Lesson B4

Constructed Wetlands for Wastewater Treatment

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Constructed wetlands, planted soil filter, reed beds

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Overview and summary of this lesson

Constructed wetlands are one of the most promising treatment options for municipal wastewater with respect to the decentralised settlements, especially in rural and suburban areas, because they are low in cost and maintenance requirements with a good performance. They need more land compared to technical intensive treatment but less space than pond systems.

Constructed wetlands can be installed as two different technological systems according to its hydraulic regime: the free water surface (FWS) and subsurface-flow constructed wetlands, in which the latter can be further categorized to horizontal and vertical subsurface-flow (HSF and VSF). The FWS system in one sense is similar to a pond system incorporating with the emergent macrophytes. For SF system, the water is maintained below the surface of the wetland bodies, usually made up of gravel planted with the emergent macrophytes. In HSF, the flow is usually continuous thereby creating a saturated condition within the wetland body, whereas in VSF, the media is completely unsaturated due to intermittent feeding.

This lesson discusses the capabilities and limits between these constructed wetland systems and the management requirements to achieve the designed purpose. Design and proper operation are explained for some applications. Some future trends with focus on maximization of efficiency, cost minimisation, ecological sanitation and water reuse are presented as well.

1. Introduction

1.1 Terminology

Constructed wetlands are artificial wastewater treatment systems consisting of shallow ponds or channels which have been planted with aquatic plants and which rely upon natural microbial, biological, physical and chemical processes to treat wastewater. They have impervious clay or synthetic liners and engineered structures to control the flow direction, liquid detention time and water level. Depending on the type of system, they contain an inert porous media such as rock, gravel or sand [US EPA 2000].

Historically, constructed wetlands were already used since centuries to treat a variety of wastewaters such as municipal wastewater, urban runoff, agricultural drainage, etc. However, this lesson focuses mainly on the treatment of municipal wastewater or its separated flows such as greywater. The constructed wetlands according to this application are considered as a mayor treatment step, which usually need a pre-treatment and, depending on the reuse purpose, a post treatment.

This system can be divided into two types, on the one hand is free-water surface type (FWS) in which the water level is over the surface, and on the other hand is subsurface type (SF), in which the water level is maintained below the surface. The latter one can be further categorized into two types based on the pattern of flow, one with horizontal subsurface (HSF) and one with vertical subsurface flow (VSF) (Crites, et. al., 2000). The SF type can also be called “reed bed”. The illustration of each system can be seen in the figure below.

The free water surface constructed wetlands (FWS) closely resemble natural wetlands because they look like ponds containing aquatic plants that are rooted in the soil layer on the bottom. The water flows through the leaves and stems of the plants. Their design and operation is very close to pond systems.

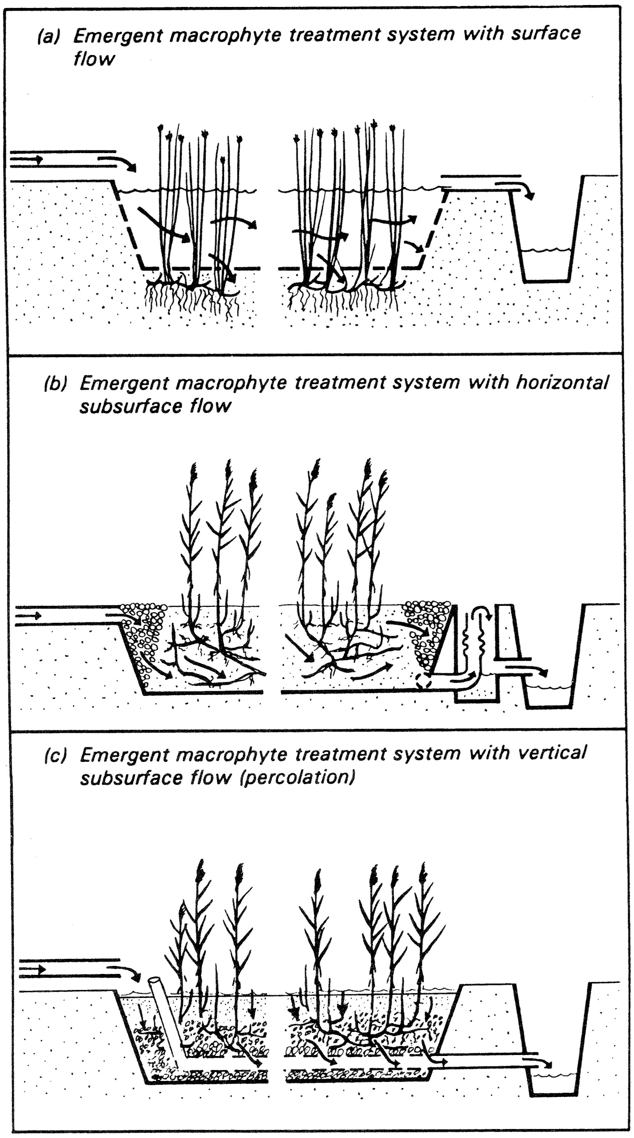


Figure 1: Schematic presenting each type of constructed wetlands which A: FWS, B: HSF, and C: VSF (Brix, 1993)

The focus of this lesson is based on the constructed wetlands with subsurface flow. This is due to several researches indicating that the pollutant removal efficiency is better than in FWS per unit of land, implying the area requirement is lower. These systems also pose no problem of mosquito or other insects breeding as well as the human, probably children, exposure to surface wastewater. Some disadvantages of this type are higher cost and have lower ecological value comparing to the FWS wetlands, which are of minor concerns.

The HSF and VSF systems do not resemble natural wetlands because they have no surface flow of water. They contain a bed of media which is typically gravel and sand, but also soil or crushed rocks can be also used. Within the media, emergent macrophytes are planted and the water is introduced beneath the surface of the media and is flowing through the roots and rhizomes of the plants. Conventionally, the flow in HSF systems is continuous, hence it creates a “saturated” condition within the wetland body whereas the flow in VSF systems is commonly intermittent, which results in an “unsaturated” and thus aerobic condition. Figure 2 depicts the photo of one VSF system in Hannover, Germany.

Figure 2: Unsaturated vertical flow constructed wetlands in Hannover, Germany

It should be noted that FWS and SF constructed wetlands work differently because the latter system does not support any aquatic wildlife. Some biological and chemical interactions only occur in an open water column and thus these will happen only in a FWS system. Moreover, constructed wetlands should not be mixed with created or restored wetlands which are not designed for wastewater treatment but have the function of wildlife habitat.

1.2 Application and Importance of Constructed Wetlands

Constructed wetlands are an appropriate technology for small communities in rural and suburban areas. Many rural projects with activated sludge plants failed because it was not properly operated, often no skilled stuff is available or the energy costs is no longer affordable. Constructed wetlands are principally using the same natural degradation processes and nutrient uptake but they are acting as extensive systems. There is wide acceptance and interest because of the following advantages (SWAMP 2002):

- Simple in construction, operation and maintenance
- Low operation and maintenance costs (low energy demand)
- High ability to tolerate fluctuations in flow
- High process stability
- Aesthetic appearance

Constructed wetlands are used in various fields and at various treatment levels. Nevertheless, this lesson deals mainly with the conventional use of constructed wetlands, which are to treat the pre-treated municipal wastewater, or so-called primary effluent. The typical treatment cycle is shown in Figure 3.

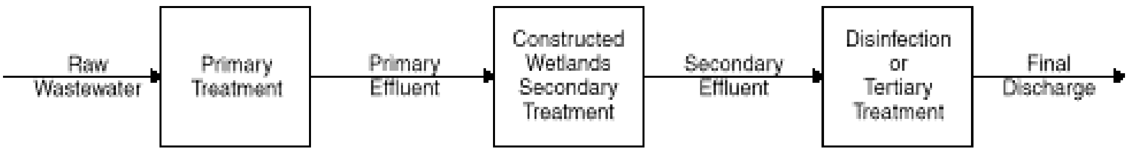


Figure 3: Constructed wetlands in the treatment cycle

In general, primary effluent constitutes of these characteristics; data shown in mg/l (adapted from Metcalf & Eddy, 2003)

BOD	COD	TSS	VSS	TN	TP
40-200	90-400	55-230	45-180	20-85	4-15

Constructed wetlands may also be applied for primary or tertiary treatment but these cases will only be mentioned in the last chapter of this lesson.

Constructed wetlands may need a post treatment particularly to completely remove nitrogen (nitrification and denitrification) and phosphorus, if the removal of both parameters is required in this region. Its capability to remove N and P has often been overestimated. Both aerobic and anoxic zones are necessary to perform complete nitrification and the subsequent denitrification. To remove significantly phosphorus the constructed wetlands must be enhanced by an accompanying P removal step, e.g. pre-precipitation in the pre-treatment unit. Recently, there are several researches running concerning the use of the constructed wetland with special P-absorbing capacity materials instead of normal gravel and sand as a substrate.

2. Understanding Constructed Wetlands

2.1 Removal Mechanisms

Treatment processes in wetland incorporate with several physical, chemical, and biological processes. The major physical process is the settling of suspended particulate matter which is a major cause of BOD reduction. The chemical processes involve adsorption, chelation, and precipitation, which are responsible for the major removal of phosphorus and heavy metals. In term of biological processes, the treatment is achieved by microorganisms (Gopal, 1999). Due to fixed film or free bacterial development, biological processes allow the degradation of organic matter, nitrification in aerobic zones and denitrification in anaerobic zones. The **microbiological activity** is the key parameter for their performance. The principle removal mechanisms in subsurface flow constructed wetlands for some constituents in wastewater are summarized in table 1.

Table 1: Principle removal and transformation mechanisms in subsurface flow constructed wetlands for the concerned constituents in wastewater (modified after Crites and Tchobanoglous, 1998)

Constituent	Mechanisms
Biodegradable organics	Bioconversion by facultative and anaerobic bacteria on plant and debris surfaces
Suspended solids	Filtration, sedimentation
Nitrogen	Nitrification/denitrification, plant uptake, volatilization
Phosphorus	Filtration, sedimentation, plant uptake
Heavy metals	Adsorption of plant roots and debris surfaces, sedimentation
Trace organics	Adsorption, biodegradation
Pathogens	Natural decay, physical entrapment, filtration, predation, sedimentation, excretion of antibiotics from roots of plants

For the role of plants in constructed wetland, they contribute to nutrient transformation, offer mechanical resistance to flow, increase the retention time, facilitate settling of suspended particulates, and improve conductance of water through the media as the roots grow. Particularly, the rhizomes of the reeds grow vertically and horizontally, opening up the soil to provide a hydraulic pathway through the media. Furthermore, they transport oxygen to the deeper layer of the media via the leaves and stems of the reeds down through the hollow rhizomes and out through the roots and hence help in oxidation and precipitation of heavy metals on the root surfaces (Gopal, 1999).

However, Hiley and Hadjichristova (1998) stated that it is still debated whether the plants contribute any oxygen or not. In order to maximize the benefit in SF wetland, the full depth of the media should be compatible with the full plant root penetration so that potential contact points could be available throughout the profile (Reed et. al., 1995). The most frequently used plants species are *Scirpus* sp. (bulrush), *Typha* sp. (cattail), and *Pragmites communis* (reeds). Their typical characteristics are described below (Crites and Tchobanoglous (1998) and Reed et. al. (1995)).

Table 2: Typical characteristics of some plant species used in constructed wetland

Characteristics	Bulrush	Cattail	Reeds
Distribution	Worldwide	Worldwide	Worldwide
Temperature, °C	16-27	10-30	12-23
pH range	4-9	4-10	2-8
Maximum salinity tolerance, ppt	20	30	45
Root penetration in gravel, m.	≈0.6	≈0.3	≈0.4
Habitat values	Seeds and rhizomes as a food source for several water birds, muskrat, nutria, and fish	Seeds and roots as a food source for water birds, muskrat, nutria, and beaver	Low food value for most birds and animals
Drought resistant	moderate	Possible	high
Growth	Moderate to rapid	Rapid	Very rapid

Note: ppt = parts per thousand

Plant uptake of nitrogen and phosphorus is not a significant removal effect because they are taken up and usually released during decay. While uptake rates are potentially high, harvesting plant biomass can remove nitrogen and phosphorus but no research shows a significant removal performance due to harvesting. Harvesting plants is anyhow limited to both HSF and VSF systems.

The detailed schematic of HSF constructed wetlands is shown in figure 4;

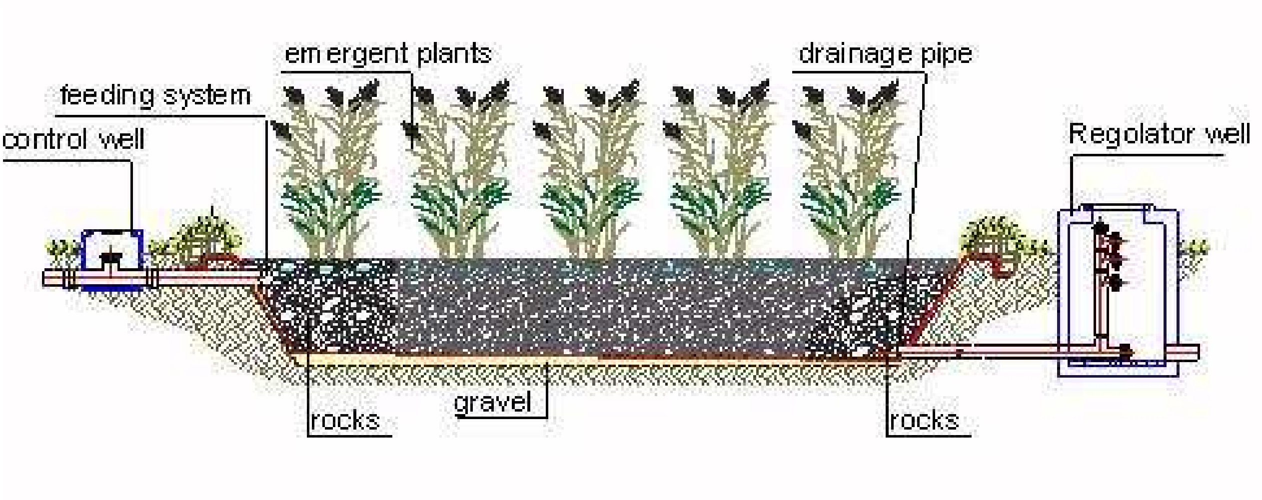


Figure 4: Detailed schematic of a horizontal flow system (HSF)

The VSF system illustrating more detail shown in figure 5 needs a well designed and constructed system to distribute the water equally over the whole area. The construction is therefore more expensive than for the horizontal flow systems. For VSF, **filtration** is also an important removal mechanism. The bed media must be carefully chosen according to the wastewater constitution.

The water level is always at the bottom. Its best performance can be achieved by intermittent feeding when aerobic and anoxic phases alternate. Due to the higher effort in designing and constructing the VF properly, the performance of these systems in term of COD and nitrification is much higher than in the other constructed wetland systems.

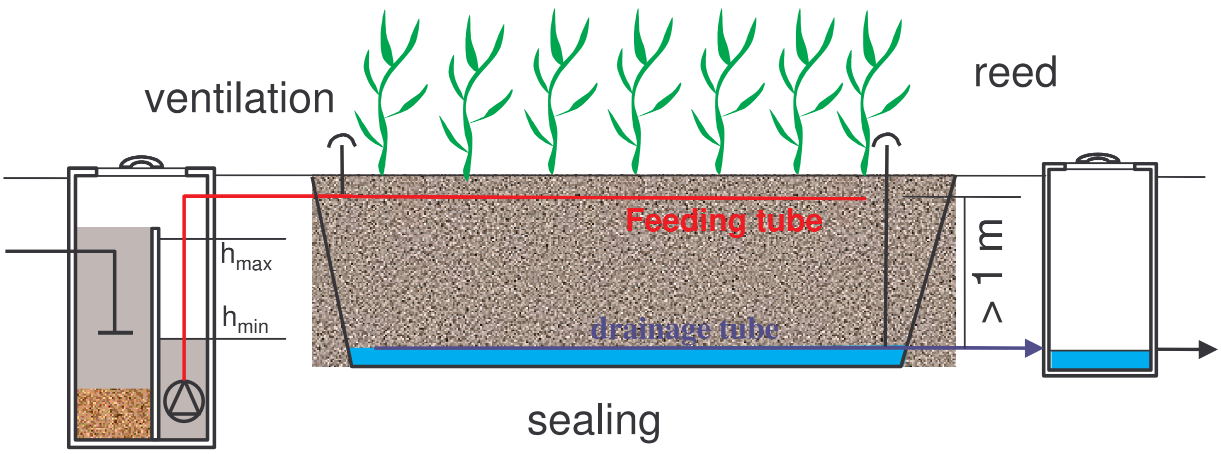


Figure 5: Detailed schematic of an unsaturated vertical flow system (VSF)

Waterborne pathogens including helminth, protozoa, bacteria and viruses are of great concern in assessing water quality. Pathogens in wastewater are usually associated with TSS and can be removed like TSS, mainly sedimentation. Thus removal of pathogens (measured by indicators) in wetlands appears to be correlated with TSS removal and hydraulic residence time (US EPA 2000). Analyses in constructed wetlands show a significant reduction of pathogens about two to three logs, which mean more than 99% removal which is significant but usually not sufficient to meet standards for water reuse.

2.2 Comparison tables among each type of CWs

The table below compares the effectiveness of each type of technology according to each environmental parameter.

Table 3: The effectiveness of each technology based on each parameter (European Commission, 2001)

Parameters	Organic matter (OM)	TKN	Total N	Total P	Microbial removal
Horizontal flow CW	Yes	Poor nitrification	Good denitrification	No	No
Vertical flow CW	Yes	Yes	No*	No	No
Free water surface CW	Average	Yes	Yes	Yes, the first years	yes

* In intermittent fed system a simultaneous N elimination takes place (see case study Lambertsmühle chapter 6.2).

3. Design and construction

3.1 Location

In general, wetland sites should be located outside of flood plains, or protection from flooding should be provided (Tchobanoglous and Burton 1991).

For reasons of possible odour nuisance, constructed wetlands should be placed in a reasonable distance to residential areas. The distance of 15-20 m to the nearest building is recommended. The constructed wetland should be secured against entry by unauthorised persons under local arrangements. They have to be marked clearly as wastewater treatment systems.

3.2 Primary treatment

A successful physical pre-treatment is necessary for a good performance of all constructed wetlands; exceptions are the FWS and see also Future Trends.

The influent has to free from coarse and floating material probably by screening them out. Unsatisfactory pre-treatment may lead to build-ups in the inflow area, to odour nuisances, to clogging of the filter or to blockages of the soakage links.

The pre-treatment can be realised as primary sedimentation in tanks, for small scale plants typically septic tanks are used. Imhoff tank is a possibility which reduces sludge production.

Ponds may be an option for pre-treatment, often used before a VSF system. The size of wastewater ponds for pre-treatment typically range from 1.5 – 4 m^2/PE. A partly reduction of COD, BOD and TSS < 100 mg/l can be achieved (SWAMP 2002).

3.3 Sealing

Constructed wetlands must be sealed at the bottom and sidewalls to avoid any groundwater pollution. As natural sealing there are different recommendations as shown in the following table:

Table 4: Recommendation for natural sealing of constructed wetlands

	SWAMP 2002	DWA 2004 Germany
Permeability coefficient k_f	< 10^{-7} m/s	< 10^{-8} m/s
Thickness of sealing	> 30 cm	> 60 cm

If natural soil is not available, an artificial layer with impermeable layer is required. The material should be acid resistant and alkali proof, frost and UV resistant, root and rodent resistant, non toxic, easy to carry and move and preferably made of recyclable materials (preferred HDPE or LDPE).

3.4 Construction and sizing of the bed

The design criteria for HSF constructed wetlands can be seen in the table below;

Table 5: Design criteria for horizontal flow submerged beds (HSF)

Criteria	Germany, DWA 2004	US EPA 2000	EC Guidelines CEMAGREF	United Kingdom, Cooper 1996
Surface area	5 m^2/pe minimum size 20 m^2		5 m^2/pe for BOD > 300 mg/l, otherwise 10 m^2/pe	5 m^2/pe** 0.5-1 m^2/pe***
Hydraulic surface load	40 mm/d			< 50 mm/d** < 200 mm/d***
Max organic load	*BOD: 8 g/(m^2*d)**	BOD: 6 g/(m^2*d)		
Depth	0.5 m			0.6 m

* calculated with 40 g BOD/(PE*d)
** for secondary treatment
*** for tertiary treatment

Apart from those specified in the presented guidelines, Rousseau et. al. (2004) performed a review concerning different design methods. In general, the rules of thumb suggested by several works can be served as a safe bed. However the investment costs tend to be higher due to conservative aspects of this approach.

For the vertical subsurface-flow type, the design criteria are shown below;

Table 6: Design criteria for vertical subsurface-flow constructed wetlands (VSF)

Criteria	**Germany, ATV 2004,**	**Lange & Otterpohl 1998**	**EC Guidelines CEMAGREF**	**United Kingdom, Cooper 1996**
Surface area	4 m^2/pe minimum size 16 m^2	1-2 m^2/pe for greywater	5 m^2/pe for BOD > 300 mg/l, otherwise 10 m^2/pe	5 m^2/pe** 0.5-1 m^2/pe***
Hydraulic surface load	80 mm/d			< 50 mm/d** < 200 mm/d***
Max organic load	COD: 20 g/(m^2*d)			
Depth	0.5 m			0.6 m

** for secondary treatment
*** for tertiary treatment

4. Operation and Maintenance

To ensure successful planting of constructed wetlands, there are several options available, namely seeds, pot grown plant, shoot with rhizomes/root or soil spread, which are suitable for all species (Nuttall et. al., 1997). Meanwhile, rhizomes option is suitable for *Phragmites, Typha,* and *Iris* spp whereas stem cuttings technique is suitable for *Phalaris* and *Glyceria* spp. Seeds can be relatively inexpensive to cover large areas but it is not suitable for the case of SSF constructed wetlands. In contrast, pot grown plants is considered to be more expensive but comes with several advantages, such as rapid tillering and cover, simple to plant, rapid development of dense cover if high planting density is applied, etc. Techniques accompanying with rhizomes are relatively inexpensive, but require higher horticulture skill and time consuming during preparation.

In order to ensure the successful operation, it is crucial to perform a monitoring of constructed wetland. At least influent and effluent quality, water levels, and microbial indicators have to be measured periodically.

Suggested monitoring parameters and frequencies are (Tchobanoglous, 1996)
Continuous; flow rate (in/out)

Weekly; Water Quality: DO, temp., BOD, COD, SS, particle size distribution, nutrients (in/out along CW) pH, conductivity (only in and out)
Monthly; Bacteria (in/out)

Quarterly; chlorophyll, metals, sediment characteristics (redox potential, salinity, pH, OM) (in/out along CW)
Annually; flow rate distribution (within CW), organics (in/out along CW)

Moreover, it may also be necessary to monitor any happening competition from weeds species by carefully monitoring and hand-weeding if such are presented. Insect and grazing damage can harmfully affect the emergent plants, which require some control measures such as fencing and some monitoring.

General management activities include regulating the water levels, reducing loadings for short- or long-term periods, harvesting of undesired plants species as well as subsequent replanting (Kadlec and Knight, 1996).

5. Future Trends

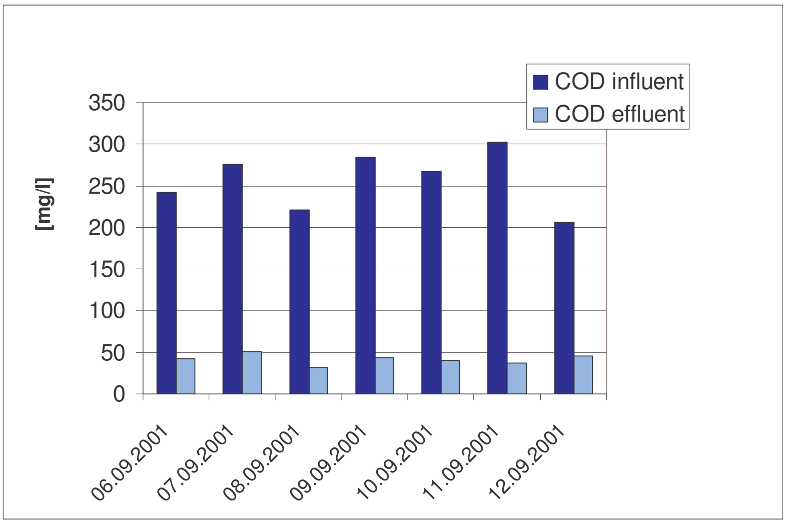
5.1 Hybrid system

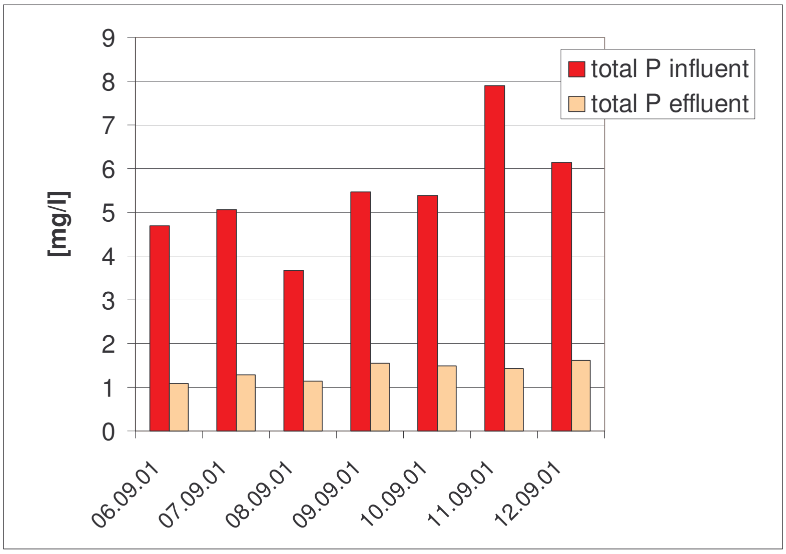
The system is proposed to compliment and overcome the drawback of each HSF and VSF technology. The idea is to put the VSF and HSF in series due to the fact that VSF is more effective in terms of low space requirement and nitrification, despite of poor denitrification due to its unsaturated nature and HSF is more effective in terms of bacteria removal and denitrification due to its saturated nature.
For more details concerning this kind of system please look in Cooper, 1999.

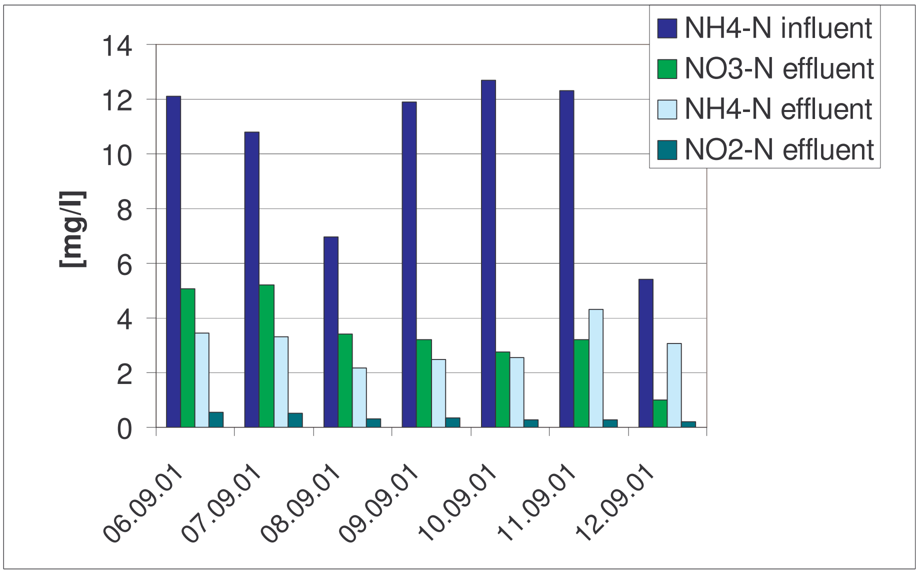
5.2 Greywater treatment

Lambertsmühle, Germany
In this pilot project, a source separation system of wastewater for a museum has been installed, see http://www.otterwasser.de/english/concepts/lande.htm.

In this case, greywater is separated from other wastewater streams and is treated with a vertical flow constructed wetland preceded by septic tanks. The required area is less than 2 m^2/PE. This system uses gravel as a substrate due to the idea that particle size should not be too fine in order to prevent clogging. After some month of start up (for biofilm growing and adopting) this system is very effective in reducing organic, nitrogen, and phosphorus. Performance of the system can be seen in the following diagrams:







Figures 6, 7 and 8: COD, N and P removal in the constructed wetlands Lambertsmühle

5.3 Constructed Wetlands without Sealing

The principal behind this concept is to combine the benefit of constructed wetland with another treatment technology so-called “groundwater percolation”. Generally, this system is applied as a polishing and reuse option so that parts of the pollutant will be treated during the infiltration and hence the groundwater will be recharged with treated and clean water. With this combination, the total land requirement for the overall treatment plant will be reduced as well as the polishing step can be integrated to the system without added cost and area.

5.4 Constructed Wetlands for raw wastewater

The French systems

In France, several VSF systems were adapted to treat raw wastewater by using gravel as a substrate. The system was developed by CEMAGREF (Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement) and promoted by SINT (La Société d’Ingénierie Nature et Techniques) company. The idea behind this system is that sludge management can be simpler comparing to the conventional imhoff or digesting tank (Molle et. al., 2005).

It is recommended to divide the system into 2 stages,
1st stage: 3 filters with >30 cm of fine gravel (2-8 mm) as a 1st layer substrate
2nd stage: 2 filters with >30 cm of ($0.25 < d_{10} < 0.4$ mm) sand as a 1st layer substrate

Both stages also constitute of transition layer (2nd layer, 10-20 cm) and drainage layer (10-20 cm). The feeding phase generally lasts for 3 to 4 days, after that it is needed to rest for twice this time in order to maintain “unsaturated” (aerobic) condition within the wetland bodies as well as to mineralise the organic accumulated due to suspended solid (SS). The plant uses special-designed siphon to maintain the hydraulic condition without an external energy source, provided the appropriate topography. In term of its performance, significant removal of COD, TSS and almost complete nitrification can be expected (Boutin et. al., 1997). The sludge withdrawal should be performed approximately once every 10-15 years, and this has no subsequent effect to the regrowth of reeds from the rhizomes. Schematic of the first stage CW can be seen below;

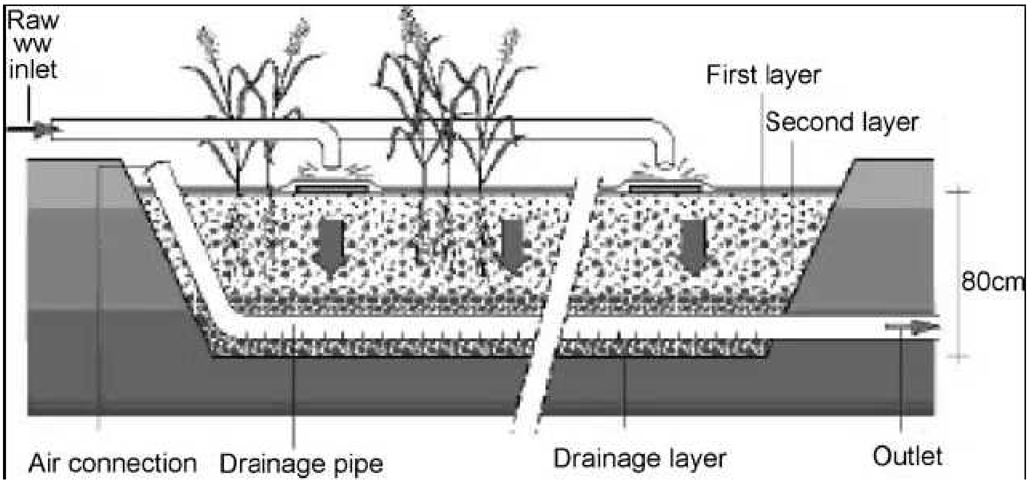


Figure 6: Schematic of the first stage French system (Molle et al., 2005)

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7. Further websites

Case study in Syria
http://www2.gtz.de/ecosan/download/ecosan-pds-015-Syria-HaranAlAwamied.pdf

Case studies Greywater treatment in Germany
http://www.otterwasser.de/english/concepts/lande.htm
http://www2.gtz.de/ecosan/download/ecosan-pds-004-Germany-Luebeck-Flintenbreite.pdf

General information about Constructed Wetlands
http://www.bodenfilter.de/engdef.htm

US EPA Manual
http://www.epa.gov/ordntrnt/ORD/NRMRL/Pubs/2001/wetlands/625r99010.pdf

EU Guide "Extensive Wastewater Treatment Processes"
http://europa.eu.int/comm/environment/water/water-urbanwaste/waterguide_en.pdf

EU project SWAMP focussing on natural wastewater treatment
http://www.swamp-eu.org/