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Wastewater Treatment by Constructed Wetlands

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Abstract

The first experiments using wetland macrophytes for wastewater treatment were carried out in Germany in the early 1950s. Since then, the constructed wetlands have evolved into a reliable wastewater treatment technology for various types of wastewater.

The classification of constructed wetlands is based on: the vegetation type (emergent, submerged, floating leaved, free-floating); hydrology (free water surface and subsurface flow); and subsurface flow wetlands can be further classified according to the flow direction (vertical or horizontal). In order to achieve better treatment performance, namely for nitrogen, various types of constructed wetlands could be combined into hybrid systems.

Keywords

Constructed wetlands; macrophytes; nutrients; organics; wastewater

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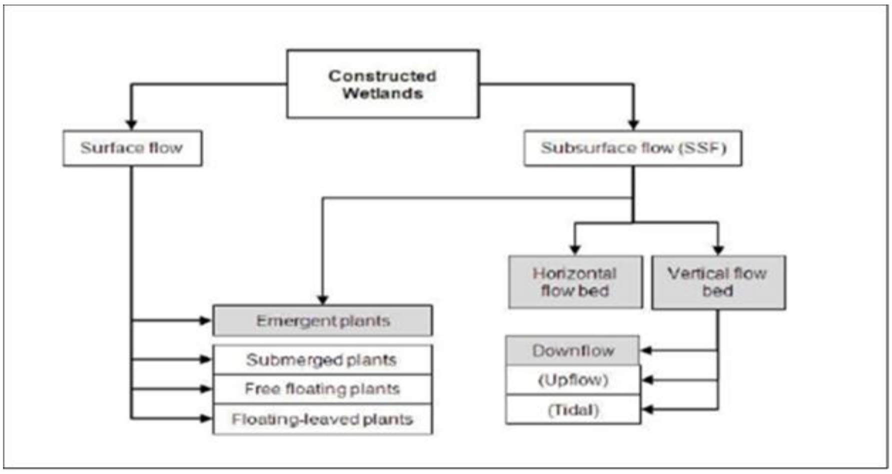
I. Introduction

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.

These types of subsurface flow wetlands also differ from one another in system layout, the removal efficiency of certain pollutants, area requirements, technical complexity, applications, and costs. Each type is briefly in the sections that follow.

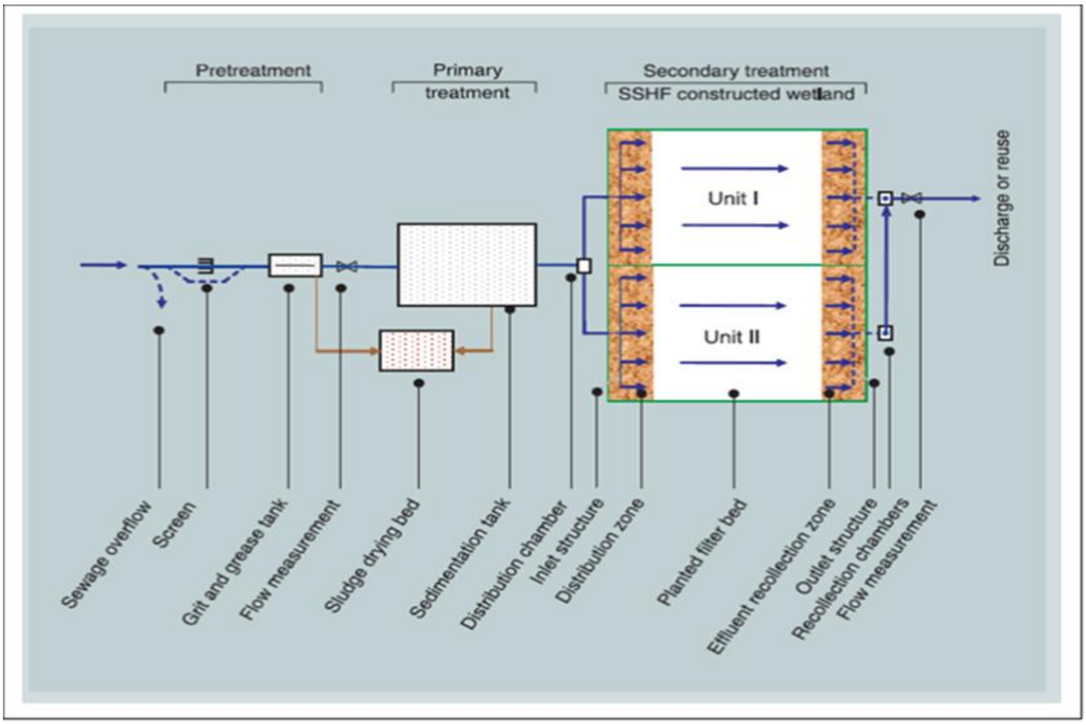
Figure 1. The major characteristics of various types of constructed wetlands for wastewater treatment. H = horizontal, V = vertical.



A promising treatment system:
Constructed wetlands

Constructed wetlands are natural wastewater treatment systems. Designed to maximize the removal of wastewater contaminants, they consist of beds of aquatic macrophytes (wetland plants). These wetlands are used as secondary or tertiary treatment units, wastewater is generally treated first in primary treatment units such as settling tanks or technical treatment plants. A variety of treatment processes then takes place in constructed wetlands, such as filtration, sedimentation, and biological degradation, which together effectively remove the contaminants in domestic wastewater. In general, constructed wetlands require little operation and maintenance when compared with technical treatment systems.

Figure 2. Basic layout of a SSHF Constructed Wetland System



CWs for wastewater treatment may be classified according to the life form of the dominating macrophyte, into systems with free-floating, floating leaved, rooted emergent and submerged macrophytes.

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

Seidel then carried out numerous experiments aimed at the use of wetland plants for treatment of various types of wastewater, including phenol wastewaters, dairy wastewaters or livestock wastewater. Most of her experiments were carried out in constructed wetlands with either horizontal (HF CWs) or vertical (VF CWs) subsurface flow, but the first fully constructed wetland was built with free water surface (FWS) in the Netherlands in 1967. However, FWS CWs did not spread substantially in Europe where subsurface flow constructed wetlands prevailed in the 1980s and 1990s [1].

In North America, FWS CWs started with the ecological engineering of natural wetlands for wastewater treatment at the end of the 1960s and beginning of the 1970s [8-10]. This treatment technology was adopted in North America not only for municipal wastewaters but all kinds of wastewaters. Subsurface flow technology spread more slowly in North America but, at present, thousands of CWs of this type are in operation [2].

Various types of constructed wetlands may be combined in order to achieve higher treatment effect, especially for nitrogen. Hybrid systems comprise most frequently VF and HF systems arranged in a staged manner but, in general, all types of constructed wetlands could be combined in order to achieve more complex treatment efficiency [3].

II. Main Characteristics of Various Types of Constructed Wetlands

Various types of constructed wetlands differ in their main design characteristics as well as in the processes which are responsible for pollution removal. For the purpose of this paper, only FWS CWs with emergent macrophytes are considered.

2.1. Free Water Surface Constructed Wetlands

A typical FWS CW with emergent macrophytes 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 a significant fraction of the surface, usually more than 50% (Figure 3). Besides planted macrophytes, naturally occurring species may be present [3]. Plants are usually not harvested and the litter provides organic carbon necessary for denitrification which may proceed in anaerobic pockets within the litter layer.

Figure 3. A free water surface constructed wetland (FWS CW) for stormwater runoff in Woodcroft Estate near Sydney, NWS, Australia. Photograph taken by the author.

FWS CWs are efficient in removal of organics through microbial degradation and settling of colloidal particles. Suspended solids are effectively removed via settling and filtration through the dense vegetation. Nitrogen is removed primarily through nitrification (in water column) and subsequent denitrification (in the litter layer), and ammonia volatilization under higher pH values caused by algal photosynthesis. Phosphorus retention is usually low because of limited contact of water with soil particles which adsorb and/or precipitate phosphorus. Plant uptake represents only temporal storage because the nutrients are released to water after the plant decay. Constructed wetlands with FWS are frequently used in North America (Figure 4) and Australia [4] (Figure 5).
In Europe, this technology has recently gained more attention, especially in Sweden and Denmark where these systems are used to eliminate nitrogen from diffuse pollution [5].
Besides municipal wastewater, FWS CWs with emergent vegetation have been used to treat various types of wastewaters (Table 1).

Figure 4. A FWS CW for treatment of alkaline mine drainage waters in Monastery Run, Pennsylvania, U.S. Photograph taken by the author.

Figure 5. A FWS CW for tertiary treatment of municipal wastewater in McGrath Hill, Hawkesbury, near Sydney, NSW, Australia. Photograph taken by the author.

Table 1. Examples of the use of FWS CWs for various types of wastewater.

Type of wastewater	Location	Ref.
Animal wastes	U.S.	[6-8]
Dairy pasture runoff	New Zealand	[9]
Agricultural drainage	U.S.	[10]
Stormwater runoff-residential	Australia	[11]
Stormwater runoff-highway	United Kingdom	[12]
Stormwater runoff-airport	Sweden	[13]
Acid coal mine drainage	U.S., Spain	[14,15]
Metal ores mine drainage	Germany, Ireland, Canada	[16-18]
Refinery process waters	U.S., Hungary	[19,20]
Paper and pulp wastewaters	U.S.	[21]
Shrimp aquaculture	U.S.	[22]
Landfill leachate	Sweden, Norway, U.S.	[23-25]
Sugar factory	Kenya	[26]
Olive mill	Greece	[27]
Woodwaste leachate	Canada	[28]
Metallurgic industry	Argentina	[29,30]

Sizing of FWS CWs is usually based either on volume or area. Volume-based methods use a hydraulic retention time to assess the pollutant removal while area-based methods assess pollutant reduction using the overall wetland area [31]. In Table 2, the basic sizing criteria for BOD_5, TSS and TKN removal are given. Wallace and Knight [31] pointed out that FWS CWs are generally not effective for phosphorus removal and only inflow loading less than 0.1 g P/m^2 d would provide low effluent concentrations.

Table 2. Loading rates recommended for achieving target effluent concentration in FWS CWs.

Parameter	Effluent	Loading rate	Ref.
BOD_5	30 mg/L 25 mg/L 20 mg/L	6 g/m^2 d 3 g/m^2 d 4.5 g/m^2 d	[31,32] [31] [32]
TSS	30 mg/L 30 mg/L 25 mg/L 20 mg/L	7 g/m^2 d 5 g/m^2 d 3.5 g/m^2 d 3 g/m^2 d	[31] [32] [31] [32]
TKN	10 mg/L	1.5 g/m^2 d	[31]

2.2. Constructed Wetlands with Horizontal Subsurface Flow

HF CWs consist of gravel or rock beds sealed by an impermeable layer and planted with wetland vegetation (Figure 6). The wastewater is fed at the inlet and flows 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 and discharged. In the filtration beds, pollution is removed by microbial degradation andchemical and physical processes in a network of aerobic, anoxic, anaerobic zones with aerobic zones being restricted to the areas adjacent to roots where oxygen leaks to the substrate [33].

This type of constructed wetland was developed in the 1950s in Germany by Käthe Seidel who designed the HF CWs using coarse materials as the rooting medium. In the 1960s, Reinhold Kickuth suggested soil media with high clay content and called the system the "Root Zone Method" [33]. In the early 1980s, the HF CWs technology was introduced to Denmark and by 1987 nearly 100 soil-based systems were put in operation [33]. Despite problems with surface flow soil-based systems exhibited high treatment effect for organics and suspended solids if reed bed area 3–5 m2 PE−1 (population equivalent) was used [33]. During the late 1980s, the HF CWs were also introduced to other countries, such as Austria and United Kingdom and then in the 1990s, this system spread into most European countries and also to North America, Australia, Asia and Africa. In the late 1980s, soil material was replaced by coarse material and at present, washed gravel or rock with grain size of about 10–20 mm are commonly used.

Organic compounds are effectively degraded mainly by microbial degradation under anoxic/anaerobic conditions as the concentration of dissolved oxygen in the filtration beds is very limited [34]. Suspended solids are retained predominantly by filtration and sedimentation and the removal efficiency is usually very high. The major removal mechanism for nitrogen in HF CWs is denitrification. Removal of ammonia is limited due to lack of oxygen in the filtration bed as a consequence of permanent waterlogged conditions [35]. Phosphorus is removed primarily by ligand exchange reactions, where phosphate displaces water or hydroxyls from the surface of iron and aluminum hydrous oxides. Unless special materials are used, removal of P is usually low in HF CWs [35].

The most important roles of plants in HF CWs are provision of substrate (roots and rhizomes) for the growth of attached bacteria, radial oxygen loss (oxygen diffusion from roots to the rhizosphere), nutrient uptake and insulation of the bed surface in cold and temperate regions [35].

For a long time, the HF CWs have been designed using either simple "rule of thumb" set at 5 m^2 PE−1 or plug-flow first order models. Recently, more complex dynamic, compartmental models [36,37] have been developed. However, in these models many parameters are difficult to measure and therefore many assumptions must be made. Hence, it is important to realize that more complex models do not necessarily bring more precise design parameters. However, no matter which design model is used, for municipal sewage, the area of HF CWs is usually about 5 m^2 PE−1 [1]. To achieve the outflow BOD5 and TSS concentration of 30 mg/L, the U.S. EPA recommends the respective inflow loads of 6 g/m^2 d and 20 g/m^2 d.

HF CWs have always been used to treat municipal (Figure 7) wastewaters around the world. However, at present, HF CWs are used to treat many other types of wastewaters including industrial and agricultural, landfill leachate and runoff waters (Table 3).

Figure 6. Schematic layout of a constructed wetland with horizontal subsurface flow.
inflow distribution zone filled with large stones; impermeable layer; filtration material; vegetation; water level in the bed; outflow collection zone; drainage pipe; outflow structure with water level adjustment [33]. With permission from Backhuys Publishers.

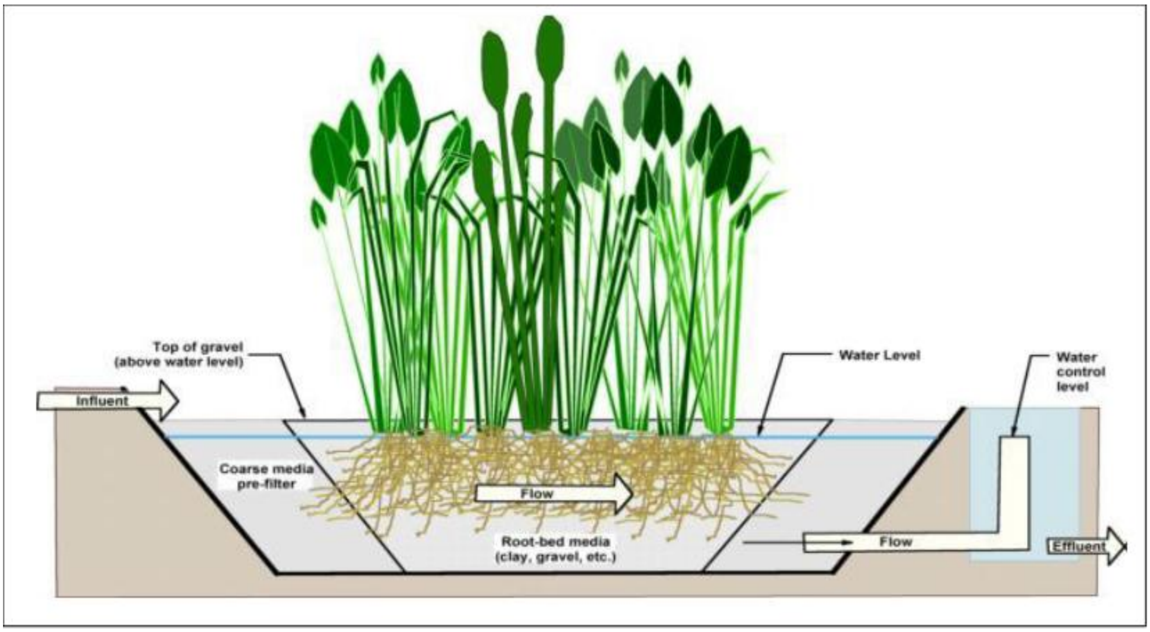


Figure 7. HF CWs at Staverton, United Kingdom. Tertiary treatment for 603 PE.

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

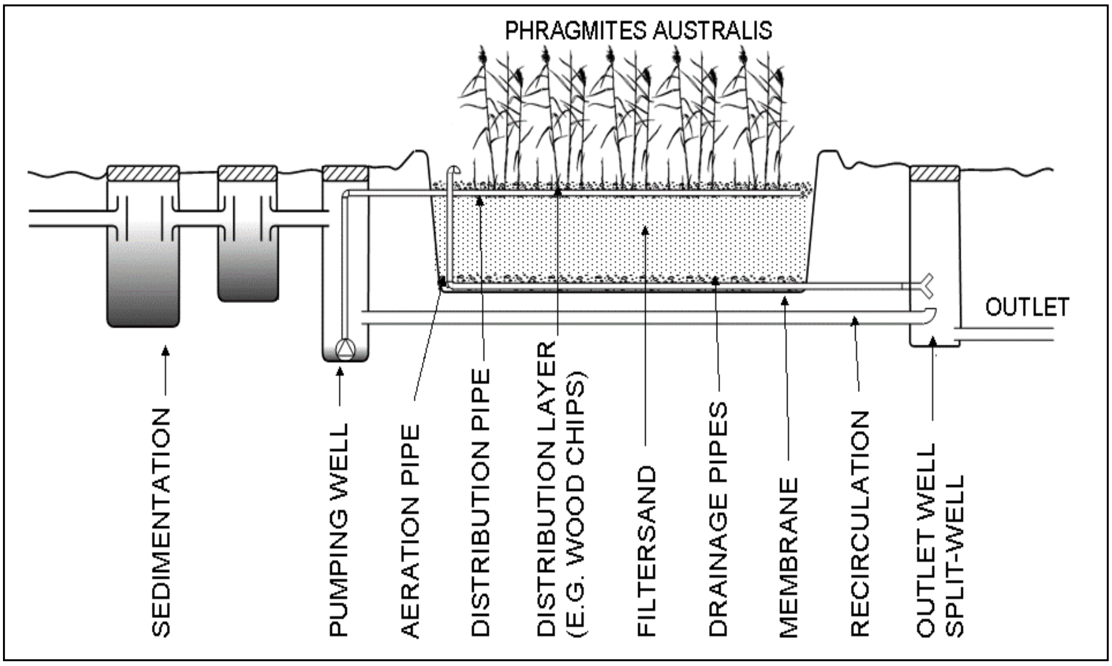
Type of wastewater	Location	Ref.
Petrochemical	U.S., China	[34,35]
Chemical industry	United Kingdom	[36]
Paper and pulp wastewaters	U.S.	[36]
Abattoir	Mexico, Ecuador	[37,38]
Textile industry	Australia	[39]
Tannery industry	Portugal	[40]
Food industry	Slovenia, Italy	[41,42]
Distillery and winery	India, Italy	[43,44]
Pig farm	Australia, Lithuania	[45,46]
Fish farm	Canada, Germany	[47,48]
Dairy	U.S., Germany, Uruguay	[49-51]
Highway runoff	United Kingdom	[52]
Airport runoff	U.S.	[53]
Nursery runoff	Australia	[54]
Landfill leachate	Poland	[55]

2.3. Constructed Wetlands with Vertical Subsurface Flow

Vertical flow constructed wetlands (VF CWs) (Figure 8) were originally introduced by Seidel to oxygenate anaerobic septic tank effluents. However, the VF CWs did not spread as quickly as HF CWs probably because of the higher operation and maintenance requirements due to the necessity to pump the wastewater intermittently on the wetland surface (Figure 9). The water is fed in large batches and then the water percolates down through the sand medium. The new batch is fed only after all the water percolates and the bed is free of water. This enables diffusion of oxygen from the air into the bed. As a result, VF CWs are far more aerobic than HF CWs and provide suitable conditions for nitrification. On the other hand, VF CWs do not provide any denitrification. VF CWs are also very effective in removing organics and suspended solids. Removal of phosphorus is low unless media with high sorption capacity are used [1]. As compared to HF CWs, vertical flow systems require less land, usually 1–3 m2 PE−1. The early VF CWs were composed of several stages with beds in the first stage fed in rotation. At present, VF CWs are usually built with one bed and the system is called "compact" VF CWs.[56].

VF CWs are very often used to treat domestic and municipal wastewater and especially when discharge limits are set for ammonia-nitrogen. However, in the literature, numerous reports have been published on the use of VF CWS for various types of wastewaters such as refinery effluent, composting leachate, airport runoff, dairy or cheese production effluent [57].

Figure 8. Layout of a vertical flow constructed wetland system for a single household.
Raw sewage is pre-treated in a sedimentation tank. Settled sewage is pulse-loaded onto the surface of the bed by a level-controlled pump. Treated effluent is collected in a system of drainage pipes, and half of the effluent is recirculated back to the pumping well (or to the sedimentation tank). With permission from Elsevier.



In upflow vertical CWs, the wastewater is fed on the bottom of the wetland. The water percolates upward and then it is collected either near the surface or on the surface of the wetland bed. These systems are commonly used, for example, in Brazil. Recently, the "fill and drain" or "tidal" CWs have been developed. In tidal flow systems the wastewater percolates upwards until the surface is flooded. When the surface is completely flooded, the feeding is stopped, the wastewater is then held in the bed and, at a set time later, the wastewater is drained downwards. After the water has drained from the filtration bed, the treatment cycle is complete and air can diffuse into the voids in the filtration material [58].

Figure 9. Wastewater distribution at vertical flow (VF) CWs at Bexhill, NSW, Australia. Photograph taken by the author.

2.4. Hybrid Constructed Wetlands

Constructed wetlands could be combined in order to achieve a higher treatment effect by using advantages of individual systems. Most hybrid constructed wetlands combine VF and HF stages [59].

The VF-HF system was originally designed by Seidel as early as in the late 1950s and the early 1960s but the use of hybrid systems was then very limited. In the 1980s VF-HF hybrid constructed wetlands were built in France and United Kingdom. At present, hybrid constructed wetlands are in operation in many countries around the world and they are used especially when removal of ammonia-N and total-N is required [60].

Besides sewage, hybrid constructed wetlands have been used to treat a variety of other wastewaters, for example, landfill leachate, compost leaching, slaughterhouse, shrimp and fish aquaculture or winery.

Comparative advantages and limitations

Constructed wetlands are natural treatment systems that offer a variety of advantages that make them suitable for small to medium-size communities in developing countries, particularly in tropical regions [61].

Comparative ***advantages****,* in particular of the subsurface horizontal flow type, include the following:

1- Operation and maintenance (O&M) costs are low because (1) the natural biological treatment processes are enhanced by high ambient and wastewater temperatures; (2) there are low or no external energy requirements; and (3) there is no need for sophisticated equipment, spare parts, and chemicals.

2- The O&M requirements are relatively simple, which may allow a community organization or a private, small-scale entrepreneur to manage the system after adequate capacity building and with technical support.

3- Constructed wetlands are characterized by robustness, performance reliability, and resistance to flow fluctuations.

4- The subsurface flow conditions limit insect breeding and proliferation of vectors.

5- Certain wetland plant species grown on the constructed wetland can be reused as animal fodder (such as elephant grass) or ornamental flowers (such as *Heliconia* species) and can generate income.

6- Organic pollutants, suspended solids, and helminth eggs can be removed with greatefficiency.

7- The reduced levels of pathogens in the effluent and remaining nutrients render the effluent appropriate for crop irrigation, provided that additional health protection measures are taken.

8- The SSHF constructed wetland has low odor emissions.2

9- The treatment plant is attractive because of the use of natural materials and plants.

10- Constructed wetlands create a habitat for wildlife.

The ***limitations*** of the technology, and particularly the subsurface horizontal flow type, include the following:

1- The surface requirements are high compared with those of conventional technical treatment technologies.

2- A relatively large amount of adequate filter material and sealing material is required.

3- The deposition of inert solids and biomass can lead to the clogging of certain parts of the filter material.

4- The replacement of clogged material is expensive and, in the case of community-managed systems, may not be carried out easily without technical assistance.

5- Because of the limited control capacities of local authorities, it is essential that schemes be designed according to the rules of the art and that construction of the systems be carried out carefully and under close professional supervision.

III. Treatment Performance

3.1. Organics and Suspended Solids

Removal of organics is high in all types of constructed wetlands (Table 4). While in FWS and VF constructed wetlands, the microbial degradation processes are mostly aerobic, in HF constructedwetlands, anoxic and anaerobic processes prevail. The treatment efficiency is similar for FWS and HF CWs, while for VF CWs the percentage efficiency is higher due to higher inflow concentrations [62].

VF constructed wetlands are nearly always used for primary or secondary treatment while FWS are often used for tertiary treatment [63] and HF CWs are often used for treatment of wastewater diluted with stormwater runoff [1]. However, the outflow concentrations for secondary treatment systems are comparable for all types of constructed wetlands (Table 4). Removal of suspended solids is very high in all types of constructed wetlands (Table 4). The results presented in Table 4 also indicate that hydraulic retention time is usually lower in FWS CWs as compared to sub-surface flow CWs.

Table 4. Treatment efficiency (Eff, in %) of various types of constructed wetlands (CWs) for organics and suspended solids. Inflow (In) and outflow (Out) concentrations in mg/L.
HLR = hydraulic loading rate (cm/d). N = number of CWs. * updated.

Type of CW	Ref	BOD5					TSS				
		In	Out	Eff	HLR	N	In	Out	Eff	HLR	N
FWS	[2]*	161	42	74	4.1	50	185	43	77	4.8	52
	[90]	34.6	9.8	72	3.3	51	57.8	18.3	68	3.1	52
HF	[2]	170	42	75	11.8	438	141	35	75	15.4	367
VF	[2]*	274	28	90	8.2	125	163	18	89	9.7	98

Removal of nutrients in various types of constructed wetlands is presented in Table 5. Phosphorus retention is low in all types of constructed wetlands and CWs are seldom built with phosphorus being the primary target of the treatment. Most studies on phosphorus cycling in wetlands have shown that soil/peat accumulation is the major long-term phosphorus sink. Among the various types of constructed wetlands, soil accretion occurs only in FWS CWs as the vegetation is not harvested and wastewater gets in contact with top soil layer. However, the magnitude of phosphorus retention is very low as compared to loads commonly occurring in wastewaters. In sub-surface flow CWs, the major removal mechanisms are adsorption and precipitation. However, materials which are commonly used for sub-surface flow CWs, *i.e.*, washed gravel or crushed rock, provide very low capacity for sorption and precipitation. Recently, manufactured filtration materials such as LECA (light weight clay aggregates) or by- and waste-products such as furnace steel slags, have been tested in constructed wetlands. The removal of phosphorus is very high with these substrates, but it is important to realize that sorption and precipitation are saturable processes and the sorption decreases over time [64].

Table 5. Treatment efficiency (Eff, in %) of various types of constructed wetlands (CWs) for nitrogen and phosphorus. Inflow (In) and outflow (Out) concentrations in mg/L. HLR = hydraulic loading rate (cm/d). N = number of CWs. *updated.

Type of CW	Ref.	TP					TN					NH4-N				
		In	Out	Eff	HLR	N	In	Out	Eff	HLR	N	In	Out	Eff	HLR	N
FWS	[2]*	14.7	9.7	34	5.4	52	42.6	23.5	45	4.9	29	30	16	48	5.4	40
	[42]	4.0	1.8	49		207	11.7	6.2	47		192					
	[11]	7.9	5.1	35	12.3	282	84	49.5	41	8.9	116	75	46	39	7.3	118
	[90]	3.6	1.8	50	3.5	52	10.9	4.6	58	3.2	36	5.8	2.7	53	3.1	59

Table 6. *Cont.*

Type of CW	Ref.	TP					TN					NH4-N				
HF		In	Out	Eff	HLR	N	In	Out	Eff	HLR	N	In	Out	Eff	HLR	N
VF	[2]	9.6	4.8	50	11.4	272	63	36	43	10.6	208	36	22	39	14.1	305
	[11]						54	36	33	7.6	123	40	28	30	7.0	
	[2]*	10.3	4.5	56	8.2	118	73	41	43	9.1	99	56	14.9	73	8.4	213
																129

Removal of total nitrogen (Table 6) is also usually low due to low nitrification in water-saturated HF constructed wetlands and low or zero denitrification in FWS and VF CWs, respectively.

In FWS CWs nitrogen is removed via nitrification in aerobic water column and subsequent denitrificaton in anoxic litter layer on the bed surface. Volatilization may be a significant route for nitrogen removal in constructed wetlands with open water surface where algal assemblages can create high pH values during the day through their photosynthetic activity. In vertical-flow constructed wetlands, very high nitrification proceeds but, because of entirely aerobic conditions in the vertical bed, no denitrification takes place. In order to achieve effective removal of total nitrogen VF CWs could be combined with HF CWs which, in contrast, do not nitrify but provide suitable conditions for reduction of nitrate formed during nitrification in VF beds. Plant uptake in all types of constructed wetlands is effective only when plants are harvested, but the amount sequestered in the aboveground biomass is usually very low and does not exceed 10% of the inflow nutrient load [1].

More details on treatment performance of constructed wetlands for various types of wastewater could be found elsewhere [1,2].

3.2. Nutrient removal

Plant growth leads to removal of nutrients such as nitrogen and phosphorus: The reduction of ammonia and phosphate from domestic wastewater by growing plants is about 10-20% during the vegetation period. More important for nitrogen removal are however the nitrification/denitrification processes carried out by bacteria.

3.2.1. Nitrogen removal:

· **HFBs:** As the oxygen transport into HFBs is limited, enhanced nitrification cannot be expected. On the other hand denitrification can be very efficient, even at very low carbon to nitrogen ratios (Platzer, 1999). The produced nitrate can be reduced under anoxic conditions by heterotrophic bacteria to nitrogen (N_2); this is called denitrification.

· **VFBs:** In VFBs with sufficient oxygen supply, ammonia can be oxidised by autotrophic bacteria to nitrate; this process is called nitrification. An almost complete nitrification with 90% ammonia oxidation is commonly reported for VFBs. Nevertheless nitrification depends strongly on the oxygen supply. For the dimensioning it is essential to calculate the oxygen consumption in the VFB (Platzer, 1999; Cooper, 2005; Platzer et al., 2007).

On the other hand, since VFBs do not provide much denitrification, the nitrogen remains as nitrate in the effluent and the total nitrogen removal ratio is therefore only around, 30%.

· Combination: Often a combination of a VFB followed by a HFB and flow recirculation is used when nitrogen removal is required. For details see Section

3.2.2. P hosphorus removal:

Most CWs are *not* designed primarily for phosphorus removal and in developing countries they are practically *never* designed for phosphorus removal since this is generally not a requirement there. Phosphorus removal is not such an important issue in those countries compared to the other health risks from untreated wastewater discharge. If excess phosphorus in receiving water bodies such as lakes and rivers became an important problem, a first step could be to ban detergents which contain phosphorus, as has been done for example in Switzerland.

A reliable design for phosphorus removal has not yet been developed although many subsurface flow CWs do present a relatively high phosphorus removal rate for a period of time (Rustige and Platzer, 2001). Phosphorus removal can be achieved in CWs by adsorption and precipitation, and a small amount is also taken up by plant growth.

The authors estimate that a phosphorus removal ratio by plant growth of up to 10% is possible depending on the climate, plants, type of wastewater, etc. The capacity of chemical phosphorus binding, and thus the phosphorus removal efficiency, decreases during the lifetime of a subsurface flow CW. This is due to limited adsorption sites of the sand.

If phosphorus removal is indeed required, a separate unplanted soil filter can be used downstream of the subsurface flow CW, where the substrate can be replaced once its phosphorus adsorption capacity has been reached.

Exchange of substrate is theoretically also possible for subsurface flow CWs but in practice it is not economically feasible.

3.3. Role of plants in subsurface flow CWs

Subsurface flow CWs are planted with macrophyte plants which are commonly found in natural wetlands or nonsubmerged riverbanks in the region. The plants are an essential part of a constructed wetland5. They are aesthetically pleasing and add greenery to a built-up area. They serve as a habitat for animals like birds and frogs, and act as a local "green space". Most significant in comparison to unplanted filters is the ability of the subsurface flow CWs – which are by definition *with* plants – to maintain or restore the hydraulic conductivity of the filter bed. Unplanted soil filters on the other hand have to be treated to regain their hydraulic conductivity, for example by removing the top few centimeters of substrate.

The plants also play an important role in the treatment process. They provide an appropriate environment for microbial growth and significantly improve the transfer of oxygen into the root zone, which is part of the filter bed. Furthermore, in cold climate zones dead plant material provides an insulation layer, which has a positive effect for the operation of subsurface flow CWs in winter. For example, in the case of reed, there is a massive network of roots and rhizomes6, which maintain a high biological activity in the constructed wetland, due to their ability to transport oxygen from the leaves to the roots (see Figure 10).

For HFBs a uniform distribution of roots in the entire filter bed is important, whereas for VFBs only the uniform distribution of roots in the *upper* layer (the first 10 cm) is essential.
The characteristics of plants such as papyrus or bamboo, which are adapted to growth conditions in temporarily submerged natural wetlands, are probably similar. In the case of bamboo, its roots may however reach too far down and therefore destroy the liner at the base of the constructed wetland. In summary, the effects of plants which contribute to the treatment processes in subsurface flow CWs include:
· The root system maintains the hydraulic conductivity of the coarse sand substrate.
· The plants facilitate the growth of bacteria colonies and other microorganism which form a biofilm attached to the surface of roots and substrate particles.
· The plants transport oxygen to the root zone to allow the roots to survive in anaerobic conditions. Part of this oxygen is available for microbial processes, although the exact contribution is still a point of discussion.

Figure 10. Root and rhizome system of reed (*Phragmites australis*) (left picture) and (arundo donax) (right picture) (photos by M. Blumberg, 1995).

IV. Costs

The basic investment costs for constructed wetlands include land, site investigation, system design, earthwork, liners, filtration (HF and VF CWs) or rooting (FWS CWs) media, vegetation, hydraulic control structures and miscellaneous costs (e.g., fencing, access roads) [31]. However, the proportions of individual costs vary widely in different parts of the world. Also, larger systems demonstrate greater economies for scale [31]. For example, Vymazal and Kröpfelová [1] summarized available data from HF CWs in U.S., Czech Republic, Portugal, Spain and Portugal and found out that excavation costs varied between 7 and 27.4% of the total capital cost, while gravel varied between 27 and 53%, liner (13–33%), plants (2–12%), plumbing (6–12%), control structures (3.1–5.7%) and miscellaneous (1.8–12%). The total investment costs vary even more, and the cost could be as low as 29 USD per m2 in India [66] or 33 USD per m2 in Costa Rica [67], or as high as 257 EUR per m2 in Belgium [68].

In general, the capital costs for subsurface flow constructed wetlands are about the same as for conventional treatment systems. The capital costs for FWS CWs are usually less than for subsurface flow systems mainly because the cost for media is limited to rooting soil on the bottom of the beds.

Constructed wetlands have very low operation and maintenance costs, including pumping energy (if necessary), compliance monitoring, maintenance of access roads and berms, pretreatment maintenance (including regular cleaning of screens and emptying septic or Imhoff tank and grit chambers), vegetation harvesting (if applicable) and equipment replacement and repairs. The basic costs are much lower than those for competing concrete and steel technologies, by a factor of2–10 [1,2]. In addition, because wetlands have a higher rate of biological activity than most ecosystems, they can transform many of the common pollutants that occur in conventional wastewaters into harmless byproducts or essential nutrients that can be used for additional biological productivity.

These transformations are accomplished by virtue of the wetland´s land area, with the inherent natural environmental energies of sun, wind, soil, plants, and animals. Because of the natural environmental energies at work in constructed treatment wetlands, minimal fossil fuel energy and chemicals are typically needed to meet treatment objectives [2].

Constructed wetlands in Yemen

In Yemen, although the lack of awareness of CW technology and uses locally available materials, there are an interest in this technology has been growing and only have been for municipal wastewater.

Challenges

The experience with constructed wetlands over the last decade has clearly shown that this simple and cost-effective system can be used to treat various types of wastewater ranging from grey water to leachate and septage. However, in spite of the enormous potential for the use of CW for wastewater treatment, there are some challenges in the promotion of this technology in yemen, which are as follows:

1- Due to the lack of awareness of CW technology, it is often difficult to convince people that it will work

2- Although the cost of the technology is relatively low, it is still difficult to convince people to invest in a treatment plant instead of just discharging effluent into the sea or wadi.

3- Although CW technology uses locally available materials, in some places specified types of sand and gravel or reeds may not be readily available

4- This is a low maintenance system, but people often think it is a no maintenance system. This sometimes leads to carelessness in taking care of simple operation and maintenance requirements such as checking for blockage in the pipes, harvesting the plants etc.

5- Wastewater treatment is not a priority for city governments, private industrialists or institutions, due to the lack of strong legislation and standards.

V. Conclusions and Recommendation

Constructed treatment wetlands have evolved during the last five decades into a reliable treatment technology which can be applied to all types of wastewaters including sewage, industrial and agricultural wastewaters, landfill leachate and stormwater runoff. Pollution is removed through the processes which are common in natural wetlands but, in constructed wetlands, these processes proceed under more controlled conditions. All types of constructed wetlands are very effective in removing organics and suspended solids, whereas removal of nitrogen is lower but could be enhanced by using a combination of various types of CWs. Removal of phosphorus is usually low unless special media with high sorption capacity are used. Constructed wetlands require very low or zero energy input and, therefore, the operation and maintenance costs are much lower compared to conventional treatment systems. In addition to treatment, constructed wetlands are often designed as dual- or multipurpose ecosystems which may provide other ecosystems services such as flood control, carbon sequestration or wildlife habitat.

It would recommend that we need more interesting in CWs for wastewater treatment for various applications such as the treatment of hospital wastewater, grey water, septage, landfill leachate, that give more removed of pollutants of nutrients from the wastewater.

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