Constructed wetlands for wastewater treatment

Constructed wetlands for wastewater treatment

Characteristics and yield efficiency

A main part of the pollutants contained in wastewater are nutrients that can be removed in wastewater treatment plants by reproducing natural self purification processes. Conventional treatment plants like activated sludge plants enforce biological organisms with energy-intensive mechanical equipment to decompose complex compounds, to incorporate the nutrients in biomass and finally to separate that biomass from the purified water. Thus such plants are energy intensive reactors with relatively small area demand that are suitable for centralized wastewater treatment.

Constructed wetlands are principally using the same natural degradation processes and nutrient uptake but they are acting as "extensive systems". The high degree of biodiversity present in these systems allows multiple and various degradation pathways for several classes of compounds, and therefore higher performances in comparison with the technological treatment plants in which only few families of specialized bacteria are grown. There is no excess sludge to be removed since there is a balance of biomass growth and decomposition in the constructed wetland system. As compensation to the low energy demand there is a relatively large area demand. Accordingly constructed wetlands are usually suitable and cost effective for small and medium size wastewater treatment plants.

Figure 1: Fischerhof constructed wetland for 160 pe, Sirnitz/Austria

Constructed wetlands for wastewater treatment

Within the last 20–30 years various types of constructed wetlands have been developed in several countries. There is a wide acceptance and interest within the population because of the following advantages:

- Simple construction, operation and maintenance
- Low operation and maintenance costs
- High ability to tolerate fluctuations in flow
- High process stability
- Sludge only from primary treatment
- High pathogen removal – good water reuse and recycling options
- Aesthetic appearance
- Creating biotopes

The usual applications of constructed wetlands are:

- Domestic wastewater: Treatment of domestic wastewater (blackwater and greywater) meanwhile is a conventional application.
- Industrial wastewater: There are numerous possibilities also for industrial wastewater like chemical industry, laboratory effluents, landfills, acid mines and agricultural wastewaters, e. g. from wineries, olive oil mills, dairies …
- Sludge drying: Special reed beds can be used to dewater and stabilize excess sludge from technical plants and sludge from primary pretreatments
- Furthermore highway runoff, polluted groundwater, surface water and storm water can be treated in constructed wetlands

Figure 2: Constructed wetland of a vinery, Italy

Constructed wetlands for wastewater treatment

Classified within treatment process constructed wetlands are usually applied as secondary treatment for mechanically pretreated wastewater. They can also be used as tertiary treatment; in this case they will work for upgrading conventional biological treatment plants. Constructed wetlands can be classified according the life form of the macrophytes (plants) in the system:

1. Floating macrophyte-based system
2. Submerged macrophyte-based system
3. Rooted emergent macrophyte-based system

Following only type 3 is described with more detail because it is the most common used in Europe and in the world. It can be categorized according to the flow pattern:

Subsurface flow

a) Systems with horizontal subsurface flow (HF)

This type of RBTS consists in a properly designed water proof basin that contains a filter material, wetland plants (normally reeds) and microorganisms. The bed is fed with wastewater coming from a suitable primary treatment by a simple inlet device. The filling material (coarse gravel, fine gravel and coarse sand) has to offer an appropriate hydraulic conductivity but also a large surface for the biofilm growing.
The water level remains always under the surface of the bed; the wastewater flows horizontally by a slope (about 1 %) which is obtained by a sand layer under the membrane liner.

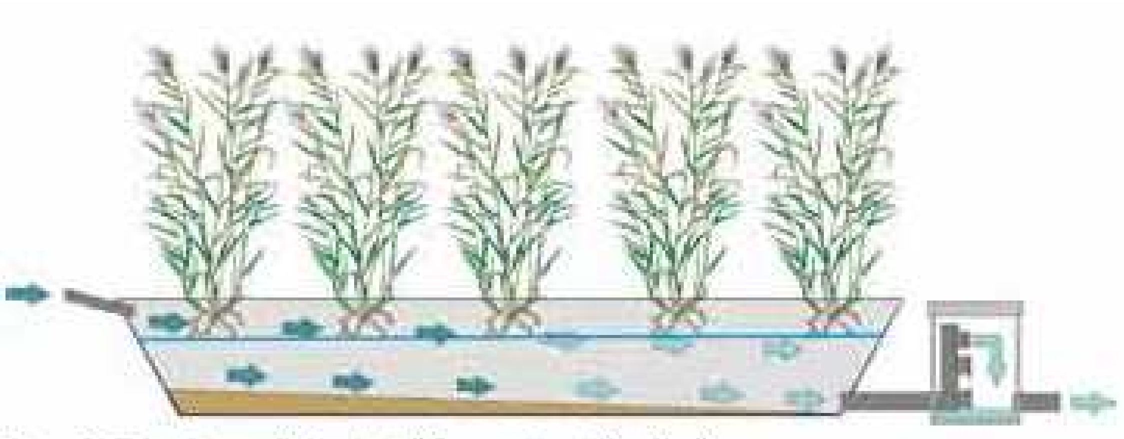

Figure 3: Flow scheme of a horizontal flow constructed wetland

The subsurface flow prevents odors and mosquitoes and permits public access in the wetland area. This kind of CW is particularly efficient in suspended solids, carbon and pathogens removal, as well as for denitrification, while, due to its prevalently anoxic conditions, nitrification is limited.

b) Systems with vertical subsurface flow (VF)

In the vertical flow systems (VF) the wastewater is applied through a distribution system on the whole surface area and passes the filter in a more or less vertical path. The pre-treated wastewater is dosed on the bed in large batches (intermittent feeding), thus flooding the surface. During the time between the feedings the pores within the filter media can fill up with air which is trapped by the next dose of liquid. Thus oxygen requiring nitrifying bacteria are favored and full nitrification can be achieved, but only a small part of the formed nitrate is denitrified under aerobic conditions. The denitrification and thus total nitrogen elimination can be increased by a partial recirculation of the nitrified effluent into the first chamber of the septic tank. The treated water is collected in a bottom drainage system to be discharged.

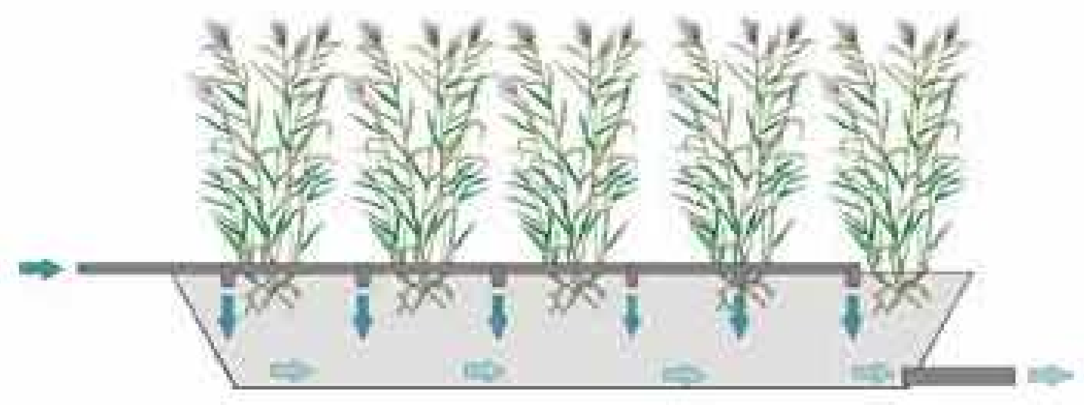

Figure 4: Scheme of vertical flow constructed wetland

The water level can be maintained with a height of about 5–10 cm from the bottom of the bed, or otherwise the beds can be totally empty after each feeding pulse. This kind of CW is particularly efficient in nitrification, carbon and suspended solids removal. Due to its prevalently aerobic conditions denitrification is poor.

Free water surface

c) Systems with free water surface (FWS)

Surface flow wetlands are densely vegetated basins optionally including open water areas. They need some sort of subsurface barrier to prevent seepage and soil or another suitable medium to support the emergent vegetation. The water flows through the unit at a relatively shallow depth. Particulates tend to settle and to be trapped in the system; in such a way they enter into the biogeochemical element cycles within the water column and surface soils of the wetland. At the same time dissolved elements enter the overall mineral cycles of the wetland system. This kind of constructed wetlands is particularly efficient in the pathogens removal, due to the high exposure of the wastewater to the UV component of the sunlight. For that reason, and also for a good denitrification power, these systems are often used as tertiary treatment (polishing stage).

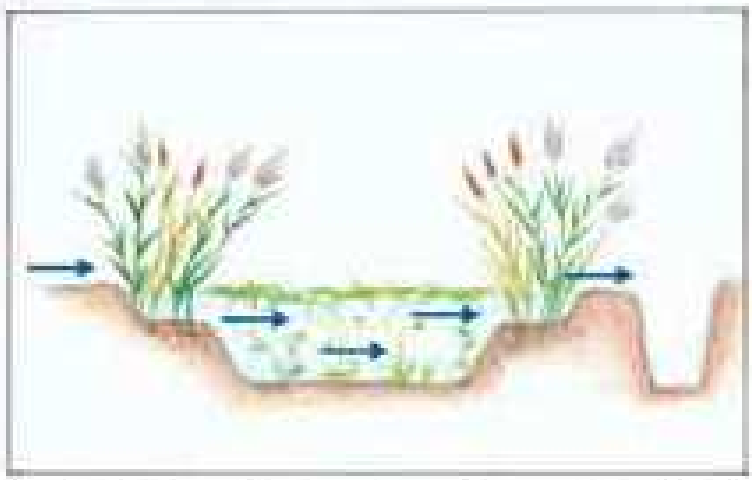

Figure 5: Scheme of a free water surface constructed wetland

Wastewater ponds without vegetation that are used as primary and/or partly secondary treatment are not described in this chapter but in pretreatment systems.

hybrid systems

Combinations of a,b,c: Using the different properties and abilities of the above mentioned three types a wastewater treatment plant can be assembled out of the different types.

Design and layout recommendations/devices available

Pretreatment

A good mechanical pretreatment of the wastewater is an important precondition for the functioning of all subsurface flow systems. Especially in VF filters filled with fine sand the entry of high amounts of solids might cause the clogging of the filter. As exception the special "French type" of VF is designed to work without separate pretreatment [Molle, 2004]. This system is described more detailed in chapter 2.9.2. Apart from the below described pretreatment systems, grids or degreasers have to be installed if necessary.

Three chamber septic tanks
Three chamber septic tanks are particularly suitable for small-medium tourist facilities as agro tourism, hotels, camping and villages. Their functionality is also guaranteed in case of floating hydraulic load or seasonal use. In the three chamber septic tank a fall-out of the sedimentable solids contained in the wastewater (primary sedimentation) takes place. The three chambers of the septic tank are hydraulically connected in series. The minimum design requirements are described in the national guidelines for constructed wetlands.
Emscher Brunnen/Immhoff tanks The Emscher Brunnen or Immhof tank consists of two separate compartments, a first sedimentation compartment and second a digestion compartment, where anaerobic fermentation and stabilization takes place. The sedimentable solids are captured in the first chamber of the septic tank and then fall down through the slots that are connecting the second chamber, where the organic substances are subject to anaerobic fermentation and stabilization processes.

Wastewater ponds
Ponds are used as a pretreatment before vertical constructed wetlands especially at bigger constructed wetlands (up to 4,000 pe) in Germany. The size of wastewater ponds for pretreatment ranges from 1.5 to 4 m^2 per pe A partly reduction of COD, BOD_5 and a very effective reduction of settleable (SS) and suspended solids (TSS) <100 mg/l can be achieved. Floating macrophytes, like Lemna, can be used in order to reduce odor and isolate the wastewater from the surrounding. The usage of large volume primary treatment can also provide a better quality of the secondary treatment influent, especially if it consists in VF reed beds

Sealing of the filter beds

Bottom and sidewalls of the filter bed have to be waterproof, if a contamination of the groundwater can be expected. In the case of sealing with natural soil a Kf <10-7 m/sec is required and a minimum thickness of 30 cm should be given.
Artificial sealing with impermeable layer: The material should be acid-resistant and alkali proof, frost-resistant, roots and rodent resistant, non toxic, easy to carry and move, made of recyclable materials (preferred material: HDPE or LDPE).

Construction and sizing of the filter

In several European countries national guidelines for constructed wetlands have been established that differ from each other in their sizing and construction recommendations.
They are derived from the experiences with different construction practices, different materials used and different purification requirements prescribed.
The examples in table 1 and 2 show the variety of possible construction ways. Constructed wetlands are not yet a wide spread way for waste water treatment, but they are a prospering technique. In some countries the official guidelines do not necessarily represent the state of the art.

Experts specialized on constructed wetlands can choose the appropriate system according to the needs of the user, the treatment requirements prescribed by the water authorities and the local circumstances, like the special aspects at tourism facilities.
An important fact for tourism facilities is how to deal with seasonal, weekly or other fluctuations in wastewater flow which is typical in hotels, restaurants, holiday apartments, camping sites and others. They should be measured or estimated as precise as possibly before planning the system (see also chapter 1.1). The size (and costs) of the filters also can be reduced by implementing a buffer tank before or after the pre treatment. Constructed wetlands usually are dealing very well with fluctuations of wastewater quantity. They can also be rested for a period and "switched on" again without loosing purification efficiency.

Horizontal flow filter

The sizing procedure can be performed using the scientifically approved methods, like the various first order kinetic equations [Kadlec et al., 2000] for the pollutants removal and the Darcy law for the hydraulic aspects.
As alternative and simpler way it is possible to use guideline recommendations for the design (see table 1). They are based on area coefficients like "area per pe" or "area per gram of COD" (area loading rate, EPA manual).

Parameter	**Germany** ATV DVWK A 262 (draft 2004)	**Austria** ÖNORM B2505 (draft 2003)	**Great Britain** Cooper et al., 1996	**Denmark** Brix and Jo-hansen 2004	**France** Molle et al., 2004
Area (m²)/pe	5 min. 20 m²	5 (2) 2 (3)	5 (2) 0.5-1 (3)	5 min. 25 m²	5 (BOD 150√300 after a 1° septic tank or Imhoff tank) 2-3 (for BOD 100 mg/l, after vertical filters as1st stage)
Filling mate-rial Main layer	> 50 cm	> 50 cm sand: 0/4 (greywater) > 50 cm sand:1/4 (3°) >50 cm sand: 4/8 (2°)	gravel: 3/6 mm or 5/10 mm or 6/12 mm	0.3 mm<d_{10}<2 mm 0.5mm<d_{60}<8 mm	Pea gravel: 4/8 1/4 in second stage vertical filters
Permeability of the main layer K_f (m/s) $U=d_{60}/d_{10}$	10^{-4}-10^{-3} < 5	≈ 0^{-4}	≈ 0^{-3}	$1*10^{-3}$ <4	≈ $1x0^{-3}$ – $3x10^{-3}$ in operation: $3x0^{-3}$ – $5x10^{-3}$
Hydraulic surface load	40 mm/d	50 mm/d	< 50 mm/d (2) < 200 mm/d (3)	–	–
Organic load	–	112 kg/ha*d		–	–
depth	0.5 m	–	0.6 m	0.6 m	0.6 m

Table 1: Examples for the design of horizontal flow systems
(2) = secondary treatment; (3) = tertiary treatment

Vertical flow filter

The sizing procedure for VF beds is mainly based on the nitrification process; in fact, when the treatment goals required for ammonium concentration are fulfilled, all the other parameters are satisfactory eliminated too. A common practice for dimensioning VF reed beds is to calculate an area coefficient per person equivalent like described in several national guidelines.

Parameter	**Germany** ATV DVWK A 262 (draft 2004)	**Austria** ÖNORM B2505 (draft 2003)	**Great Britain** Cooper et al., 1996	**Denmark** Brix and Johansen 2004	**France** Molle et al., 2004
Area m²/pe	4 min. 16 m²	4 (2) 1 (3)	(2): 1 (BOD_5), 2 (BOD_5+N) < 100 pe: 1st 3,5 x $pe^{0.35}$ + 0.6 pe 2nd 50% of the 1st	3.2 m²/pe min. 16 m²	1st 1,2 (3 x 0,4) 2nd 0,8 (2 x 0,4)
Filling material (from top to bottom) Main layer drainage	> 50 cm sand 20 cm gravel 2/8 mm	10 cm gravel 8/16 mm > 50 cm sand 0/4 20 cm gravel 16/32	8 cm sand 15 cm gravel 6 mm 10 cm gravel 12 mm 15 cm gravel 3/6 cm	15 cm woodchips or seashells 90 cm sand 15 cm gravel	1st: > 30cm 2/8 mm 10–20 cm 5/20 mm 10–20 cm 20/40 mm 2nd: >30 cm 10–20 cm 3/10 mm 10–20 cm 20/40 mm
Permeability of the main layer K_f (m/s) $U=d_{60}/d_{10}$	10^{-3}–10^{-4} U < 5	≈10^{-4}	–	d_{10} 0,25– 1,2 mm d_{60} 1-4 mm U < 3,5	1st: clean surface media ≈ 5,0 x 10^{-4} with organic deposits ≈ 0,2 x 10^{-4} 2nd: upper layer 0,25 mm < d_{10} < 0,4 mm
Hydraulic surface load mm/d	80	–	70–80	100	400 mm on the filter in operation(dry weather flow)

Parameter	Germany ATV DVWK A 262 (draft 2004)	Austria ÖNORM B2505 (draft 2003)	Great Britain Cooper et al., 1996	Denmark Brix and Johansen 2004	France Molle et al., 2004
Organic load (g/m²*d)	COD < 20	–	BOD_5 20-25	–	1st up to 40 g BOD_5BOD_5
Depth	0.8 m	0.5–0.8 m	1 m	> 1 m	0.6–0.8 m

Table 2: Examples for the design of vertical flow systems
(2) = secondary treatment; (3) = tertiary treatment
1st = first stage 2nd = second stage

Another approach for the sizing is to calculate the necessary area demand by verifying the oxygen availability within the filter with respect to the oxygen demand [Platzer, 1998].
With respect to clogging prevention one attempt is to define maximum organic and hydraulic loads. A German investigation [Umweltbundesamt, 2003] led to the recommendation of a maximum TSS concentration of 100 mg/l or a TSS loading rate less than 5 g/m2 d to prevent clogging.
The main filter layer consists of washed sand of selected size. The drainage can be achieved either with drainage pipes and/or with coarse gravel. In cold climate a shallow gravel cover upon the main sand layer is recommended.
In Norway the vertical beds are worked out as so called "Pre-Filters" which are covered to keep the temperature [Vatmarksfiltre, 2001]. The French VF construction [Molle, 2004] is working without special pretreatment. In the UK the vertical reed beds are assembled in series (multistage) and the beds consist of several layers of filter substrates (multilayer).
Intermittent feeding system Through intermittent feeding the pre-treated wastewater can be charged to the filter area in intervals. The wastewater is distributed on the whole surface by perforated pipes. Depending on the terrain different options are given: the presence of a difference in height between the pre treated wastewater and the vertical filter bed allows the utilization of mechanical devices without using electric, fossil or solar energy. The intermittent feeding device could be switched either quantity or time related, or both. Usually a quantity related feeding is applied.
Different mechanical systems have been developed like valves, siphons or tipping buckets. Alternatively electric systems like pumps and electric slides can be used.

Distribution system
An even distribution of the wastewater on the whole surface has to be achieved. It is dependant on the cross section of the pipes, the distance of pipes, the distance of holes and the feeding quantity per interval. The feeding system should be situated above the surface to be accessible for maintenance works.

Free water surface system (FWS)
In order to improve the denitrification and disinfection processes it is recommended to insert deep water zones in the inlet (denitrification, settling) and shallow water zones close to the outlet (UV activity). Denitrification is taking place especially during summer season when biomass production through algae provides the necessary carbon. One or more gravel barriers near the outlet can prevent presence of algae in the outlet. Due to the different depth zones in such systems a rich and natural-like ecosystem can be easily obtained.
Investigations about pathogen removal in free water systems showed, that the total elimination increases when the whole area is divided into several single units instead of one.

Vegetation
The filter beds are usually planted with the same types of emergent macrophytes as present in the natural wetlands. Most common is 'Phragmites australis' (reed) but also 'Typha ssp.' (cattail) and 'Scirpus ssp.' (bulrush) can be used.

Operation requirements

Pretreatment

The sludge of the pretreatment has to be emptied in time in order to prevent sludge drift into the reed beds. The emptying intervals depend on the size of the pretreatment system and vary between one year and several years. The sludge can be stabilized in a separate sludge drying reed bed on the spot. Alternatively it can be transported to a central sewer plant for further treatment.

Horizontal flow filter
Operation and maintenance routine for the HF Systems is easy to do and requires no specialized personnel (in most cases there are no electro-mechanical units).
The main periodic checks are listed below:
• Wetland vegetation uniform diffusion
• Presence of weeds
• Presence of vegetal diseases or damages by insects or animals.
The plants density must be kept over 10 plants per square meter; otherwise it is necessary to plant new reeds.

Vegetation management: the first action is to cut the reeds mechanically or manually 3 years after the plant started. The reeds debris must be subsequently removed from the bed. Further vegetation cuttings will be performed every 2 years.
The inlet pipe and the first meters of the filling medium should be checked every 6 months, to verify if clogging by sedimentation of the suspended solids and biomass growing on medium surface has occurred.

Vertical flow filter
During the first year attention should be paid to the growing of the plants. Weeds should be removed until the reed is established. The following parts should be controlled in regular intervals:
• functioning of the mechanic devices especially the intermittent feeding device
• even distribution of wastewater on the filter area
• water level in the filter bed
• cutting of the plants is not necessary each year and depends on the climatic conditions. Every second or third year is reasonable in alpine climate, preferably in spring.

Free water system
The inlet settling zone has to be emptied whenever necessary. Bank vegetation maintenance is required with frequency depending on the used plants.

System costs

Costs are varying in the different countries. Since the technique is quite simple it is possible to reduce building expenses (cost of labour) considerably by involving the owner in the construction process.

	Vertical filter			Horizontal filter		
Area [m²]	50–500	500–1,000	1,000–10,000	50–500	500–1,000	1,000–10,000
Austria	120–75	–	–	–	–	–
Germany	125–110	110–90	90–75	140–105	105–70	
Italy	145	120	105	130	110	100
Latvia	150–80	–	–	–	30	–
Lithuania	110–80	–	–	–	–	–

Table 3: Costs for vertical and horizontal flow filters, €/m² including distribution, sealing, control shaft and pipes to the pretreatment

Trouble shooting

Reasons for malfunctioning and the adequate trouble shooting can be:

Horizontal filter

- Superficial runoff, overload: Enlarge filter area or reduce hydraulic load
- Sludge drift from the pretreatment system: Empty pretreatment or reconstruct pretreatment
- Clogged inlet pipes: clean pipe system Consecutively the inlet coarse rock has to be removed and washed for the first 30 centimeters.
- Plant disease: If vegetal diseases or damages by insect or animals have happened, an intervention of specialized personnel is required to achieve the right solutions.
- Presence of weeds: remove them manually or by controlled flooding of the bed

Vertical filter

Apart from to the above mentioned points in VF systems the following troubles might occur:

- Displacement of distribution system upon the filter area: Adjust distribution system
- Uneven building of the sand layer: adjust sand layer
- Clogged distribution system: clean pipe system

In the case of long term these malfunctions might lead to soil clogging. After the repairing a complete restoration of the filtration capacity is possible giving a resting period of few weeks. If a resting period is not possible the filter will also recover after the clogging layer is opened and the reasons for clogging are restored.