_4^+-N	59	62	51	14
NO_3^--N	0	0	2.9	
Norg	24.2	9.1	1.1	95
TN	85	72	55	35

Results presented in Table 3 represent a typical performance of HF constructed wetland with very high removal of organics and suspended solids and low removal of nutrients. The data clearly indicate the importance of pre-treatment and the fact that the vegetated bed area of 4.5 m^2 per connected person is sufficient to provide very low outflow concentrations of organics and suspended solids.

In Table 4, results from one of the first constructed wetlands in the Czech Republic, Spálené Poříčí, are presented. The system was built in 1992 for 700 PE. Pre-treatment consists of an Imhoff tank but local septic lanks were left in operation. The sewer system is combined and, in addition, drainage waters were also intentionally flowed into the sewer system. As a result, an average flow over the period 1999–2002 was as high as 200 m^3 day^{-1} and the inflow concentrations of all parameters were very low. However, this represents a very common situation in the Czech Republic where most small villages have combined sewerage. The vegetated bed area of 2500 m^2 is divided into four beds of

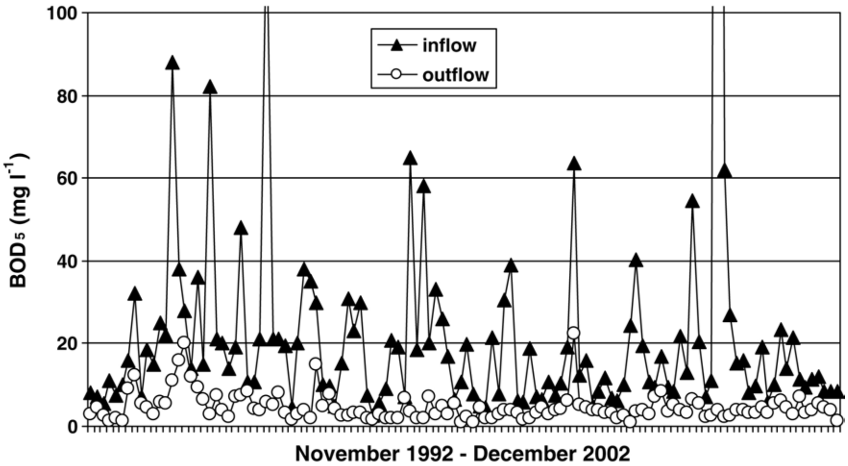

Fig. 2. Removal of BOD_5 at HF CW Spálené Poříčí during the period November 1992–December 2002.

equal size and two beds in series are in parallel. The filtration medium is gravel (0–16 mm). Common reed (*P. australis*) and reed canarygrass (*Phalaris arundinacea*) were planted in bands perpendicular to the flow of wastewater. However, over the years common reed took over the reed canarygrass and at present, only *Phragmites* is present.

The inflow concentrations of organics (BOD_5, COD) are so low that the use of conventional treatment systems such as activated sludge or RBC is questionable and most probably these technologies would not work properly. In addition, the fluctuation in inflow concentrations is quite high but the outflow is quite steady (Table 4, Fig. 2).

Table 4
Treatment efficiency of HF CW at Spálené Poříčí, Czech Republic during the period November 1992–December 2002

Parameter	Inflow	Outflow	Efficiency
BOD_5	23.3 (43)	4.6 (3.4)	80
COD	85 (147)	26.1 (11.5)	69
TSS	91 (228)	9.5 (8.0)	90
NH_4^+-N	11.6 (5.9)	9.4 (5.0)	19
NO_3^--N	3.0 (2.9)	1.79 (2.2)	40
TP	2.25 (1.25)	2.09 (1.52)	7
TC[a]	6.14 (6.47)	5.01 (5.42)	1.1
FS[a]	4.47 (4.64)	3.62 (4.03)	0.9

Values in mg l^{-1}, bacteria in log_{10} CFU/100 ml, efficiency in % for chemical parameters, in log units for bacteria. Standard deviations in parentheses.
[a] TC, total coliforms; FS, fecal streptococci.

3. Hybrid constructed wetlands

Various types of constructed wetlands may be combined in order to achieve higher treatment effect, especially for nitrogen. However, hybrid systems comprise most frequently VF and HF systems arranged in a staged manner (Fig. 3). There are now many fine examples of HF systems for secondary treatment and they proved very satisfactory where the standard required only BOD_5 and SS removal. However, there has been a growing interest in achieving fully nitrified effluents. HF systems cannot do this because of their limited oxygen transfer capacity. VF systems, on the other hand do provide a good conditions for nitrification but no denitrification occurs in these systems. Therefore, there has been a growing interest in hybrid systems (also sometimes called combined systems). In combined systems, the advantages of the HF and VF systems can be combined to complement each other. It is possible to produce an effluent low in BOD, which is fully nitrified and partly denitrified and hence has a much lower total-N concentrations (Cooper, 1999, 2001).

3.1. VF–HF systems

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, 1978). The Seidel design consists of two stages of sev-

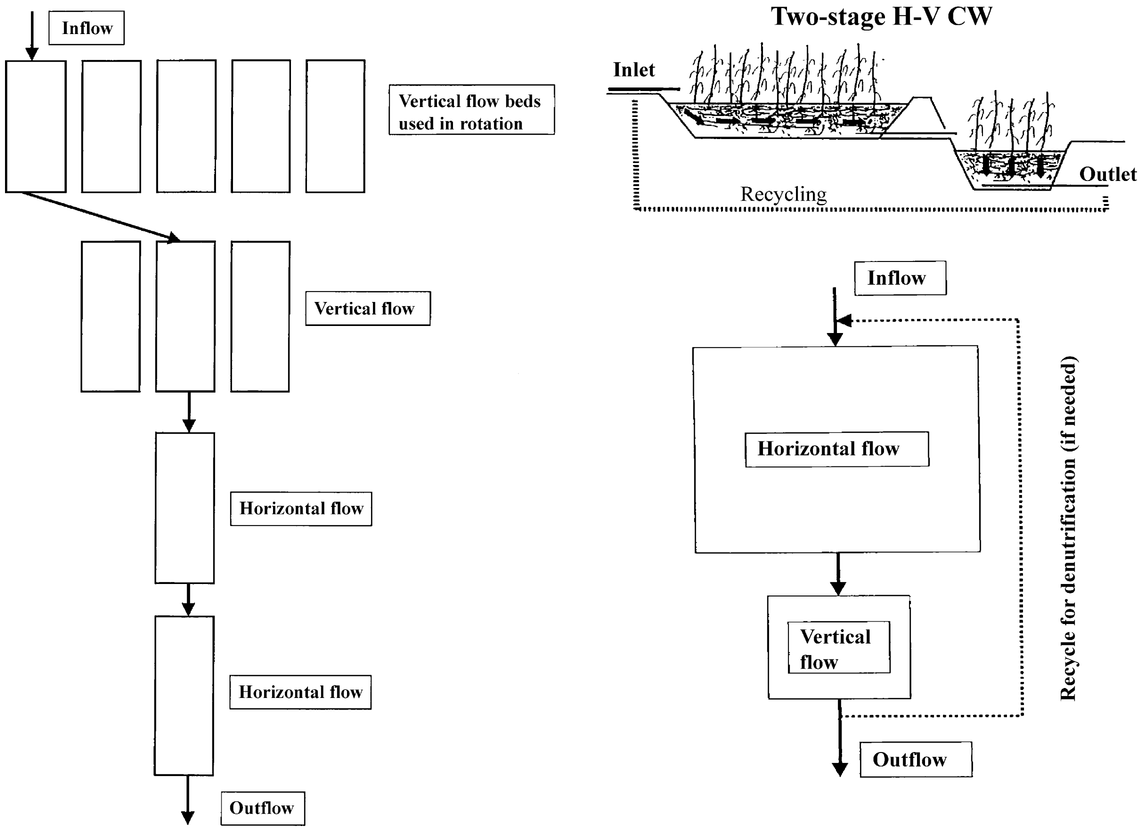

Fig. 3. Hybrid systems based on concepts by Seidel (left) and Brix and Johansen (right) (Brix, 1998; Cooper, 1999).

eral parallel VF beds followed by two or three HF beds in series. The VF stages were usually planted with *P. australis*, whereas the HF stages contain a number of other emergent macrophytes, including *Iris*, *Schoenoplectus*, *Sparganium*, *Carex*, *Typha* or *Acorus*. The VF beds were loaded with pre-treated wastewater for 1–2 days, and were then allowed to dry out for 4–8 days. The thin crust of solids that forms on top of the VF beds is mineralized during the rest period and achieves an equilibrium thickness (Brix, 1994).

In early the 1980s, several hybrid systems of Seidel's type were built in France with a system at Saint Bohaire, which was put in operation in 1982, being the best described (Boutin, 1987; Vuillot and Boutin, 1987; Lienard et al., 1990). It consisted of four and two parallel VF beds in the first and second stages, respectively, the third, fourth and fifth levels consisted of one HF bed in each level. A similar system was built in 1987 in UK at Oaklands Park (Burka and Lawrence, 1990, Table 5). The first stage consisted of six vertical beds (8 m^2 each) intermittently fed and planted with *P. australis*. The second stage consisted of three vertical beds (5 m^2 each) planted with. *P. australis*, *Schoenoplectus lacustris* (bulrush) and *Iris pseudacorus* (yellow flag). The third stage was a HF bed (8 m^2) planted with yellow flag and the fourth stage was 20 m^2 bed planted with

Table 5
Performance data from Oaklands Park CW (August 1989–September 1991, numbers in mg l^{-1}) (Cooper, 1999)

Parameter	Influent	Effluents			
		Stage 1 (VF)	Stage 2 (VF)	Stage 3 (HF)	Stage 4 (HF)
BOD_5	285	57	14	15	7
TSS	169	53	17	11	9
$NH_4{}^+$-N	50.5	29.2	14	15.4	11.1
$NO_{2,3}{}^-$-N	1.7	10.2	22.5	10.0	7.2
Ortho P	22.7	18.3	16.9	14.5	11.9

Table 6
Performance of the VF–HF Colecott hybrid system (data from O'Hogain, 2003)

Parameter	Inflow	VF1out	VF2out	HFout	Efficiency
COD	462	210	66	47	89
BOD_5	269	171	43	23	91
TSS	53	28	3	1	98
NH_4^+-N	45	28	16	7	84
NO_3^--N	0.1	4.7	3.8	2.7	
NO_2^--N	0.1	0.2	0.1	0.1	
PO_4	18	16	15	11	39

Concentrations in mg l^{-1}, efficiency in %.

bulrush, *Sparganium erectum* (bur reed) and *Acorus calamus* (sweet flag).

In the 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), Austria (Mitterer-Reichmann, 2002), France (Reeb and Werckmann, 2003) and Ireland (O'Hogain, 2003) and now this type is getting more attention in most European countries. In Table 6, a typical treatment effect of the VF–HF system based on original Seidel's concept is presented. The Colecott system consists of four VF beds (total of 64 m^2) at the first stage, two VF beds (60 m^2) at the second stage and one HF bed (60 m^2) at the third stage. The system is designed for 60 PE.

VF–HF systems at Oklands Park and Colecott exhibit a high removal of organics (COD, BOD_5) and suspended solids. As compared to single HF systems, there is much higher removal of total nitrogen as a result of high nitrification in the VF section. Nitrate produced in the VF section is successfully reduced in the HF section. However, removal of phosphorus is low.

Table 7
Performance of a HF (456 m^2)–VF (30 m^2) constructed wetland (55 PE) at Bjødstrup-Landborup, Denmark (Brix et al., 2003)

	Inflow (mg l^{-1})	Outflow (mg l^{-1})	Removal (%)
COD	216	48	78
BOD_5	98	4	96
TP	9.9	0.11	99
TN	72.2	28	61
NH_4^+-N	60	2	97

Table 8
Performance of the HF (140 m^2)–VF (120 m^2) hybrid system at Dhulikhel, Nepal (Laber et al., 2003)

	STin (mg l^{-1})	STout (mg l^{-1})	HFout (mg l^{-1})	VFout (mg l^{-1})	Removal (%)
BOD_5	118	67	25	2	98
COD	261	162	45	10	96
TSS	159	57	19	1.5	99
NH_4^+-N	32	32	27	0.1	99
NO_3^--N	0.2	0.2	0.4	27	
TP	4.6	4.4	2.6	1.4	70
E. coli	7.2	6.2	3.6	1.3	5.9[a]

ST, septic tank; *E. coli* in log_{10} CFU/100 ml.
[a] Log units.

3.2. HF–VF systems

In mid-1990s, Johansen and Brix (1996) introduced a HF–VF hybrid system (Fig. 3). 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) pointed out that special care must be taken not to affect the performance of the sedimentation tank or the nitrifying capacity of the VF bed by recycling too large volumes of wastewater. The results (Table 7) are very promising, especially for amonia removal. A similar system was built in Poland at Sobiechy (Ciupa, 1996).

The importance of recycling could be demonstrated from the results given by Laber et al. (2003) for a HF–VF hybrid system in Nepal (Table 8). The system shows an excellent removal of organics (BOD_5, COD), suspended solids, bacteria and ammonia. How-

Table 9
Treatment performance of a hybrid constructed wetland at Darzlubie, Poland (Kowalik and Obarska-Pempkowiak, 1998)

	Inflow	Outflow	Removal (%)
BOD_5	265	29.2	89
COD	574	68.9	88
TSS	308	55.5	82
TN	101	14.1	86
NH_4^+-N	28.5	5.7	80
TP	5.0	1.0	80

Concentrations in mg l^{-1}.

Table 10
Casa Vincicola Cecchi, Italy—treatment performance for the period 13.2.01–11.3.03 (based on Masi et al. (2002))

	BOD_5	COD	TSS	TN	TP	pH
Inflow ($mg\,l^{-1}$)	1833	3906	213	18.9	4.7	6.1
HFout ($mg\,l^{-1}$)	49.4	131	13.3	4.8	1.5	6.9
FWS out ($mg\,l^{-1}$)	25.4	84	23.4	3.5	1.3	7.4
Removal (%)	99	98	89	82	72	

Table 11
Treatment effect of the hybrid constructed wetland in Yantian

	Influent	Lagoons out	Hyacinth out	HFout	Removal
BOD_5	189	98	82	58	69
COD	456	242	192	88	81
TSS	232	116	65	3.2	99
TP	4.7			1.8	62
TN	22.3			15.5	31
$NH_4{}^+$-N	14.7			12.2	17

Concentrations in $mg\,l^{-1}$, removal in % (Wang et al., 1994).

ever, removal of total nitrogen would be very low because of low denitrification in the last VF stage. The ammonia nitrogen is oxidized to nitrate in the vertical-flow stage but without recycling is then discharged.

HF and VF constructed wetlands could also be combined in more than two stages. The system in Darzlubie (Table 9) in Poland consists of a combination of HF bed (1200 m^2), cascade of five alternate HF and VF beds (total are of 270 m^2) and HF (II) bed (500 m^2). After this point 50% of the flow is directed to two VF (II) beds (total area 500 m^2) and the final stage of the treatment system is a 1000 m^2 HF bed where the outflow from VF (II) and HF (II) are combined (Obarska-Pempkowiak, 1999).

3.3. Other types of hybrid systems

Recently, hybrid constructed wetlands comprise more than two types of CWs and quite often include a FWS stage. The system for the treatment of municipal wastewaters at Kõo in Estonia consists of two VF beds (each 64 m^2 planted with *P. australis*), followed by a HF bed (350 m^2 planted with *P. australis* and *Typha latifolia*) and two FWS wetlands (3600 and 5000 m^2 planted with *T. latifolia*). The removal of BOD_7, total N and total P amounted to 88, 65 and 72%, respectively (Mander et al., 2003). In Italy, hybrid constructed wetlands are successfully used for the treatment of concentrated winery wastewaters (Masi et al., 2002). System at Cecchi, consists of a HF bed (480 m^2) followed by a free water surface (FWS) wetland (850 m^2). The system is heavily loaded with organics, the organic load of the HF bed amounted to 1336 $kg\,ha^{-1}\,day^{-1}$ but the treatment effect is very high for organics, suspended solids and nutrients (Table 10). FWS stage improves the water quality in terms of organics, nitrogen and phosphorus but suspended solids concentrations increases after passing this stage. This is most probably caused by the presence of phytoplankton; this explanation is supported by higher pH values.

Wang et al. (1994) described a hybrid system for industrial wastewaters at Yantian industry area in Shenzen City in southeast China, which consists of anaerobic lagoon (247 m^2), three water hyacinth ponds (275 m^2 each) and two HF beds planted with *P. australis* (805 m^2 each). Despite very high hydraulic loading (36 $cm\,day^{-1}$ for the HF stage) the treatment effect was very good (Table 11), especially for organics, suspended solids and phosphorus.

Laouali et al. (1996) reported the use of a combination of aHF and FWS wetlands in Montreal,

Table 12
Treatment performance (numbers in $mg\,l^{-1}$ and in CFU/100 ml for bacteria) of a hybrid system in Montreal (calculated from Laouali et al. (1996))

	BOD_5	COD	TKN	$NH_4{}^+$-N	TP	TSS	*E. coli*	*F. streptococci*
Inflow	130	283	52.8	37.3	7.10	67	4.8×10^5	2.6×10^4
Stage I-out	16.2	51	27.7	19.8	0.73	19.8	1287	75
Stage II-out	3.0	39	16.7	10.7	0.30	22.5	195	130
Stage III-out	5.5	39	10.2	6.1	0.17	18.5	190	70
Removal (%)	96	86	81	84	98	72	3.4[a]	2.6[a]

[a] Log units.

Canada (Table 12). The system has been designed as a three-stage wetland; it consists of: (1) two parallel HF beds (stage I) planted with *P. australis* (200 m^2 each), (2) 300 m^2 pond (stage II) divided into three 100 m^2 sections in series planted with *Scirpus lacustris* (bulrush), *Typha latifolia* (common cattail) and *Iris versicolor* (larger blueflag), and (3) 100 m^2 pond (stage III) divided into two 50 m^2 sections in series planted with *Mentha aquatica* (water mint) and *Elodea canadensis* (canadian waterweed). As for most systems where the FWS stage is at the end of the treatment line, removal of nutrients and bacteria improves at this stage but suspended solids and organics removal exhibit a slight increase due to algal growth.

4. Conclusions

Constructed wetlands with horizontal sub-surface flow are a viable alternative for wastewater treatment for small sources of pollution especially when organics and suspended solids are the treatment target. Removal of organics (BOD_5 and COD) and suspended solids is very high and steady over the years of operation. Removal of nutrients (nitrogen and phosphorus) is usually low and does not exceed 50% for municipal sewage when systems are dimensioned at about 5 m^2 per population equivalent. Nitrogen removal is limited by the lack of oxygen in the filtration bed and the consequent low nitrification occurs while phosphorus removal is limited by low sorption capacity of the filtration materials (gravel, crushed rock). Hybrid constructed wetlands combine various types of constructed wetlands in order to achieve higher treatment effect especially for nitrogen. The most common hybrid systems combine horizontal sub-surface flow beds with vertical flow ones in a staged manner. However, other types of constructed wetlands such free water surface wetlands are used as well.

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