Technology review of constructed wetlands

Subsurface flow constructed wetlands for greywater and domestic wastewater treatment

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Sustainable sanitation - ecosan program
Postfach 5180, 65726 Eschborn, Germany
T +49 61 96 79-4220
F +49 61 96 79-80 4220
E ecosan@giz.de
I www.gtz.de/ecosan

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Authors:

Dr. Heike Hoffmann, Dr.-Ing. Christoph Platzer,
Dr.-Ing. Martina Winker, Dr. Elisabeth von Muench

Responsible editor:

Dr. Elisabeth von Muench

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Juergen Staeudel, Prof. Chris Buckley, Dr. Guenter Langergraber (for contributing to the critical review of this document);
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Contact:

Dr. Elisabeth von Muench, GIZ (ecosan@giz.de)
Dr. Heike Hoffman, Rotaria del Peru (heike@rotaria.net)

Design:

Matthias Hartmann (GIZ)

Photos:

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Foreword

This publication is an important contribution of the GIZ program “Sustainable sanitation – ecosan” as it provides valuable guidance on constructed wetlands in developing countries and countries in transition for wastewater and greywater treatment. This program is commissioned by the German Federal Ministry for Economic Cooperation and Development (BMZ).

The ecological sanitation (ecosan) approach is able to address both: child health which needs to be improved through better household sanitation and wastewater treatment, and sustainable management and safe recycling of important resources such as water and nutrients.

It is a positive development that more and more people are now becoming aware of the present worldwide sanitation crisis which is killing thousands of young children each day. A major reason is the large amount of excreta and untreated wastewater discharged into surface waters and polluting the groundwater.

Constructed wetlands are flexible systems which can be used for single households or for entire communities. Also, due to climate change, more and more regions are experiencing droughts or flooding. Hence, water recycling as well as resilient technologies are key aspects to adapt to these effects of climate change.

Based also on our own past experiences with constructed wetlands in diverse countries such as the Philippines, Syria and Albania, we consider constructed wetlands as a suitable technology for sustainable wastewater management. I am sure this technology review will inspire people working on such solutions. Feedback about this publication is welcome and should be sent to ecosan@giz.de.

Andreas Kanzler
Head of Water Section
Division Water, Energy, Transport

Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH
Eschborn, Germany

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List of Abbreviations:

BOD	Biochemical oxygen demand after 5 days (for simplicity reasons: wherever in this document BOD is used, BOD_5 is meant)
cap	Capita (= person)
C/N	Carbon to nitrogen ratio
COD	Chemical oxygen demand
CW	Constructed wetland
DEWATS	Decentralised wastewater treatment systems
ecosan	Ecological sanitation
FOG	Fat, oil and grease
FWS	Free water surface (a type of CW)
GW	Greywater
HFB	Horizontal flow bed (this is a type of subsurface flow CW)
N/A	not applicable
OM	Organic matter
p.e.	Person equivalent (also called EP for equivalent persons)
SS	Suspended solids
SSF CW	Subsurface flow constructed wetland
TKN	Total Kjeldahl Nitrogen is the sum of the organic and ammonia nitrogen
TN	Total nitrogen
TP	Total phosphorus
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket reactor
VFB	Vertical flow bed (this is a type of subsurface flow CW)
WW	Wastewater

Document specific definitions:

Cold climate:	In this document a “cold climate” means annual average temperatures lower than 10℃.
Warm climate:	In this document a “warm climate” means annual average temperatures higher than 20℃.
Moderate climate:	In between cold and warm climate.

1 Summary

Constructed wetlands (CWs) can be used as part of *decentralised* wastewater treatment systems and are a robust and "low tech" technology with low operational requirements. CWs can be used for the treatment of various types of wastewater, and play an important role in many ecological sanitation (ecosan) concepts.

There are many different types of CWs designed for a variety of wastewater types. This publication deals only with **subsurface flow constructed wetlands with a substrate of coarse sand** for treatment of greywater, domestic or municipal wastewater in developing countries and countries in transition. Subsurface flow CWs are reliable treatment systems with very high treatment efficiencies for the removal of organic matter and pathogens, as well as for nutrients.

The treatment process of CWs is based on a number of biological and physical processes such as adsorption, precipitation, filtration, nitrification, decomposition, etc. The most important process is the biological filtration by a biofilm composed of aerobic and facultative bacteria. The efficiency of the aerobic treatment processes depends on the ratio between oxygen demand (i.e. load) and oxygen supply which is determined by the design of the CW. Professionals with knowledge of wastewater treatment systems are needed to design these biologically complex systems.

Furthermore the planning always has to consider the specific local circumstances, such as temperature, land availability and the intended reuse or disposal of the treated wastewater.

Constructed wetlands can be considered as a secondary treatment step since suspended solids, larger particles including toilet paper and other rubbish as well as some organic matter need to be removed before wastewater can be treated in subsurface flow CWs. Pre-treatment is extremely important to avoid clogging of subsurface flow CWs, which is an obstruction of the free pore spaces due to accumulation of solids.

The main pre-treatment technologies which are used upstream of the CW filter bed are:

- Sand and grit removal
- Grease trap
- Compost filter (for small scale-systems)
- Septic tank
- Baffled tank (or anaerobic baffled reactor)
- Imhoff tank
- Upflow anaerobic sludge blanket (UASB) reactor (only used for large-scale systems)

The issue of unintended biogas generation and lack of biogas capture from the pre-treatment units is discussed in this document. While use or flaring of biogas is very desirable for climate protection reasons, this is unfortunately often not economically feasible in practice for small-scale systems.

CWs lose their treatment capacity when they are overloaded for an extended period of time. Short loading peaks on the other hand do not cause performance problems. Overloading may occur if the pre-treatment system fails and suspended solids, sludge or fats pass into the CW.

Subsurface flow CWs can be designed with vertical or horizontal flow. Vertical flow beds (VFBs) have a higher treatment efficiency and less area requirement compared to horizontal flow beds (HFBs), needing about half as much space. On the other hand VFBs require interval loading (4-8 times per day) which needs more design know-how, whereas HFBs receive wastewater continuously. HFBs are easier to design and are currently more common in developing countries than VFBs.

For municipal wastewater treatment the "French System" for combined raw wastewater pre-treatment and secondary treatment is an interesting option. This system uses VFBs in two separate process stages and requires no additional pre-treatment step.

The apparent simplicity of CWs often leads to the *false* assumption that this technology does not need specialised design knowledge nor regular maintenance. In fact, most CWs which show poor treatment performance had design flaws or lack of maintenance. The most important maintenance tasks include regular checking of the efficiency of the pre-treatment process, of pumps, of influent load and distribution on the filter bed. The actions required to prevent clogging of the filter bed are also explained in this document.

This publication intends to spread awareness and knowledge about subsurface flow constructed wetlands in developing countries and countries in transition.

2 Introduction

2.1 Target audience

The target audience for this publication are people with some basic technical background who:

- want to obtain an overview of subsurface flow CWs, their designs, performance and maintenance requirements;
- want to understand whether subsurface flow CWs could be a possible option for a given wastewater treatment problem;
- work with consultants who are designing CWs and thus need to be able to ask the right questions;
- have an interest in sustainable sanitation solutions for developing countries and countries in transition.

2.2 Scope of this document

This document focuses on treating domestic/municipal wastewater or greywater with *subsurface flow* constructed wetlands with *coarse sand* as a filter medium. The emphasis is on the application in developing countries and countries in transition (with a moderate to warm climate), although constructed wetlands can in principle be used in all types of countries and climates.

This document is **not a design manual**. An experienced expert should always be consulted for the design of constructed wetlands.

Constructed wetlands are generally used as a *decentralised* wastewater treatment process. They are used as a secondary treatment process which means that the wastewater is treated in a primary treatment step before entering the CW filter bed; except for the "French System" which works without primary treatment.

This document provides an overview and basic guidance on the design and maintenance of horizontal flow beds (HFBs), vertical flow beds (VFBs) and the "French System". It also includes a description of the most common pre-treatment systems due to their vital importance for the proper functioning of CWs.

2.3 Definition and terminology

Constructed wetlands (CWs) are "*engineered systems, designed and constructed to utilise the natural functions of wetland vegetation, soils and their microbial populations to treat contaminants in surface water, groundwater or waste streams*" (ITRC, 2003).

Synonymous terms of CWs include: Man-made, engineered, artificial or treatment wetlands.

There are also a number of terms used for subsurface flow CWs, which can be confusing for novices:

- Planted soil filters: Their vegetation is composed of macrophyte plants from natural wetlands and this sets them apart from the unplanted soil filters, also called subsurface biofilters, percolation beds, infiltration beds or intermittent sand filters.
- Reed bed treatment system: A term used in Europe resulting from the fact that the most frequently used plant species is the common reed (*Phragmites australis*).
- Vegetated submerged beds, vegetated gravel-bed and gravel bed hydroponics filters.

This great number of terms is confusing for novices who are searching for information.

In this document, the terms "bed", "filter" or "filter bed" are used interchangeably, denoting the sand filled main body of the subsurface flow CWs.

We use the term "pre-treatment" in this document to denote the treatment step *before* the wastewater reaches the subsurface flow CW filter bed. Other authors call this step "primary treatment", and the treatment in the CW would in that case be called "secondary treatment".

2.4 Historical development

Historically, natural wetlands have been used as convenient sewage and wastewater disposal sites. This led to many wetlands, such as marshes, being saturated with nutrients and experiencing severe environmental degradation.

The German scientist Dr. Seidel conducted the first experiments on the possibility of wastewater treatment with wetland plants in 1952 at the Max Planck Institute in Germany (Seidel, 1965). A major increase in the number of CWs took place in the 1990s as the application expanded to treat different kinds of wastewater such as industrial wastewater and storm water.

The use of constructed wetlands for wastewater treatment is becoming more and more popular in many parts of the world. Today subsurface flow CWs are quite common in many developed countries such as Germany, UK, France, Denmark, Austria, Poland and Italy. Constructed wetlands are also appropriate for developing countries but they still have to become better known there (Mohamed, 2004; Heers, 2006; Kamau, 2009).

2.5 Classification of constructed wetlands

Constructed wetlands are classified according to the water flow regime (see Figure 1) into either free water surface flow (FWS CWs) or subsurface flow CWs, and according to the type of macrophyte plant as well as flow direction. Constructed wetlands used macrophyte plants which are aquatic plants that grow in or near water.

Subsurface flow CWs are designed to keep the water level totally below the surface of the filter bed. They can even be walked on. This avoids the mosquito problems of FWS CWs.

Different types of constructed wetlands may be combined with each other to form hybrid systems in order to exploit the specific advantages of the different systems.

The coarse sand used in subsurface flow CWs contributes to the treatment processes by providing a surface for microbial growth and by supporting adsorption and filtration processes. This results in a lower area demand and higher treatment performance per area for subsurface flow CWs, compared to FWS CWs. Subsurface flow CWs are the predominant wetland type in Europe.

There are two different types of filtering material, i.e. sand or gravel. Gravel bed systems are widely used in North Africa, South Africa, Asia, Australia and New Zealand. The sand bed systems have their origin in Europe and are now used all over the world.

This publication only deals with subsurface flow CWs with **coarse sand** as filter media.

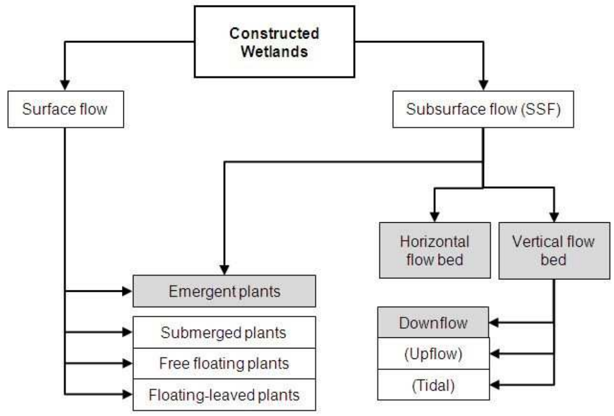

Figure 1. Classification of constructed wetlands (modified from Vymazal and Kroepfelová, 2008). The dashed ellipse signifies the focus of this document. HFB and VFB are abbreviations for horizontal and vertical flow bed, respectively. Hybrid systems are also possible. "Emergent plants" are a type of macrophyte where the leaves are *above* the water level.

2.6 Range of applications

Constructed wetlands can be used for a variety of applications[1]:

1. Municipal wastewater treatment
2. Treatment of household wastewater or greywater
3. Tertiary treatment of effluents from conventional wastewater treatment plants
4. Industrial wastewater treatment such as landfill leachate, petroleum refinery wastes, acid mine drainage, agricultural wastes, effluent from pulp and paper mills, textile mills.
5. Sludge dewatering and mineralisation of faecal sludge or sludge from settling tanks.
6. Storm water treatment and temporary storage
7. Treatment of water from swimming pools without chlorine

This publication only deals with the *first two* applications of the list above. Note that pre-treatment of some form is required in most of the applications.

2.7 Technology selection

Subsurface flow CWs offer significant potential for decentralised wastewater treatment, but they are not the only available technology. The right treatment technology for a given application should be carefully selected taking into account a whole range of aspects and sustainability indicators[2].

Figure 2. Urban decentralised greywater treatment with a subsurface flow CW in Klosterenga in Oslo, Norway (photo by L. Ulrich, 2008).

2.7.1 Space requirements as a selection criterion

The high space requirement compared to high-rate aerobic treatment processes can limit the use of subsurface flow CWs especially for urban applications.

In warm climates, horizontal flow beds have approximately the same area requirement as facultative ponds which are another "low tech" wastewater treatment option, whilst vertical flow beds need about 20% less space than ponds.

In most urban situations neither HFBs nor ponds can be implemented for wastewater treatment because of the space requirement. VFBs for decentralised applications may however be small enough to fit into available urban spaces, especially in warm climates.

In order to save space in urban applications, subsurface flow CWs could be constructed on roofs of buildings. This is an interesting research area for the future but currently has a lot of practical draw-backs.

Further details on the required area of subsurface flow CWs are provided in Section 3.2.4.

2.7.2 Comparison of subsurface flow CWs with high-rate aerobic treatment processes

High-rate aerobic treatment processes require less space than constructed wetlands. Process examples are: activated sludge plants, trickling filters, rotating discs, submerged aerated filters or membrane bioreactor plants.

The main argument in favour of subsurface flow CWs compared to high-rate aerobic treatment processes is their operational robustness which is very important in the case of developing countries and countries in transition.

Another important aspect is the lack of secondary sludge production in constructed wetlands, whereas excess secondary sludge is produced in high-rate aerobic treatment processes and needs to be managed. In developing countries, this excess sludge is often discharged in an uncontrolled manner to the environment, leading to pollution and health risks.

Constructed wetlands are very effective as a tertiary treatment system *after* activated sludge or trickling filter plants[3]:

- The constructed wetland can serve to compensate temporary variations of effluent quality.
- Constructed wetlands achieve more pathogen removal than conventional high-rate aerobic processes (see Section 8.2 in the Appendix).

2.7.3 Comparison of subsurface flow CWs with ponds

Constructed wetlands and ponds both score high in terms of process reliability and simplicity since no special equipment is required. The main arguments to choose subsurface flow CWs over ponds include:

- Subsurface flow CWs do not have open water bodies; therefore they do not encourage mosquito breeding.
- Subsurface flow CWs produce clear water, whereas ponds have a high algae production which influences the effluent quality.
- Due to their open water surface, mosquitoes and odour, ponds are much more difficult to integrate in a neighbourhood, particularly an urban neighbourhood.

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1 For an overview of these applications see this presentation: http://www.susana.org/lang-en/library?view=ccbktypeitem&type=2&id=1035.

2 See vision document of Sustainable Sanitation Alliance (SuSanA) for a definition of sustainability indicators for sanitation (http://www.susana.org/lang-en/intro/156-intro/267-vision-document).

3 The lower organic load entering the CW in that case (after secondary treatment) significantly reduces the area requirement for the CW.

- Well-functioning constructed wetlands have no odour generation, whereas in most ponds odour generation is common.
- Constructed wetlands do not produce sludge except for the sludge produced from the pre-treatment step upstream of the filter beds. In ponds on the other hand, sludge accumulates over time, and the sludge has to be removed after about ten years. This is often neglected in developing countries and instead the ponds are abandoned.

And what are the advantages of ponds over subsurface flow CWs? They are easier to design and construct, do not need a substrate (sand) and have lower capital costs for large-scale plants (see Section 2.7.4).

2.7.4 Cost considerations

The capital costs of subsurface flow CWs are highly dependent on the costs of sand since the bed has to be filled with sand. Secondly the capital costs are also dependent on the cost of land.

Financial decisions on treatment processes should not primarily be made on capital costs, but on net present value or whole-of-life costs, which includes the annual costs for operation and maintenance.

The following points can be made when comparing costs for constructed wetlands and high-rate aerobic treatment processes:

- Constructed wetlands do not exhibit economies of scale to the same degree that high-rate aerobic treatment plants do. For small plants of up to 500 p.e., constructed wetlands are usually cheaper to build than high-rate aerobic plants but for larger plants, they are usually more expensive in terms of capital costs.
- Constructed wetlands have significantly lower operation and maintenance costs compared to high-rate aerobic processes for energy use and operator time.

For large scale treatment plants of more than 10 000 person equivalents (p.e.) in areas where land is available cheaply, ponds have lower capital costs than constructed wetlands. But there is a range of other aspects which have to be taken into account when making the decision between the two different treatment processes, as shown above.

We argue that the capital costs argument should be less important than the reliability and long-term sustainability of the treatment plant, including its financial sustainability which is strongly influenced by annual operation and maintenance costs.

2.8 Reuse aspects

2.8.1 Reuse for irrigation

Subsurface flow CWs treat wastewater to a standard fit for discharge to surface water or fit for various reuse applications according to WHO guidelines (WHO, 2006). The legal requirements for the effluent quality vary depending on the specific regulations of each country and also on the intended reuse or disposal pathway. The design of the subsurface flow CW should be in line with the desired effluent quality for disposal or reuse.

The most common type of reuse is irrigation, such as drip irrigation or subsurface irrigation, for lawns, green spaces or crop production. In this case, *utilisation* of nutrients contained in wastewater rather than nutrient *removal* is desirable.

Relevant guidelines must be followed to ensure this practice is hygienically safe for the consumers of the crops as well as for workers who can be in contact with treated wastewater. International standards for reuse and an explanation of the important multiple-barrier concept can be found in WHO (2006).

2.8.2 Hygiene aspects (pathogens)

Humans excrete many different types of disease causing pathogens if they are infected or carriers of a disease. The human intestinal tract contains coliform bacteria which are discharged with the faeces. These coliform bacteria are not pathogens but if present in environmental samples indicate that intestinal pathogens may also be present.

Greywater which has been treated in subsurface flow CWs usually meets the standards for pathogen levels for safe discharge to surface water without further treatment. In the case of *domestic wastewater,* disinfection by tertiary treatment might be necessary, depending on the intended reuse application.

For further information on pathogen types and pathogen removal by various treatment processes please see the Appendix.

Figure 3. The treated effluent (left) of the vertical flow constructed wetland in Haran Al-Awamied, Syria, is collected in this storage tank (right) before its reuse for irrigation in agriculture (photos by E. von Muench, 2009; project supported by GIZ).

2.8.3 Quantity aspects

Horizontal flow beds in warm climates can lose all the wastewater due to evapotranspiration. This needs to be considered in the water balance. The larger the surface area, the more significant are the effects of precipitation (rain) and evapotranspiration, especially in warm and dry climates.

If water loss is regarded as a problem, VFBs are preferable to HFBs, because they have an unsaturated upper layer in the bed and a shorter retention time than HFBs.

2.8.4 Colour aspects

The effluent from any biological wastewater treatment process such as a constructed wetland can have a yellowish or brownish colour. This is caused by humic substances, such as humic acids or humins (Figure 4). The colouration may reduce the social acceptance of wastewater reuse.

Humic acids originate from the biological degradation of organic matter, being the unbiodegradable fraction of organic matter. Humic acids are a natural compound of soil, lake and river water. They are not harmful to the environment but they have a negative impact on disinfection processes with chlorine or UV radiation.

When treated wastewater is used for toilet flushing, it is easier to use coloured porcelain for the toilet bowl than to attempt to remove the coloration, since humic substances can be only removed by advanced technologies such as activated carbon, ozone, photo catalytic oxidation (Guylas et al., 2007; Abegglen et al., 2009).

From the main authors' experiences, greywater after treatment in a constructed wetland tends to have *no colour*. On the other hand, domestic wastewater or blackwater after treatment in a constructed wetland is often, but not always, *slightly yellow or brown* (see for example Figure 4).

Figure 4. Wastewater samples before and after treatment in a VFB. Left photo: pre-treated greywater (left bottle) and effluent of the CW which is reused for irrigation of crops (right bottle). Right photo: pre-treated blackwater (left bottle) and effluent of the CW which has the typical brownish colouration caused by humic acid (right bottle) (photos by: H. Hoffmann, 2008).

3 Design criteria for subsurface flow CWs

3.1 Treatment principles

3.1.1 Overview of main processes

Subsurface flow CWs achieve the removal of the following pollutants (see Table 1 for details):

- Organic matter measured as "biological oxygen demand" (BOD) or "chemical oxygen demand" (COD)
- Suspended solids measured as "total suspended solids", TSS
- Nutrients[4], i.e. nitrogen and phosphorus
- Pathogens, heavy metals and organic contaminants.

Constructed wetlands are often referred to as "simple, low tech systems", but the biological, physical and chemical treatment processes involved are actually far from simple. They occur in different zones in the main active layer of the constructed wetland, the "filter bed". These zones include:

- Sediment, sand bed
- Root zone, water in pores
- Litter, detritus (non-living particulate organic material, such as leaf litter)
- Water
- Air
- Plants and plant roots
- Biomass zones, such as bacteria growing in sand and attached to roots

The wastewater treatment in the filter bed of constructed wetlands is the result of complex interactions between all these zones. A mosaic of sites with different oxygen levels exists in constructed wetlands, which triggers diverse degradation and removal processes.

Table 1. Overview of pollutant removal processes in subsurface flow CWs.

Pollutant	Process
Organic material (measured as BOD or COD)	• Particulate organic matter is removed by settling or filtration, then converted to soluble BOD. • Soluble organic matter is fixed by biofilms and removed due to degradation by attached bacteria (biofilm on stems, roots, sand particles etc.).
Suspended solids (TSS)	• Filtration • Decomposition by specialised soil bacteria during long retention times
Nitrogen	• Nitrification and denitrification in biofilm • Plant uptake (only limited influence)
Phosphorus	• Retention in the soil (adsorption) • Precipitation with calcium, aluminium and iron • Plant uptake (only limited influence)
Pathogens	• Filtration • Adsorption • Predation ("feeding") by protozoa • Die-off due to long retention times
Heavy metals	• Precipitation and adsorption • Plant uptake (only limited influence)
Organic contaminants	• Adsorption by biofilm and clay particles • Decomposition due to long retention times and specialised soil bacteria is possible

[4] Nutrient removal is not necessary when treated wastewater shall be reused for irrigation purposes (see Section 2.8).

The filter bed acts as a mechanical and biological filter. Influent suspended solids and generated microbial solids are mainly retained mechanically, whereas soluble organic matter is fixed or absorbed by a so-called biofilm. All organic matter is degraded and stabilised over an extended period by biological processes. The biological treatment in the filter bed is based on the activity of microorganisms, mainly aerobic and facultative bacteria. These microorganisms grow on the surface of the soil particles and roots, where they create a highly active biofilm.

Subsurface flow CWs are designed for aerobic and facultative treatment. Aerobic processes always need the presence of oxygen (air). Facultative processes can occur under temporary oxygen limited conditions or in the absence of oxygen, when nitrate (NO_3^-) is used by specialised bacteria for the oxidation of organic matter. This is then called an anoxic process.

CWs are *not designed* for anaerobic treatment (which occurs in absence of oxygen) but some small anaerobic zones may still exist in CWs, particularly for free water surface flow CWs and HFBs. The possible biogas emissions due to these anaerobic processes are however negligible compared to other sources.

A low organic load to the CW allows for the degradation of less degradable organic matter (organic contaminants), which will be decomposed by specialised natural soil bacteria. These specialised bacteria have very low growth rates. All organic matter, suspended solids and also generated microbial solids are finally reduced by aerobic and anoxic processes into CO_2, H_2O, NO_3 and N_2.

The uptake of **heavy metals** by plants in constructed wetlands has been reported. The physiological reasons for heavy metal uptake are not yet fully understood and probably depend strongly on the plant species. Nevertheless it has to be pointed out that heavy metals do not disappear, but still remain in the plant tissues. In greywater and domestic wastewater heavy metals are usually not an issue, because their concentration is low in such types of wastewater.

3.1.2 Pollutant removal ratios for greywater treatment

The removal efficiencies for greywater treatment with two types of subsurface flow CWs are summarised in Table 2. It is obvious that different removal ratios exist for HFBs and VFBs as well as for the different parameters. The removal ratios for BOD and TSS are up to 99%, while total nitrogen removal ratios are only up to 40% (but higher for hybrid systems). The values can be expected to be similar for *domestic wastewater* treatment.

The effluent concentrations of pollutants can be calculated by multiplying the influent concentrations in the flow to the filter bed (i.e. after pre-treatment) with the removal ratio.

Table 2. Removal ratios (in %) of HFBs and VFBs (subsurface flow CWs) for greywater treatment. The values are similar for domestic wastewater treatment.

Pollutant	**HFB (Morel and Diener, 2006)**	**VFB (Ridderstolpe, 2004)**
BOD (biological oxygen demand)	80-90	90-99
TSS (total suspended solids)	80-95	90-99
TN (total nitrogen)	15-40	30
TP (total phosphorus)	Phosphorus removal rates depend on the properties of the filter material and on the length of time the CW has been operating for.	

3.1.3 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.

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 5.4.

Phosphorus 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.

3.1.4 Role of plants in subsurface flow CWs

Subsurface flow CWs are planted with macrophyte plants which are commonly found in natural wetlands or non-submerged riverbanks in the region. The plants are an essential part of a constructed wetland[5]. 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 centimetres 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 rhizomes[6], 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 5). 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 5. Root and rhizome system of reed (*Phragmites australis*) (left picture) and arundo donax (right picture) (photos by M. Blumberg, 1995).

3.2 Basic design considerations

3.2.1 Necessary conditions and basic setup

The necessary conditions to be able to use constructed wetlands for wastewater treatment are listed below:

- Enough space must be available because it is a low-rate system with a higher space requirement than high-rate systems (Section 2.7.1).
- Climates without longer freezing periods are preferable, even though subsurface flow CWs with adjusted designs do work in cold climates (Jenssen et al., 2008).
- Full sunlight situation is preferable and full shadow conditions need to be avoided. Especially for subsurface flow CWs it is very important that the surface area can regularly dry out completely because otherwise the risk of clogging rises due to excessive biofilm growth in wet conditions.
- Plants used must be adapted for growth under partially submerged conditions, the local climate and the sunlight/shadow conditions of the respective wetland location.
- As for all biological treatment processes the wastewater should not contain toxic substances, although the high retention time makes constructed wetlands more robust to toxic events compared to more highly loaded systems.
- Well trained maintenance staff to carry out the basic maintenance tasks is needed.

Urbanisation and future population development have to be considered when calculating the expected wastewater flowrate to the constructed wetland.

[5] There are other types of treatment systems which have some similarities with SSF CWs but work without plants; these systems are called "unplanted soil filters" – see relevant literature for more details on those systems, as they are not included in this document.

[6] A rhizome is a characteristically horizontal stem of a plant that is usually found underground, often sending out roots and shoots from its nodes (source: www.wikipedia.org).

There are some general considerations about constructing subsurface flow CWs, which are usually adhered to:

- A 15 cm freeboard for water accumulation is recommended.
- The surface must be flat and horizontal to prevent unequal distribution or "surface run-off" (which means in the case of HFBs that wastewater is flowing across the surface of the CW to the outlet but not infiltrating and hence not receiving treatment).
- The **design of the inlet area and distribution pipes** has to assure uniform distribution of the wastewater, without allowing short circuits of the flow.
  - The right selection of filter material is crucial (see Section 3.3 for details).
  - The wastewater is applied to the bed via distribution pipes which have small holes equally distributed along the length of the pipes.
- **Drainage pipes** collect treated wastewater at the base below the filter bed.
- **Liner at the base**: Plastic PVC lining, a clay layer or a concrete base is used to seal the filter bed at the base (see Figure 9). For HFBs this is always necessary. For VFBs it is only necessary when the effluent will be reused or when the groundwater table is high and groundwater is used for drinking water purposes. Sometimes the authorities also stipulate the sealing of the base.
  - The lining prevents contact of wastewater with groundwater but otherwise does not improve the effluent quality nor prevent clogging.
  - Disadvantages of lining are the additional costs, the difficulties with finding a local supplier (especially in rural areas), environmental pollution during production of PVC lining and the need for specialists to lay the PVC sheets properly in the hole.

Details on the design of subsurface flow CWs are given in Section 5. Special attention should always be paid to the pre-treatment (see Section 4).

3.2.2 Major components and design life

The major components of a constructed wetland are an influent pump (for VFBs; this is not required for HFBs), plastic pipes, plastic lining underneath the drainage pipes, gravel and sand. Therefore, the design life is determined by the design life of these major components. The pumps and feeding pipes can easily be replaced if necessary. The gravel and sand is in practice never replaced. The design life of the plastic lining is difficult to predict and the condition of the plastic lining is unfortunately impossible to assess in a constructed wetland while it is in use.

There are no theoretical reasons to indicate that constructed wetlands would stop removing organic matter, nitrogen and pathogens after a certain length of time[7]. If a constructed wetland ever has to be abandoned, it is easy to use the space for other purposes, or to just let the plants grow wild.

Constructed wetlands can be expected to have a design life at least as long as other wastewater treatment systems, such as high-rate aerobic processes or ponds. Some constructed wetlands have now been in continuous operation for over 20 years and these plants are still producing good treatment results.

3.2.3 Design parameters

There are several design parameters for designing subsurface flow CWs which are used at different points in the design calculations, depending on the type of wastewater and climate:

- Area per person in m^2/p.e., where p.e. stands for "person equivalent";
- Organic loading per surface area in gBOD/(m^2·d) or gCOD/(m^2·d);
- Hydraulic load in mm/d or m^3/(m^2·d);
- Oxygen input and consumption (kg/d).

There is no commonly accepted design approach which uses the *retention time* to size a subsurface flow CW.

The best method to minimise the size of a constructed wetland is an efficient pre-treatment (see Section 4) and the precise calculation of the actual load. The organic load to a CW (in g/d) equals the flowrate (in m^3/d) multiplied by the BOD concentration in the pre-treated wastewater (in mg/L).

Figure 6. VFB under construction, during influent pumping with greywater to test for uniform distribution in Lima, Peru. Note the small holes in distribution pipes. The entire surface is used as an inlet area, and the pipes are later covered with gravel after completing the testing (photo by H. Hoffmann, 2008).

Figure 7. VFB under construction in Bayawan City, Philippines; the wetland will treat wastewater from a landfill (photo by J. Boorsma, 2009; project supported by GIZ).

7 The situation is different for phosphorus removal, see Section 3.1.3.

3.2.4 Typical values for area requirements

The simplest design parameter for constructed wetlands is the area required per person, but this design parameter on its own is *not* sufficient for properly sizing constructed wetlands. This parameter can only be used for a basic assessment in order to obtain a first indication of the space requirement (see Section 5 for detailed design information).

Table 3 shows how the climate and the type of constructed wetland (HFB versus VFB) influence the area requirement of constructed wetlands. This table can be used as a guide and should be read as follows: if a constructed wetland is smaller than the recommended value in Table 3, then an overload situation can occur which would cause serious operational problems and reduced treatment performance. Oversized constructed wetlands on the other hand, do not have problems with treatment efficiency and are more robust, but are unnecessarily large and expensive.

To give an example: a VFB to treat wastewater of 3 000 people needs about 3 000 to 12 000 m² depending on the climate and design. A HFB would need at least twice as much space.

It should be noted that the required pre-treatment is the same for HFBs and VFBs. But the pre-treatment for *wastewater* is different than the pre-treatment of *greywater*, as the wastewater characteristics differ (see Section 4 for details).

Table 3. Approximate design values to estimate the area requirement for subsurface flow CWs in different climate conditions for domestic wastewater (after pre-treatment)[8].

Design value	**Cold climate, annual average < 10℃**		**Warm climate, annual average > 20℃**	
	HFB	**VFB**	**HFB**	**VFB**
Area per person (m²/p.e.)	8	4	3	1.2

3.2.5 Design differences between CWs for domestic wastewater versus CWs for greywater

Domestic wastewater and greywater have different characteristics and these have to be considered when dimensioning a CW. The characterisation of domestic wastewater and greywater is outlined in the Appendix.

The main differences between the design of constructed wetlands for treating *greywater* compared to treating *domestic or municipal wastewater* include:

- **Nitrogen and phosphorus** removal are much easier to achieve for greywater than for domestic wastewater treatment since the nutrient loads and concentrations are much lower in greywater due to the lack of urine and faeces.
- **Pathogen** removal is not a design consideration for greywater treatment since the pathogen levels are very low in greywater, but it is an important consideration for domestic wastewater.

3.3 Substrate used in subsurface flow CWs

The selection of a suitably permeable substrate in relation to the hydraulic and organic loading is the most critical design parameter for subsurface flow CWs. Most treatment problems occur when the permeability is not adequately chosen for the applied load.

This publication refers only to the use of **coarse sand** as a substrate for filtration. In our view, this is the most suitable substrate for the application of subsurface flow CWs for wastewater or greywater treatment in developing countries or countries in transition (with a warm to moderate climate).

The drainage pipes at the base are covered with gravel. On top of this gravel layer, there is a sand layer of 40-80 cm thickness which contains the actual filter bed of the subsurface flow CW. On top of this sand layer there is another gravel layer of about 10 cm thickness, in order to avoid water accumulating on the surface. This top gravel layer does not contribute to the filtering process.

Figure 8. Example of filter material used for VFBs for municipal wastewater treatment in Brazil: coarse sand from river, containing neither loam nor silt (photo by C. Platzer, 2008).

It is *not* recommended to construct layers with different grain sizes such as larger grains on top, smaller grain sizes at the base – as this design approach has led to poorly performing constructed wetlands in the past.

It is also *not* recommended to use a layer made of fabric between the lower gravel layer and the sand layer. This had been included in some constructed wetlands in Germany and led to clogging in deeper zones of the VFBs which was impossible to revert. Also in the case of HFBs such a fabric separation layer would have a negative impact on the hydraulic conductivity.

Design recommendations regarding the substrate to be used in subsurface flow CWs are listed below:

- The sand should have a hydraulic capacity (k_f value) of about 10^{-4} to 10^{-3} m/s.
- The filtration sand layer needs to have a thickness of 40 to 80 cm.
- The recommended grain size distribution for the substrate is shown in Figure 32.

[8] The values are the same for greywater treatment if the pre-treatment unit has resulted in the same effluent concentrations (the pre-treatment unit can be smaller for greywater treatment when the calculation is done on a per person basis).

- The substrate should not contain loam, silt nor other fine material, nor should it consist of material with sharp edges. Figure 8 illustrates the visual appearance of suitable sand.

Figure 9. Left: VFB during construction in Palhoça, Santa Catarina, Brazil; drain pipes situated on top of the PE liner are being covered with gravel. Right: VFB in Lima, Peru during filling with sand (photos by H. Hoffmann, 2007).

3.4 Types of plants used

For the selection of plants to be used in constructed wetlands (mostly macrophyte plants i.e. aquatic plants which grow in or near water), the following recommendations can be made:

- Use local, indigenous species and do not import exotic, possibly invasive species.
- Use plant species which grow in natural wetlands or riverbanks because their roots are adapted to growing in water saturated conditions.
- Plants with an extensive root and rhizome system below ground are preferable (see Figure 5).
- Plants should be able to withstand shock loads as well as short dry periods.
- Plants should *not require* permanent flooding but be able to cope with temporary flooding and water logged soils.

Whether the wetland plants should be harvested or not is discussed in Section 6.4 as part of the operational tasks.

Plants used in subsurface flow CWs in **cold climates** of Europe, Southern Australia and North America include for example:

- Common reed *(Phragmites australis)*: this is the most common plant used in Europe and in countries with a cold climate.
- Broad-leaved cattail (*Typha latifolia*), reed sweet grass (*Glyceria maxima*), reed canary grass (*Phalaris arundinacea*) and yellow iris (*Iris pseudacorus)*.

The types of plants used in subsurface flow CWs in **warm climates** of South America, Africa, and Asia are summarised in Table 4.

Table 4. Overview of some possible plants which can be used in subsurface flow CWs in warm climates. All plants shown below are macrophyte plants, except vetiver which is a perennial grass. Many other plants are possible, see for example Brisson and Chazarenc (2009).

Plant name	**Characteristics**	**Disadvantages**
Papyrus sedge (*Cyperus papyrus*)	Decorative (see Figure 11).	3 m high, forms a layer on the CW surface, roots are only formed from the mother plant.
Umbrella sedge (*Cyperus albostriatus* and *Cyperus alternifolius*)	Very robust plants, excellent also for highly concentrated or salt containing wastewater.	
Dwarf papyrus (*Cyperus haspens*)	Excellent when it is the only plant.	Does not survive in the shadow of larger plants.
Bamboo, smaller ornamental species	Decorative.	Slow growth especially in the first 3 years and if the plant is not well adapted to the climate.
Broad-leaved cattail (*Typha latifolia)*	Is often more resistant in warm conditions than common reed.	
Species of genus – *Heliconia:* lobster-claws, wild plantains – *Canna:* Canna lily – *Zantedeschia:* Calla lily	Decorative	Some plants of these species prefer half shadow, others full sunlight conditions.
Napier grass or Elephant grass (*Pennisetum purpureum*)	Species of grass native to the tropical grasslands in Africa. It has a very high productivity, both as forage for livestock and as a biofuel crop.	
Vetiver (*Chrysopogon zizanioides*, previously called *Vetiveria zizanioides* or cuscus grass)	It can grow up to 1.5 m high and forms an efficient root system. This grass is used in warm climates for erosion control and for producing essential oil which is distilled from its roots. The grass is also used as fodder plant or for handicraft material.	The roots do not grow so well when the plant is used for wastewater treatment in constructed wetlands, but the roots are still sufficient to maintain the functionality of a VFB. Hence, vetiver is only recommended for VFBs, but *not* for HFBs.

Figure 10. Reed after two years of growth in a VFB treating domestic wastewater at Haran Al-Awamied near Damascus, Syria (photo by E. von Muench, 2009; project supported by GIZ).

Figure 11. Papyrus after six months of growth in a VFB treating domestic wastewater in Florianópolis, Brazil (photo by C. Platzer, 2008).

Figure 12. Simsen (*Scirpus sp.*) in a VFB treating domestic wastewater in the Olympic Forest Park in Beijing, China (photo by J. Germer, 2008).

4 Pre-treatment of wastewater before subsurface flow CW treatment

4.1 Overview of processes

Constructed wetlands can be called a secondary treatment step since suspended solids, larger particles including toilet paper and other rubbish as well as some organic matter need to be removed before wastewater can be treated in subsurface flow CWs. The technology used for pre-treatment (also called primary treatment) depends on the type and quantity of wastewater. Table 5 provides a general overview.

Pre-treatment is extremely important to avoid clogging of subsurface flow CWs, which is an obstruction of the free pore spaces due to accumulation of solids (see Section 5.2.2 for details).

This section provides only general guidance on pre-treatment processes. Specialised literature or local experts should be consulted to design the pre-treatment process. See for example Gutterer et al. (2009) for design equations for septic tanks, baffled tanks and Imhoff tanks.

Small household treatment plants (less than 1 000 p.e.) are usually designed without screens. In this case septic tanks, baffled tanks or compost filters carry out the screening function.

About 60% of suspended solids in the wastewater is removed in the pre-treatment step. As a basic rule, the aim is to have **less than 100 mg/L TSS** in the influent to a SSF CW (i.e. after pre-treatment).

Table 5. Overview of available pre-treatment processes and their suitability for different wastewater types: GW stands for greywater, WW stands for wastewater (X means: can be used).

Pre-treatment process	**GW with low organic load**	**Domestic WW or GW with high organic load**	**Scale (p.e.)**	**Biogas production**
Screens (mechanically operating)	X	X	> 1 000	No
Sand and grit removal	X	X	> 1 000	No
Grease trap	X	X	At household level	No
Compost filter	–	X	Up to 70	No
Septic tank	–	X	5-200	Yes
Baffled tank	–	X	200-2 500	Yes
Imhoff tank	–	X	500-20 000	Yes
UASB	–	X	> 5 000	Yes

Figure 13: Pumping of settled sludge from pre-treatment unit of subsurface flow CW in Tirana, Albania. The removed sludge will be taken to a local wastewater treatment plant by tanker (project supported by GIZ, photo by J. Nowak, 2010)

4.2 Biogas emissions during pre-treatment

In most of the pre-treatment facilities, anaerobic degradation processes occur in the accumulated sludge (see Table 5). These anaerobic processes lead to the emission of biogas, which contains typically around 66% methane[9]. Methane (CH_4) in the earth's atmosphere is an important greenhouse gas with a global warming potential of 25 times higher compared to CO_2 over a 100-year period[10].

Unfortunately the organic load in communal wastewater is in most cases not high enough for the economical usage of biogas for cooking, lighting or heating. Sometimes the distance between the point of biogas generation and the point of possible biogas use is also too large. In these cases the biogas should at least be burnt (also called "flared").

When biogas needs to be burnt, there are additional costs for safety equipment. The flare for a household plant has nearly the same costs as a flare for a large plant of 20 000 inhabitants – thus the specific costs per person are relatively high for flares implemented in small systems.

Due to the fact that septic tanks, baffled tanks, Imhoff tanks and UASBs lead to biogas emissions and since flares are neither economical nor practical at the small scale, the designer should be aware of the negative impact on climate change of these pre-treatment methods.

It is recommended to always check the possibility of flaring of biogas or of using other available pre-treatment methods which do not produce biogas. Whilst the greenhouse gas (methane) emissions from anaerobic processes within pre-treatment processes are relatively small compared to other sources of greenhouse gases, they should still be minimised as much as possible.

4.3 Grease trap

Fats, oil and grease (FOG) are removed by floating this material, which is lighter than water, in a container downstream of the kitchen sink before this wastewater is mixed with other wastewater streams. The outlet in the sink and/or the inlet to the grease trap should be equipped with a removable screen which retains pieces of food and sand.

The floating scum layer has to be removed periodically before it gets so thick that it would mix with the grease trap effluent. The frequency for the removal depends on the use of fat in the kitchen.

For household units, commercial plastic traps with removable buckets can be bought (see Figure 14) which simplify the cleaning. Larger grease traps (as a guideline: for more than 20 p.e.) must be cleaned with a pump.

Further recommendations regarding grease traps include:

- Common pre-treatment methods for municipal wastewater (for instance septic tanks) also eliminate a fraction of FOGs, but at least for restaurants and large kitchens it is important to have a grease trap because concentrated fats cause problems in the pre-treatment as well as blockages in the sewer. The grease traps are installed downstream of the kitchen sink.
- If the grease trap is the only pre-treatment step for greywater before it enters a constructed wetland, it may be necessary to combine it with a sedimentation tank or to have an outlet in the bottom of the trap. This enables removal of sludge/sediments which can be formed by sand, soap and pieces of food which would otherwise pass onto the wetland.
- The removed scum has to be treated, for instance by composting or by transporting it by tanker to a centralised treatment plant if there is one nearby. The high energetic value of FOGs means that the removed scum could also be used for anaerobic digestion (biogas generation).

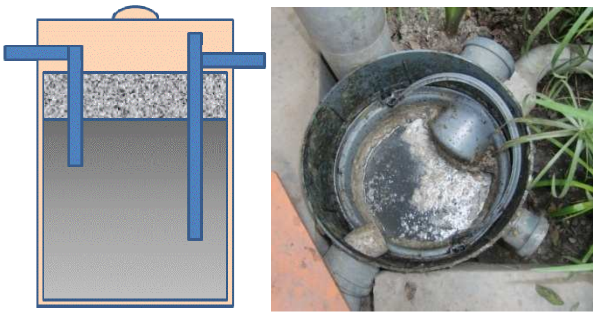

Figure 14. Left: Grease trap schematic. Right: Opened grease trap used for effluent of a kitchen sink of a household in Lima, Peru before wetland treatment. The inner bucket can be taken out to remove the grease (sources: H. Hoffmann, 2010).

4.4 Septic tank

Some basic facts about septic tanks are listed below:

- Widely used for decentralised ("on-site") domestic wastewater treatment due to their simple construction. Many countries have standards for septic tank design.
- Common in many developing countries but also in sparsely populated regions of developed countries.
- Can be used for pre-treatment of wastewater from 5 to 200 inhabitants.

[9] See also GIZ technology review on biogas sanitation: http://www.gtz.de/en/themen/umwelt-infrastruktur/wasser/9397.htm
[10] Source: http://en.wikipedia.org/wiki/Methane.

- Consist of two or three chambers (see Figure 14) which have a depth of 1.4 m or more from the point of the inlet pipe.
- Chambers are made of concrete or are installed as prefabricated plastic tanks.
- Removal ratio for organic matter, measured as BOD, is typically 30%.
- In warm climates, septic tanks are designed with 1-2 days hydraulic retention time. In cold climates up to 5 days may be required.
- The treatment process is based on sedimentation and flotation of scum, with partial anaerobic degradation of the sludge. This process leads to undesired biogas emissions (see Section 4.2).

In a three-chamber system the first chamber is designed with 50% of the total volume. It is connected to the second chamber from a level of 60-80 cm above the bottom of the tank. With this arrangement, settled solids and floated scum are mainly retained in the first chamber. The third chamber is used as reservoir for the pre-treated wastewater.

Septic tanks have to be desludged regularly when the sludge in the first chamber almost overflows. The duration between emptying events varies with the design and number of users but may be in the range of 1-5 years.

The removed faecal sludge should be properly managed and treated but is unfortunately often simply dumped anywhere in the environment. The faecal sludge from the septic tank cannot be reused without further treatment.

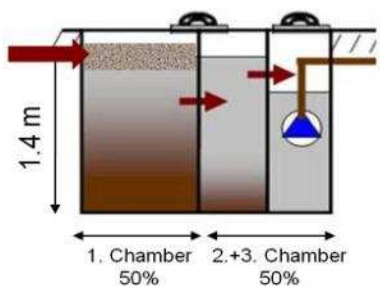

Figure 15. Left: Septic tank schematic. Right: 3-chamber septic tank under construction at a house with 15 habitants in Lima, Peru (sources: H. Hoffmann, 2009).

4.5 Compost filter

A "compost filter"[11] is a novel pre-treatment method particularly when there is a desire to avoid biogas emissions. Up to now this aerobic process has only been used for single households or up to 70 p.e. for example in ecological sanitation projects where concentrated blackwater[12] requires pre-treatment (Gajurel et al., 2004; Hoffmann, 2008; Hoffmann et al., 2009).

[11] For further information on composting of faecal matter see also GIZ technology review on composting toilets: http://www.gtz.de/en/themen/umwelt-infrastruktur/wasser/9397.htm).

[12] Blackwater is only the toilet discharge (i.e. urine, faeces and flushwater).

The process functions as follows:

- The raw wastewater passes through a **filter bag** which is made of plastic material into a chamber with a ventilation pipe.
- The liquid effluent from the compost filter is collected below the filter bags and normally needs to be pumped to the constructed wetland, as the hydraulic head loss in compost filters is about 1.5 m.
- The solid components of the wastewater, i.e. faeces, food and toilet paper, are retained in the **straw bed** which is contained in the filter bag. Once a week dry straw has to be added to obtain a suitable carbon to nitrogen (C/N) ratio and also to act as a filtering and bulking material for better aeration of the compost.
- 2-4 filter bags are used in an alternating mode in two separate chambers. The dimensions of the chambers depend on the number of users. The retained solids are composted during the resting phase of six months, during which time the second bag is being used. During this time the volume reduction can be up to 75%.

The final product, after it has been fully aerated and left without addition of new material for six months, is black, compact material which looks and smells like black soil or humus. Nevertheless, the material still needs further treatment in another composting unit as it still contains pathogens such as helminth eggs (see Section 2.8.2).

Advantages of the compost filters include:

- The effluent or filtrate from a compost filter has no objectionable odours – at least not in warm climates – according to extensive experience of the main authors.
- There is no biogas production since it is an aerobic process. This is an advantage for the reasons described in Section 4.2.

Disadvantages of compost filters include:

- They need more "hands-on" maintenance than other pre-treatment methods.
- Their use is limited to small units.
- Compost filters only work with highly concentrated wastewater (such as blackwater from low-flush toilets), because otherwise too much solids may be washed from the filter bags.
- Blockages may occur, although this is usually due to having selected the wrong filter bags where the filter pores are too small.

Overall, the process appears to work reliably in warm climates, but possibly less so in cold climates, based on experiences in Linz, Austria and Berlin, Germany.

4.6 Imhoff tank

The Imhoff tank is a two-stage anaerobic system where the sludge is digested in a separate compartment and is not mixed with incoming sewage[13]. It can be used in moderate to cold climates. It is a compact and efficient communal system for pre-treatment of municipal wastewater from 500 up to 20 000 habitants. It removes about 30-40% of the organic matter of the raw wastewater.

[13] In the German wastewater literature, the term "Emscherbrunnen" is used for this type of tank.

The Imhoff tank is designed with three compartments:
1. Upper compartment for sedimentation
2. Lower section for sludge digestion
3. Gas vent and scum section

The sludge which is settled and stored in an Imhoff tank has to be removed periodically by a pump. It is stabilised and can be dried, composted or used directly in agriculture, as long as hygienic aspects are considered and relevant safety precautions taken (see Section 2.8.2).

There is more biogas production than in septic tanks, but unfortunately the organic load in communal wastewater is usually not high enough for the economical usage or flaring of biogas.

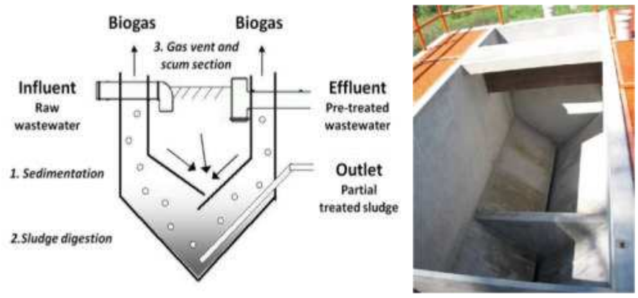

Figure 16. Left: Imhoff tank schematic with three compartments. Right: Imhoff tank under construction in a rural area of Peru (sources: H. Hoffmann, 2008).

4.7 Baffled tank

The baffled tank is an improved septic tank and is used for instance by BORDA[14] for primary wastewater treatment in communities with 200 to 2 500 inhabitants as part of their "DEWATS - decentralised wastewater treatment systems" (see Gutterer et al. (2009) for details). This type of system is also called anaerobic baffled reactor.

Characteristics of the baffled tank are:
- The baffled tank has 4-6 compartments instead of the 2 or 3 compartments of septic tanks. The total retention time is much shorter than in a septic tank: in warm climates 10-12 hours are used compared to 24-48 hours for septic tanks.
- The removal ratio for organic matter measured as BOD is about 40% in cold climates and 60% in warm climates; consequently the biogas production is higher than in septic tanks and the biogas should be burnt or used. Again, this is unfortunately not commonly done in practice due to the additional costs of the flare or gas pipework and biogas burner.
- The sludge is stabilised and can be used in agriculture as long as hygienic aspects are considered and relevant safety precautions are taken (see Section 2.8.2).

Baffled tanks have a higher removal ratio for organic matter (40-60% BOD removal) compared to septic tanks (typically 30%) due to the more efficient clarification and sludge retention in the baffled tank.

[14] BORDA is a German non-profit organisation: http://www.borda-net.org/

Also, a constructed wetland treating wastewater which has been pre-treated in a baffled tank needs only about 60% of the area of a constructed wetland which is treating wastewater after pre-treatment in a septic tank. Therefore, the higher costs of pre-treatment for the baffled tank are partially or fully offset by the lower cost for the constructed wetland.

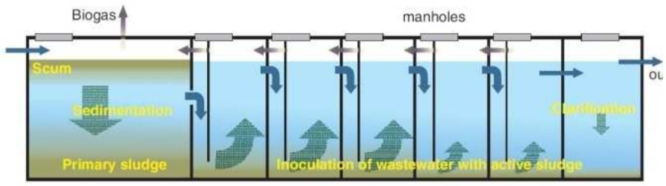

Figure 17. Schematic of baffled tank with six compartments (source: Gutterer et al., 2009).

4.8 UASB reactor

The upflow anaerobic sludge blanket (UASB) reactor is a technology for anaerobic treatment of wastewater developed by Mr. Lettinga from the Netherlands (van Haandel and Lettinga, 1995). It is often used in warm climates for municipal wastewater treatment and for industrial effluents with high organic loads such as bakery or brewery effluent. There are also many applications in Brazil for municipal wastewater.

The influent enters at the base of the UASB reactor and flows upwards. Due to the high loading and special design, the anaerobic bacteria form sludge granules, which filter the wastewater biologically and mechanically. The outlet for the treated wastewater and biogas caption is in the upper part of the reactor.

The UASB reactor is a very compact technology which achieves up to 80% organic matter reduction (measured as BOD). UASB reactors are only suitable for larger plants (> 5 000 p.e.) as they have a relatively high technical complexity. They have a low sludge production and the integrated biogas capture allows utilisation or flaring of biogas.

Sludge can be lost from the UASB reactor with the pre-treated wastewater and enter the CW filter bed. Therefore, the proper dimensioning of the decantation section in the UASB reactor is very important. The high efficiency of the pre-treatment with UASBs allows relatively small constructed wetland areas.

5 Design principles for subsurface flow CWs

This section explains general design principles for horizontal flow beds (HFBs) and vertical flow beds (VFBs), which are two types of subsurface flow constructed wetlands (SSF CWs). The filter bed consists primarily of sand and plant roots. The gravel in the bed does not have a filtering function, but is there to cover the influent distribution pipes and the drainage pipes, and to avoid puddles on the surface.

5.1 Horizontal flow beds (HFBs)

As the initial designs of subsurface flow CWs were for HFBs, these are still the most common type of subsurface flow CW. In the beginning HFBs often had poor effluent quality mainly due to inlet areas which were too small, but nowadays well-designed HFBs are widely accepted as a robust treatment system with low maintenance requirements. HFBs are an interesting option especially in locations without energy supply and low hydraulic gradient, whereas VFBs require pumps.

In HFBs the wastewater flows slowly through the porous medium under the surface of the bed in a horizontal path until it reaches the outlet zone (see Figure 18). At the outlet the water level in the HFB is controlled with an adjustable standpipe. For continuous operation the submerged height of the bed should be less than one third of the total height of the filter bed to avoid anaerobic conditions in the bed.

The organic matter in the wastewater is removed by bacteria on the surface of soil particles and roots of the plants. Oxygen supply plays an important role for the efficiency of the treatment process. Unlike for VFBs, the HFBs have very little additional external oxygen transfer. This is one of the reasons for the larger area requirement of HFBs.

The second reason is the smaller available inlet area: the inlet area consists of the width of the bed multiplied by the bed depth, whereas in VFBs the entire surface area is used as an inlet area.

Even in warm climates, there is little scope for area reduction of HFBs. They are thus less suitable than VFBs for urban applications where space is expensive.

If wastewater reuse is an objective, HFBs are not recommended in hot climates due to their very high evaporation rates in such climates.

Basic design recommendations for HFBs treating domestic wastewater are:

- While the surface of the filter is kept level to prevent erosion, the bottom slope should be 0.5-1% from inlet to outlet to achieve good drainage (Morel and Diener, 2006).
- The depth of filter beds is normally around 60 cm with an additional 15 cm freeboard for water accumulation.
- The required specific surface area is about **3-10 m²/p.e.** depending on temperature and other factors[15]. In warm climates less area is required due to the higher biological activity. In cold climates the minimum design value should not be below 5 m²/p.e. (for example in Germany).
- The organic loading per surface area should not exceed **4-10 gBOD/(m²·d)** in cold climates (Wood, 1995; Morel and Diener, 2006) or 16 gCOD/(m²·d) (DWA, 2006). No data is available for warm climates with coarse sand substrate.
- The hydraulic loading should be 60-80 mm/d for greywater (Wood, 1995; Ridderstolpe, 2004; Morel and Diener, 2006) and 40 mm/d for wastewater (DWA, 2006). However, the limiting factor is the organic load, which means that greywater with *low* organic load (from showers or laundry) can probably be applied to the HFB with even higher hydraulic loads.

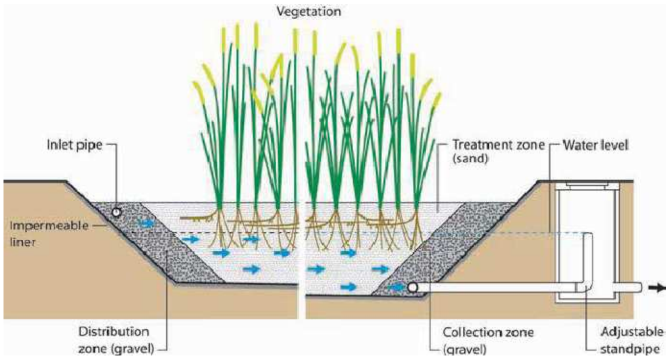

Figure 18. Schematic cross-section of a HFB (source: Morel and Diener, 2006).

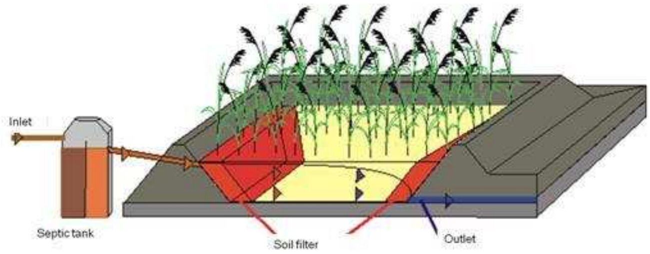

Figure 19. Schematic cross-section of a HFB showing pre-treatment with a septic tank on the left (source: Fehr, 2003).

Figure 20. Inflow zone with stones in a HFB near Leiria, Portugal (photo by J. Vymazal, 2003).

HFBs are simpler to design and build than VFBs, nevertheless they can still fail because of design errors. The most important point for proper design is the inlet zone which acts as a filter and removes a significant portion of suspended solids.

In HFBs clogging mostly occurs as an obstruction of the inlet area by suspended solids or accumulation of a biofilm (sludge). It is caused by insufficient pre-treatment, high loading, an undersized inlet area or filter material which is too fine.

[15] In general, the design parameter "area requirement per person" is lower when treating *greywater* from an average person. But since greywater characteristics vary widely (e.g. kitchen greywater versus shower greywater), it is better to use the BOD loading as a design parameter. For greywater with *low* BOD concentrations, the hydraulic loading can be used for the design.

Incorrectly designed HFBs may also exhibit "surface run-off". This occurs if the inlet area is too small or clogged, and the wastewater accumulates at the inlet area, floods the wetland and flows to the outlet without infiltration and hence without treatment.

To prevent clogging and surface run-off the following actions are recommended:

- The best method to avoid clogging and infiltration problems is to optimise the efficiency of the pre-treatment.
- The inlet zone can be filled with small rocks or coarse gravel and should have multiple vertical riser pipes to ensure that the wastewater is distributed evenly over the entire width and depth.
- Another possibility is to introduce a small dam after 2 m of the bed so that the first part of the HFB's surface serves as an inlet zone (Figure 21).
- It is absolutely necessary to carry out a hydraulic dimensioning by Darcy's law to ensure a sufficient hydraulic gradient in the filter bed[16].

The following points provide basic guidance for the design of HFBs with filter material of coarse sand:

- An efficient use of the filter area is given by a filter length (distance of inlet to outlet) of about 5-8 m (DWA, 2006). Longer filter lengths would lead to hydraulic problems.
- An inlet length (or bed width) of more than 15 m is uncommon in Germany; other design approaches use lengths up to 25 m. Certainly an inlet length of more than 30 m is not recommended as it leads to uneven flow distribution. Rather, the inlet area should be divided into several compartments with separate inlets.
- The grain size of the filter media should be large enough to allow continuous flow of the wastewater without clogging, but it should not be too large to reduce the efficiency of treatment.

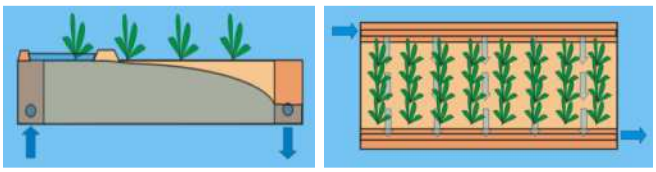

Figure 21. Left: Side view of the liquid level in a HFB showing inlet dam to control clogging and prevent surface run-off of the wastewater. Left vertical arrow is influent and right vertical arrow is effluent. Right: Top view of correct geometry of larger HFBs where filter length (see vertical arrows) is 5-8 m, and bed width (see horizontal arrows) is maximum of 30 m (source: Platzer, 2000).

5.2 Vertical flow beds (VFBs)

5.2.1 Basic design recommendations

VFBs are more suitable than HFBs when there is a space constraint as they have higher treatment efficiency and therefore need less space.

In VFBs wastewater is **intermittently pumped onto** the surface and then drains vertically down through the filter layer towards a drainage system at the bottom. The treatment process is characterised by intermittent short-term loading intervals (4 to 12 doses per day) and long resting periods during which the wastewater percolates through the unsaturated substrate and the surface dries out. The intermittent batch loading enhances the oxygen transfer and leads to high aerobic degradation activities. Therefore, VFBs always need pumps or at least siphon pulse loading, whereas HFBs can be operated without pumps.

Basic design recommendations for VFBs treating domestic wastewater are:

- The top surface of the filter has to be kept level and the distribution pipes are often covered with gravel to prevent open water accumulation during the pumping periods.
- The distribution pipes should be designed in such way that they achieve an even distribution of the pre-treated wastewater on the entire constructed wetland bed (see Figure 6). This is ensured by selecting the right diameter of the distribution pipes, length of pipes, diameter of holes and spacing between holes in the distribution pipes.
- The distance between drainage pipes is based on the detailed design but may be around 5 m. The drainage pipes are covered with gravel to enable good drainage.
- A bottom slope of 0.5-1% in direction to the outlet is important for large VFBs.
- The depth of the sand filter beds should be at least 50 cm, with an additional 20 cm of gravel at the base to cover the drainage pipes, 10 cm gravel on the top of the bed and 15 cm freeboard for water accumulation. The gravel on top prevents free water accumulation on the surface, and could in fact be omitted if there is no access to the CW for members of the public.
- The required specific surface area is usually **3-4 m²/p.e.** in cold regions and **1-2 m²/p.e.** in warm regions[17]. However, this may also vary depending on the reuse option and local legislation. The authors have good experiences with designing VFBs in warm climates with about 1.2 m²/p.e. (Platzer et al., 2007).
- The organic loading per surface area should be limited to **20 gCOD/(m²·d)** in cold climates (DWA, 2006; ÖNORM, 2009). This applies to greywater and wastewater. The authors have made good experiences with designing VFBs in warm climates with about **60-70 gCOD/(m²·d)**, corresponding to approximately 30-35 gBOD/(m²·d).
- The hydraulic loading for VFBs in cold climates should not exceed **100-120 mm/d** (DWA, 2006). The authors' experiences showed that in warm climates hydraulic rates up to 200 mm/d of pre-treated wastewater could be applied without negative influence. During rain events, a short-term hydraulic loading of up to 500 mm/d can be applied.
- The key factor in warm climates is dimensioning according to oxygen availability, see Section 5.2.2.

[16] In fluid dynamics and hydrology, Darcy's law is a phenomenologically derived equation that describes the flow of a fluid through a porous medium (source: www.wikipedia.org). See design manuals for details, such as Metcalf and Eddy (2003).

[17] In general, the design parameter "area requirement per person" is lower when treating *greywater* from an average person. But since greywater characteristics vary widely (e.g. kitchen greywater versus shower greywater), it is better to use the BOD loading as a design parameter. For greywater with *low* BOD concentrations, the hydraulic loading can be used for the design.

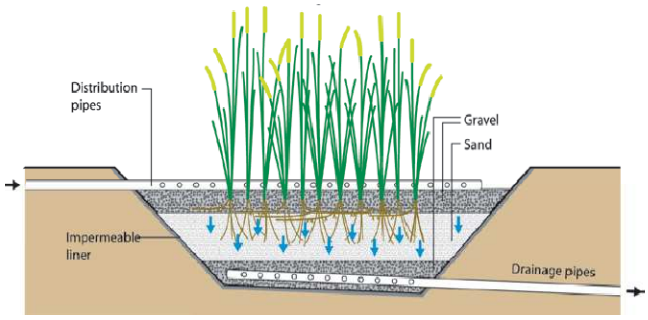

Figure 22. Schematic cross-section of a VFB (source: Morel and Diener, 2006)[18]. The middle layer of coarse sand typically has a height of 50 cm, the top gravel layer a height of 10 cm.

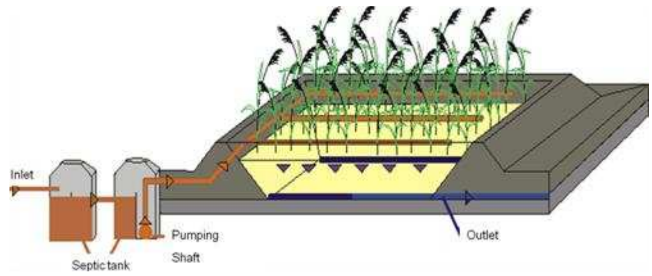

Figure 23. Schematic cross-section of a VFB showing pre-treatment with a septic tank on the left (source: Fehr, 2003).

The development of VFBs has been very rapid since the publication of first results at the IAWQ conference in Cambridge, UK (Cooper and Findlater, 1990). Due to their high treatment capacity for organic matter removal and nitrification, VFBs became "state of the art" during the past 20 years (Platzer, 1999; Philipi et al., 2006, Platzer et al., 2007).

Suspended solids and organic matter removal is around 90-99%. Almost complete nitrification with 90% ammonia oxidation is commonly reported. More information on nitrogen removal is provided in Section 3.1.3.

5.2.2 Soil clogging and soil aeration in VFBs

An extremely important aspect of VFBs is the potential risk of soil clogging which results in a general failure of the system (Cooper and Green, 1994; Platzer and Mauch, 1997; Winter and Goetz, 2003). "Temporary" soil clogging occurs regularly in VFBs and is part of the process. Regular resting of the beds reverses the temporary soil clogging.

In VFBs clogging occurs as an obstruction of the surface area by suspended solids or due to a fast growing biofilm (sludge). It is caused by poor pre-treatment, high loading or too fine filter sand. The term used in the literature is "soil clogging" even if the term "bed clogging" may be better.

Clogging is a normal reaction caused by the biological activity of the microorganisms. Therefore the system has to be designed large enough so that resting periods in parts of the filter bed can occur. Another possibility to avoid clogging is to keep the load low enough so that it does not occur due to the natural degradation processes.

The experiences with soil clogging in constructed wetlands differ widely since the problem depends on many factors. Sufficient soil (or bed) aeration is the main factor for the proper functioning of VFBs, and therefore the following design aspects are very important:

- Wastewater needs to be pumped onto the VFBs intermittently (**4-12 times per day**).
- VFBs treating municipal wastewater should have at least **4 beds** in order to be able to rest the beds on a regular basis: 6 weeks in operation and 2 weeks of rest.
- A uniform distribution of the wastewater is required.
- The filterable solids loading should be less than **5 g/(m²·d)** and this requires efficient pre-treatment.
- Adequate plants with well developed rhizome/root systems play an important role in maintaining and restoring soil conductivity.
- The hydraulic and organic load to the VFBs need to be checked regularly and should not exceed the design values given in the previous section.

In VFBs oxygen supply is the key consideration for efficient degradation of organic matter, for nitrification and to avoid clogging. That is why the commonly used design parameter "area per person equivalent" is not sufficient to guarantee good treatment results.

The dimensioning of VFBs based on oxygen demand was first developed by Platzer (1999). The design depends on the oxygen demand for oxidation of organic matter and for nitrification as well as the oxygen input (loading frequency, loading volume, roots and surface area).

The intermittent batch loading is most significant for oxygen input: an adequate oxygen transfer in VFBs is only guaranteed when application and infiltration occur in a short time with sufficient time lag to the next application.

There is still a lack of knowledge about the total impact of all the factors which can influence the treatment efficiency of the constructed wetland: The climate conditions, wastewater characteristics, plant influences and microbial degradation processes. Their interactions between each other are not yet fully understood. Every well planned, operated and monitored constructed wetland can give us important information to gain a better understanding of the treatment process.

5.3 The French System for combined primary and secondary treatment of raw wastewater

Since around 1990, a special vertical flow subsurface flow CW for treating raw wastewater has been used in France called the "French System". A very interesting aspect about this system is that it does *not* require a pre-treatment step, hence it avoids the associated problems of sludge production and unintentional biogas generation. The pre-treatment is instead performed within the first stage of the French System, which is also a VFB.

The following description of this two-stage VFB system is mainly based on a publication by Molle et al. (2005).

The first stage of the French System is a VFB filled with *gravel* and is designed for pre-treatment of raw wastewater. The raw wastewater, after screening or even without screening, is pumped onto this bed through pipes of typically 100 mm diameter. These distribution pipes have no holes along the pipe length, unlike those of conventional VFBs

[18] Note about this schematic: The distribution pipes are commonly *in* the top gravel layer.

which have small holes. The pre-treated effluent then passes through the second stage for further treatment, which is a VFB filled with *coarse sand*.

Molle et al. (2005) recommend dividing the first stage for raw wastewater treatment into three VFBs, and the second stage for secondary treatment into two VFBs as can be seen in Figure 24.

Figure 24. French System, from left to right: three VFBs (filters) for pre-treatment and two VFBs for secondary treatment in Albondón, Spain, with 800 inhabitants. The plant needs no electricity supply as it is built on a slope (photo by T. Burkard, 2005).

The first stage is operated in alternating phases to control the growth of biomass and maintain aerobic conditions in the VFB. Each VFB receives all raw wastewater for 3-4 days, and then is rested for 6-8 days while the other filter beds are used.

The raw wastewater is treated (or "filtered") in the first stage in vertical flow: it passes first through a 30 cm fine gravel layer (2-8 mm particle size), then through a 10-20 cm transition gravel layer (5-20 mm particle size) and then reaches the drainage layer (gravel with 20-40 mm particle size or even 30-60 mm particle size) in the bottom of the filter bed (see Figure 25). The solids are retained on the surface where they are mineralised[19] (see Figure 26).

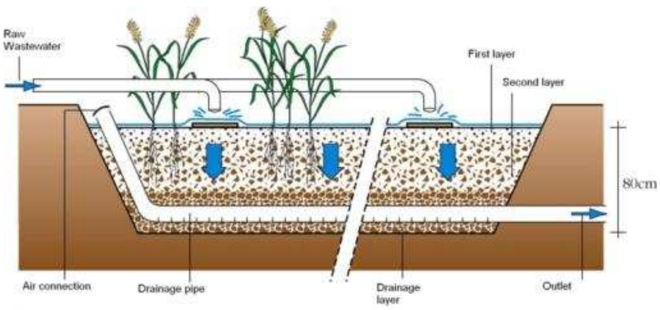

Figure 25. Pre-treatment of raw wastewater in the first stage (a VFB) of the French System (source: Molle et al., 2005). Wastewater flows out of the *end* of the distribution pipes (*without* small holes along the pipe length).

The two VFBs used in the second stage can be operated in parallel with the option to rest one filter or to alternate the operation. The VFBs of the second stage have a 30 cm sand layer (d_{10} of 0.25 mm to 0.4 mm)[20]. In France all the filter beds are usually planted with common reed (*Phragmites australis*).

Figure 26. Distribution pipes for raw wastewater in first stage (VFB) in French System in Albondón, Spain (photo by T. Burkard, 2007).

For dimensioning of the French System for municipal wastewater treatment, Molle et al. (2005) recommend:

- For the first stage: 1.2 m²/p.e. (equivalent to an average loading of 100 gCOD/(m²·d); 50 gTSS/(m²·d); 10 gTKN/(m²·d) and 120 L/(m²·d) divided over three identical alternately fed units.
- For the second stage: 0.8 m²/p.e. divided over two parallel or alternately fed filter beds. This results in a very low average load of 25 gCOD/(m²·d).

Molle et al. (2005) reported for the very highly loaded gravel bed (first stage) a removal efficiency of 80% COD, 86% TSS and 50% TKN, which is more efficient than any conventional pre-treatment process. In some countries these results would even be sufficient for river discharge. The retained solids form a sludge layer, which limits the infiltration and improves the water distribution on the surface.

The sludge accumulation on the filter bed of the first stage is about 1.5 cm per year. The sludge mineralises on the surface of the filter bed and has to be removed after 10-15 years, when a layer of up to 20 cm has accumulated. The reuse of the sludge for agricultural purposes is possible but, as always, depends also on the heavy metals content of the wastewater.

The second stage is needed to complete nitrification and to achieve pathogen removal and for further reduction of COD and TSS (this is called "polishing"). The French system for raw wastewater treatment typically removes 90% of COD, 96% of TSS and 85% of TKN.

This system is an interesting option for small communities as it is simple and low-cost. It avoids the disadvantages of conventional pre-treatment, namely primary sludge production and biogas emissions (see Section 4.2). The French System has been used since over 20 years, and approximately 500 constructed wetlands of this type exist in France. Some plants are now also in use in Germany, Portugal and Spain.

In general the space requirement of the French System in comparison to conventional VFBs and HFBs is as follows (as the French system already *includes* the pre-treatment, the

[19] In biology, mineralisation refers to the process where an organic substance is converted to an inorganic substance.

[20] The d_{10} is the grain diameter which corresponds to the grain size where 10% of the grains are smaller than that grain size (see Appendix for further details).

area requirement for pre-treatment would still need to be added in the case of VFBs and HFBs):

- for warm climates:
  HFB > French system > VFB (meaning VFBs require the least space)
- for cold climates:
  HFB > VFB > French system (meaning the French System requires the least space)

Disadvantages of the French System include:

- Due to the necessity of intermittent loading for *each* of the two stages, two pumping stations are necessary. A self priming siphon for the intermittent batch loading of the filter beds can sometimes be used to avoid pumping. Siphons need sufficient difference in height between the level of influent and the surface area.
- The French System is not suitable for small household level systems due to potential hygienic problems of having open access to raw wastewater in the garden or near the house.
- Many experts hesitate to build the French System because they fear lack of acceptance due to raw wastewater application onto the filter beds. The system should therefore not be built in densely populated areas in order to avoid problems with the social acceptance.

In our view, the French System has significant potential for the future for domestic wastewater treatment plants at community level which are fenced off to avoid uncontrolled access.

5.4 Hybrid systems

Various types of subsurface flow CWs can be combined in order to achieve higher treatment efficiencies especially for nitrogen and pathogen removal. In these systems, the advantages of the HFB and VFB systems are combined to complement each other. There has been a growing interest in hybrid systems, although they are more expensive to build and more complicated to operate than non-hybrid systems.

5.5 Project examples

Table 6 contains examples of constructed wetlands for treating greywater and domestic wastewater. In hot climates, the specific area can be relatively low, as the biological activity is high. It is however risky to build wetlands that are too aggressively designed with a low specific area, as there is a higher risk of process failure.

Table 6. Example area requirements for VFBs (see SuSanA case studies for details[21]).

Specific area (m^2/p.e.)	CW size parameters (measured values)	Location and type of wastewater
0.4	7 000 p.e.; 2 992 m^2; 300 m^3/d; (43 L/(cap·d))	Haran Al-Awamied, Syria (domestic wastewater after settling tanks)
0.9	3 000 people; 2 680 m^2; 150 m^3/d; (50 L/(cap·d))	Bayawan City, Philippines (domestic wastewater after septic tanks)[22]
1.7	140 people; 240 m^2; 10-13 m^3/d; (82 L/(cap·d))	Hamburg Allermoehe, Germany (greywater after settling tank)
1.7	460 p.e.; 771 m^2; flowrate not known	SolarCity Pichling Linz, Austria (greywater and filtrate from brownwater[23] compost filter)
1.9	270 p.e.; 500 m^2; 25-30 m³/d; (102 L/(cap·d))	Dubai, United Arab Emirates (greywater after settling)

Figure 27. Subsurface flow CW in Bayawan city, Philippines. The path in the middle separates the VFB and the HFB (photo by J. Boorsma, 2009; project supported by GIZ)[24].

Table 7 shows how the separated loads from greywater and blackwater were calculated for a school in Lima (Hoffmann, 2008; Hoffmann et al., 2009). Both wastewater streams are treated separately in two constructed wetlands and are subsequently used for irrigation purposes[25].

The school uses about 200 m³ potable water per month. 18 persons are constantly living in the school area and some 40 persons come from outside. The daily occupation was calculated with 70 p.e. As all sanitary installations already existed, greywater separation was only possible for the commercial school bakery, laundry and two kitchens (the school kitchen and a private one). In the school´s kitchen around 60 meals per day are prepared.

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[21] http://www.susana.org/lang-en/case-studies
[22] Wetland type: VFB followed by HFB
[23] Brownwater is a mixture of faeces and water.
[24] See SuSanA case study for more information: http://www.susana.org/lang-en/case-studies?view=ccbktypeitem&type=2&id=51
[25] For more information about this project in English please see SuSanA Case Study: http://www.susana.org/lang-en/case-studies?view=ccbktypeitem&type=2&id=70

The effluent from all bathrooms (with toilets, showers and sinks) and from two private kitchens is mixed together and called "blackwater". The specific blackwater load per person had to be estimated in advance, which is a common challenge in sustainable sanitation projects. It is always recommended to use adequate safety factors in the calculations in order to avoid overload situations.

Table 7. Example of the load calculation of greywater and blackwater streams and the resulting area occupation of the two CWs for a school in Lima, Peru (design basis was 70 p.e.). Italic text in brackets provides the reduction rates.

Units	Total[a]	Greywater		Blackwater	
		Separa-tion	**Grease trap**	**Separa-tion**	**Compost filter[b]**
L/d	7 000 *(100%)*	2 100 *(30%)*	*N/A*	4 900 *(70%)*	*N/A*
gBOD/d	3 500 *(100%)*	700 *(20%)*	630 *(-10%)*	2 800 *(80%)*	2 100 *(-25%)*
m² for VFB in warm climate with 30 g BOD/(m²·d)		*N/A*	21	*N/A*	70

Notes: N/A = no effect

[a] Wastewater flowrate was calculated by the known potable water use per month, BOD was based on Peruvian norm (see Table 8).

[b] Blackwater is pre-treated in a compost filter (see Section 4.5), 25% BOD reduction was estimated.

Results after two years of operation:

- The BOD removal in the VFBs for greywater (21 m²) and blackwater (70 m²) is about 95%.
- The removal of suspended solids is about 90% in the greywater VFB, and 86% in the blackwater VFB.
- The number of thermotolerant coliform bacteria is in the effluent less than 1 000 per 100 ml.
- All treated water is used for irrigation of crops, trees and green areas (Hoffmann, 2008).

6 Operation and maintenance

6.1 Operational tasks for HFBs and VFBs

Whilst constructed wetlands are "low tech" systems they still require adequate maintenance by a trained person with basic skills.

The pre-treatment unit requires maintenance as indicated in Section 4 depending on the type of technology. The efficiency of the pre-treatment units has to be checked on a regular basis. The larger the system, the higher the required frequency. The effluent from the pre-treatment system should be analysed for settleable solids by using an "Imhoff cone" in order to know the quantity of solids being transferred to the wetland. The sludge of the pre-treatment systems has to be removed regularly.

Figure 28. Left: Malfunctioning grease trap with too much sludge accumulation. Right: the sludge from the grease trap obstructs the infiltration area of the CW which has become black because there is no oxygen transport anymore and it has become clogged (photo by H. Hoffmann, 2009).

The operational tasks required for the constructed wetland filter bed includes regular checking of:

- pumps
- inlet structures for obstructions and for the water level
- outlet structures for the water level
- hydraulic loading rate and pollutant loads, i.e. influent and effluent concentrations of BOD and SS as well as influent flowrate
- wetland vegetation for disease, insects, etc. (remove weeds and predatory plants until the wetland vegetation is fully established).

If maintenance is ignored, the following consequences will occur sooner or later:

- uneven flow distribution
- local overloading and odour
- deterioration of treatment efficiency.

6.2 Tasks for the operation of HFBs

It is very important to check the filter bed for clogging. Clogging occurs for example in HFBs which were built too long, i.e. where the horizontal distance between inlet and outlet is too long. Such HFBs have a high hydraulic load in a relatively short inlet zone.

A possible refurbishment step for such HFBs is to split the HFB in the middle after half of the horizontal length, by digging a trench and placing drainage pipes there. The new trench will thus become an inlet or "feeding" trench as well. With this modification, the inlet zone doubles and the flow distance is halved.

Another possibility is to introduce a small dam after 2 m of the inlet to the bed (see Figure 21). With this measure, the first part of the HFB serves as an inlet zone.

Further tasks for the operator and thus considerations for the designer include:

- When sludge accumulates in the inlet zone of the HFB, the filter bed has to be taken out of operation so that it can dry out. In the worst case, all affected filter material in the inlet area has to be exchanged. Until the filter material is exchanged, the CW cannot operate and treat wastewater.

- Especially in the case of HFBs it is recommended to have the possibility to occasionally dam up the filter bed completely in order to be able to control the growth of the wetland plants.
- In order to guarantee sufficient aeration of the filter bed it is recommended to have the option to lower the water level down to the bottom of the HFB.

6.3 Tasks for the operation of VFBs

VFBs need more operation and maintenance than HFBs. The following operation and maintenance activities should be performed for VFBs:

- The even distribution of pre-treated effluent on the entire surface is important for VFBs and has to be monitored. Valves at the front of the distribution pipes and removable caps at the end allow the cleaning of the pipes during the pumping phases (see Figure 29). In case a filter bed, or areas of the filter bed, is affected by clogging and has to rest, the valves can be closed.
- Wastewater feeding intervals have to be maintained by an automatic system with pumps or siphons. However, VFBs for the treatment of greywater of households can be designed *without* a pump or siphon, if the production of greywater has suitable and regular intervals.
- The surface has to have the possibility to dry out between each charging with wastewater.
- Immediate action has to be taken in the case of clogging (see Section 5.2.2 for details). A VFB can recover well after a resting period of two weeks where the filter bed can dry out. However, in cold climate zones with low temperature and freezing periods (temperature 0-8℃) a VFB cannot recover so quickly. That is why VFBs have to be designed much larger in cold climate zones (see Table 3).
- It is better to *overload one part* of the filter bed in order to give the other part a rest than to expect the entire system to recover at the same time. Once clogged, the system does not recover without resting periods. It has been shown that a VFB can almost completely regain its efficiency after longer resting periods (Platzer and Mauch, 1997). Such a resting period is needed to completely dry out the clogged layer and may be as short as three weeks in a dry, sunny climate to about six months in a cold, wet climate.

Figure 29. Left: cleaning the wastewater distribution pipes by opening and closing valves and caps during the pumping phase (medium sized papyrus umbrella sedge plants just after re-planting). Right: opened cap on a blocked distribution pipe (photos of VFB for blackwater treatment at school in Lima, Peru by H. Hoffmann, 2009)

6.4 Should wetland plants be harvested or not?

Whether plants from constructed wetlands should be harvested or not is a question of debate. A general answer cannot be given, but plants need to be harvested if they affect the operation or the maintenance activities. Experiences in warm climate zones showed that in VFBs plants should be removed every two years to enable a visual check of the distribution system.

Also, there is a difference between a “hot and dry” and a “hot and humid” climate. For example, in Dubai with a hot and dry climate, the decay rate of the accumulated dead reed on the surface is very slow while in Brazil with a hot and wet climate it is very fast. Hence, a constructed wetland in Dubai will need more frequent harvesting than one in Brazil (see Figure 30 and Sievert and Schlick (2009)).

Benefits of harvesting plants from constructed wetlands include:

- Nutrients which have been taken up by the plants will be removed from the system.
- Less plant biomass can make maintenance tasks easier in the case of VFBs.
- It might be possible to use the plant material as fodder crop or straw.

Benefits of *not* harvesting plants from constructed wetlands include:

- Creation of an isolating layer of dead plant material – this is only important for moderate climate zones.
- Provision of a carbon source for denitrification if nitrogen removal is important.
- No alteration of the ecological functioning of wetlands.
- Less work for the maintenance staff.

Figure 30. Constructed wetland in Dubai for wastewater treatment where the reed reached a height of 6 m (photo by W. Sievert, 2007).

Figure 31. *Cyperus papyrus* after 12 months of growth in a VFB: Growth has occurred on the surface but without enough vertical roots. The plants may fall over and do not contribute to the treatment process anymore. They need to be removed and replanted (photo by H. Hoffmann, 2008).

6.5 Basic trouble-shooting

An indication of the performance of the filter bed can be obtained by checking the effluent of the constructed wetland for visual appearance and odour:

- Turbidity and/or greyish colour is an indicator for insufficient oxygen supply. The reaction should be:
  - In the case of VFBs, a uniform distribution should be ensured. It might be that the intervals between the influent pumping events are too short. Thus the surface cannot dry out and this may lead to clogging.
  - In case of HFBs the effluent drainage should be lowered in order to allow more oxygen supply within the filter bed.
- An unpleasant smell like foul eggs indicates anaerobic conditions within the filter bed. This is a very critical situation. The filter bed should be rested and the load to the filter bed should be lowered in order to increase the oxygen supply (see Section 5.2.2).
- Clear effluent but slightly yellowish or brownish colour due to humic acids is a normal situation in biological treatment systems, especially wetlands (see Figure 4).
- Oily matter in the effluent sometimes occurs especially in HFBs; this effect can also be caused by humic substances.

If possible, effluent samples should also be analysed professionally in a water laboratory from time to time, especially when the effluent is reused for irrigation.

7 References and further resources

Note: For all documents which are copyright-free, a URL link is provided. For journal articles use the websites www.sciencedirect.com or www.iwaponline.com to view the abstract and to see instructions for purchasing the article.

Articles from the "Water Science and Technology" journal can be viewed using www.sciencedirect.com up to volume 40, and from volume 40 onwards they are available on www.iwaponline.com.

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7.2 Further recommended reading

7.2.1 Various publications on constructed wetlands

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- Aguas de São Pedro, Brazil, 1998
- Orlando, FL, USA, 2000
- Arusha, Tanzania, 2002
- Avignon, France, 2004
- Lisbon, Portugal, 2006
- Indore, India, 2008
- Venice, Italy, 2010
- Perth, Australia, 2012 (planned)

For updated information see the IWA Water Wiki site of the Specialist Group at www.iwawaterwiki.org/.

Selected papers of the IWA Specialist Group Conferences have been published in:

- *Water Science and Technology* **35**(5), 1997
- *Water Science and Technology* **40**(3), 1999
- *Water Science and Technology* **44**(11-12), 2001
- *Water Science and Technology* **48**(5), 2003
- *Water Science and Technology* **51**(9), 2005
- *Water Science and Technology* **56**(3), 2007

Proceedings of the "Wetland Pollution Dynamics and Control (WETPOL)" conferences: www.wetpol.org

- Ghent, Belgium, 2005
- Tartu, Estonia, 2007
- Barcelona, Catalonia (Spain), 2009
- Prague, Czech Republic, 2011

Selected papers of the WETPOL Conferences have been published in:

- *Science of the Total Environment* **380**(1-3), 2007
- *Science of the Total Environment* **407**(13), 2009
- *Ecological Engineering* **35**(2), 2009
- *Ecological Engineering* **35**(6), 2009

Website of a large research project in Germany which was completed in 2003 and contains important reports (in German and English): www.bodenfilter.de/engdef.htm
(design of website: K. Tempel and H. Kolster, 2003; owner: G. Fehr)

7.2.2 Case Studies of the Sustainable Sanitation Alliance (SuSanA)

Case studies of sustainable sanitation projects with constructed wetlands are listed here (select by technology): http://www.susana.org/case-studies

7.3 Photos and technical drawings

GIZ and partners have compiled a large collection of constructed wetland photos on the photo sharing website Flickr.com, see here (or use the search word "constructed wetland"):
http://www.flickr.com/photos/gtzecosan/sets/72157622652353912/

Technical drawings are available here:
http://www.susana.org/lang-en/library/rm-technical-drawings

8 Appendix

8.1 Appendix 1: Characteristics of domestic wastewater and greywater

8.1.1 Domestic wastewater

Domestic wastewater is a mixture of all effluents in a household, i.e. from bathrooms, toilets, laundry and kitchen. Municipal wastewater contains domestic wastewater plus industrial wastewater, storm water runoff and infiltration water.

Table 8. Typical unit loading factors in raw wastewater for four countries.

Load g/(capita·d)	Brazil[a]	Peru[b]	Germany[c]	USA[d]
BOD	54	50	60	85
COD			120	198
TSS	90	90	70	95
TKN	10	12	11	13
Total P		3	1.8	3
Oil and grease	15[e]			31
Flowrate in L/(capita·d)	100-300[f]	150-250	100-150[f]	190-460

Notes:
[a] Jordão and Pessoa (2009)
[b] In Spanish: Norma de Saneamiento S.090 (1997) Resolución Ministerial Nº 048-97-MTC/15 VC del 27/01/97 – Reglamento Nacional de Construcciones, Perú
[c] DWA (2000), 85%-ile value
[d] Metcalf and Eddy (2003)
[e] Based on concentration values of oil and grease in Brazil
[f] Based on concentration values of BOD in Brazil/Germany

The characterisation of domestic wastewater is usually expressed as **load per capita**, and the typical values are well documented for industrialised countries but less so for developing countries. The mass of BOD discharged by individuals varies in a relatively narrow range (see Table 8) and this variation is primarily due to the differences in diet as well as socio-economic status. In developing countries such as Egypt, India, Palestine, Zambia or Kenya, the BOD loads are only around 30 g per person per day (Metcalf and Eddy (2003); Jordão and Pessoa (2009)).

The flowrate and concentration of the wastewater is a result of the potable water consumption. The per capital water consumption can vary immensely between countries or even within a country due to different income levels.

The Peruvian capital Lima for instance is situated in a desert, but wealthy households use up to 400 L water per person per day, whereas people who live in informal settlements without public water supply use only 20 L per person per day[26].

In contrast to the situation in Lima, the lower water consumption in Germany is due to more conscious use of water and due to higher water prices. Lower water consumption results in wastewater which is more concentrated but the mass loads per capita (such as gCOD/(person·d)) stay the same regardless of the respective water consumption.

The characterisation of domestic wastewater is not complete without discussing the presence of pathogens. This aspect is discussed separately in Section 8.2.

8.1.2 Greywater

Greywater is defined as household wastewater without toilet discharge. It should thus not contain urine and faeces but in practice it can contain traces of both, and thus traces of pathogens. For an estimate of the quantity, see Ridderstolpe (2004) and Ottoson (2003). The pathogens in greywater originate *mainly* from the following contamination pathways:

- Washing a person's anal area in the shower or bath.
- Washing nappies or underwear.
- Re-growth of pathogens (in particular bacteria) in the greywater collection tank.

Greywater is the wastewater from sources such as showers, baths, hand washing sinks, laundry, cleaning of floors, kitchen sinks and alike. Compared to domestic wastewater, greywater has significantly lower *per capita loads* of organic matter, nutrients (nitrogen and phosphorus) and pathogens. Standard values for these loads do not exist because greywater characteristics vary widely, depending on the sources of the greywater.

The *concentration* of organic matter in greywater may differ significantly from domestic wastewater: the organic matter concentration is much lower when the greywater is just from showers/laundries, but is higher when the greywater is from kitchens and restaurants.

A detailed analysis of greywater characteristics was published by Ridderstolpe (2004) for Swedish conditions and by Gulyas (2007) for German conditions. Greywater characteristics in South Africa and Kenya have been analysed by Carden et al. (2007), Mungai (2008), Kraft (2009) and Raude et al. (2009).

Greywater treatment and reuse for example as part of ecological sanitation (ecosan) concepts, is a relatively new concept which is often considered as a more simple form of wastewater treatment, but there is still a lack of experience. Most greywater treatment technologies are derived from conventional wastewater treatment and were not developed specifically for greywater treatment.

The quantity of greywater generated depends on the income level of the household. As a general rule: the richer the people, the more greywater they produce. Households without in-house water connection produce greywater which is more concentrated than wastewater from wealthy areas, due to the lower water consumption and existing reuse practices: Water is first used for personal hygiene, then for washing clothes and then for washing the floor.

For households with dry toilets such as pit latrines, urine diversion dehydration toilets[27] or composting toilets, the greywater production equals the total wastewater production of the household. On the other hand, for households with flush toilets, the greywater production is equal to the total wastewater flow minus the amount used for toilet flushing. Wastewater from toilet flushing is called "blackwater" and its quantity depends on the flush toilet type. Normally the volume varies between 40-60 L/(cap·d).

The following greywater quantities were measured at sustainable sanitation projects in Peru and Brazil by the main authors:

- Hand washing in public toilet: 0.5-1 L water per handwashing event
- Having a 5-minute shower: 40 L water
- Preparing a basic three-course meal in a restaurant and washing dishes afterwards: 5-25 L water.

The specific water use depends on the region and the appliances, and also the composition of these effluents is different and sometimes difficult to predict. Some examples are given below.

Greywater from showers or laundry:

- This greywater contains detergents, the degradability of which depends on the product; it is recommended to use biodegradable detergents. Textile fibres and human hair are often only poorly retained in greywater screens, and can cause problems in pumps and valves. Regular cleaning of the pumps and valves is required.
- Unexpected habits, such as urinating in the shower, could lead to odour problems when shower effluent is treated on its own (at hostels, sporting grounds or camping places) or when the effluent is stored before treatment.

Greywater from kitchens, bakeries or restaurants:

- This type of greywater can have a very high organic load from food scraps and oil and grease which can result in a high concentration of organic matter of more than 500 mgBOD/L. In this case anaerobic pre-treatment with use of biogas can be a suitable option, especially in warm climates.
- Greywater from kitchen sinks can have a high amount of sand from washing of vegetables, but most conventional grease traps are not designed for sand removal. See Section 4.3 for a solution of this problem.
- Furthermore the use of ash for dishwashing can cause problems with soil clogging in subsurface flow CWs, especially when the effluent is mixed with soap from laundry wastewater: Ash and soap form a coagulant which can pass grease traps but remains on the surface of the subsurface flow CW. Therefore, use of ash for dishwashing is not recommended here.

[26] 20 L water per person per day is regarded as the absolute minimum water consumption for staying healthy by the World Health Organisation (see "Water, health and human rights", 2003, http://www.who.int/water_sanitation_health/humanrights/en/).

[27] For more details on UDDTs (urine diversion dehydration toilets), see Winker and von Muench (2009).

8.2 Appendix 2: Further details on pathogens and their removal in constructed wetlands

Pathogens which are transmitted by wastewater or contaminated water (waterborne diseases) are for instance (WHO, 2006):

- Bacteria: *Escherichia coli, Salmonella typhi, Vibrio cholera, Shigella, Legionella, Leptospira, Yersinia.*
- Protozoa: *Entamoeba, Giardia* and *Cryptosporidium*.
- Helminths (intestinal worms): *Ascaris, Enterobios, Taenia, Schistosoma, Trichuris, Fasciola*.
- Viruses: *Adeno-, Entero-, Hepatitis A-, Polio-, Rota-, Norwalk Virus*.[28]

Typical diseases are unspecific diarrhoeas with cramps and vomiting, nausea, dehydration or typhoid fever, cholera, poliomyelitis or also respiratory diseases (such as adenovirus). Concentrations of pathogens in raw wastewater are shown in Table 9.

Table 9. Typical microorganism and pathogen concentrations found in raw wastewater.

Concentration (Number/100ml)	Brazil[29]	USA[30]	Typical values worldwide[31]
Thermotolerant coliforms	10^6-10^{10}	10^6-10^8	10^8-10^{10}
Helminth eggs	10-10^3	10-10^3	10-10^3
Giardia cysts	10^2-10^4	10^3-10^4	10^2-10^5
Cryptosporidium oocysts	10-10^2	10-10^3	10-10^4

Bacteria:
Most of the thermo-tolerant coliform bacteria types are not pathogens, but the probability that pathogenic bacteria are transmitted can only be minimised by reducing all of the bacteria. It is important to mention that bacteria survive in hot climates for longer periods (WHO, 2006)[32].

Helminth eggs:
The prevalence of helminth infections in the world correlate clearly with sanitation coverage. The infections rates of the population, particularly children, in developing countries can be very high. Helminths are transmitted by eggs, which are resistant against chlorine disinfection and are relative large (10-100 µm) (Metcalf and Eddy, 2003). Therefore, sedimentation in a pond with a long residence time as pre-treatment, followed by filtration in constructed wetlands show good elimination results.

The eggs persist in the sludge of waste stabilisation ponds and other sedimentation processes, and can survive for more than 10 years (Metcalf and Eddy, 2003). The eggs should be deactivated before this sludge is used in agriculture.

Helminth eggs are not affected by lime (calcium carbonate), mesophilic digestion nor by vermi-composting (composting with earthworms). Possible treatment methods to inactivate helminth eggs in faeces include thermophilic composting or long-term storage (WHO, 2006, volume 4).

Protozoa and viruses:
Protozoa like *Giardia* and *Cryptosporidium* have a significant impact on persons with compromised immune systems. The infection is caused by ingestion of contaminated water, and the cysts and oocysts are excreted with the faeces and are therefore common in wastewater. The elimination rate of these small particles (3-14 µm) is the same as for viruses.

Every stage of treatment eliminates some pathogens. Generally speaking, highly loaded systems eliminate fewer pathogens than low loaded systems with long retention times (see Table 10).

Table 10. Log unit reduction of pathogens by selected treatment processes (from WHO (2006), volume 2).

Treatment	Bacteria	Helminths	Protozoa	Virus
Primary settling	0-1	0-<1	0-1	0-1
Anaerobic digestion, UASB	0.5-1.5	0.5-1	0-1	0-1
Constructed wetland	0.5-3	1-3	0.5-2	1-2
Stabilisation pond	1-6	1-3	1-4	1-4

Experiences in Europe show that subsurface flow CWs with vertical flow and with efficient pre-treatment (septic tank or Imhoff tank) can produce effluents with only around 10^4 coliform faecal bacteria per 100 mL (Hagendorf, 2005), which is a good achievement. The pathogen removal efficiency depends on the retention time and on the filtering material: HFBs are more efficient than VFBs, and sand is always much more efficient than gravel.

Some reuse applications require a final disinfection of the effluent by tertiary treatment steps such as:

- Chlorine and chlorine compounds which cause oxidation of all organic matter. Chlorine is toxic to bacteria and all other organisms.
- UV radiation: works by inflicting photochemical damage on pathogens. UV radiation is more expensive than chlorine disinfection but is without environmental and health risks.
    - Cysts and oocytes are not inactivated by conventional disinfection using chlorine, whereas UV disinfection seems to be extremely effective (Metcalf and Eddy, 2003).
    - Viruses are inactivated by chlorine, but UV radiation seems to be more efficient for virus inactivation (Metcalf and Eddy, 2003).

Good pre-treatment and extended retention times in subsurface flow CWs with coarse sand is the best possible design for effective pathogen removal in constructed wetlands.

[28] There is no evidence that HIV, the virus that causes AIDS, is transmitted by wastewater (Metcalf & Eddy, 2003).
[29] Jordao and Pessoa (2005)
[30] Metcalf and Eddy (2003)
[31] WHO (2006), volume 2
[32] This could lead to more problems with waterborne diseases as a result of climate change in those regions where wastewater is not treated.

8.3 Appendix 3: Recommended grain size distribution of sand in subsurface flow CWs

It is important to pay attention to the grain size of the sand used as filter material in subsurface flow CWs. The most important aspect is a sufficiently coarse grain size. The d_{10} (see in the figure below), which corresponds to the grain size where 10% of the grains are smaller than that grain size, should be between 0.1 mm and 0.4 mm. Ideally, the d_{10} should be closer to 0.4 mm. The sand should not have a d_{10} coarser than 0.4 mm as the filtration effect in the filter bed would deteriorate. The steeper the sieving curve the better.

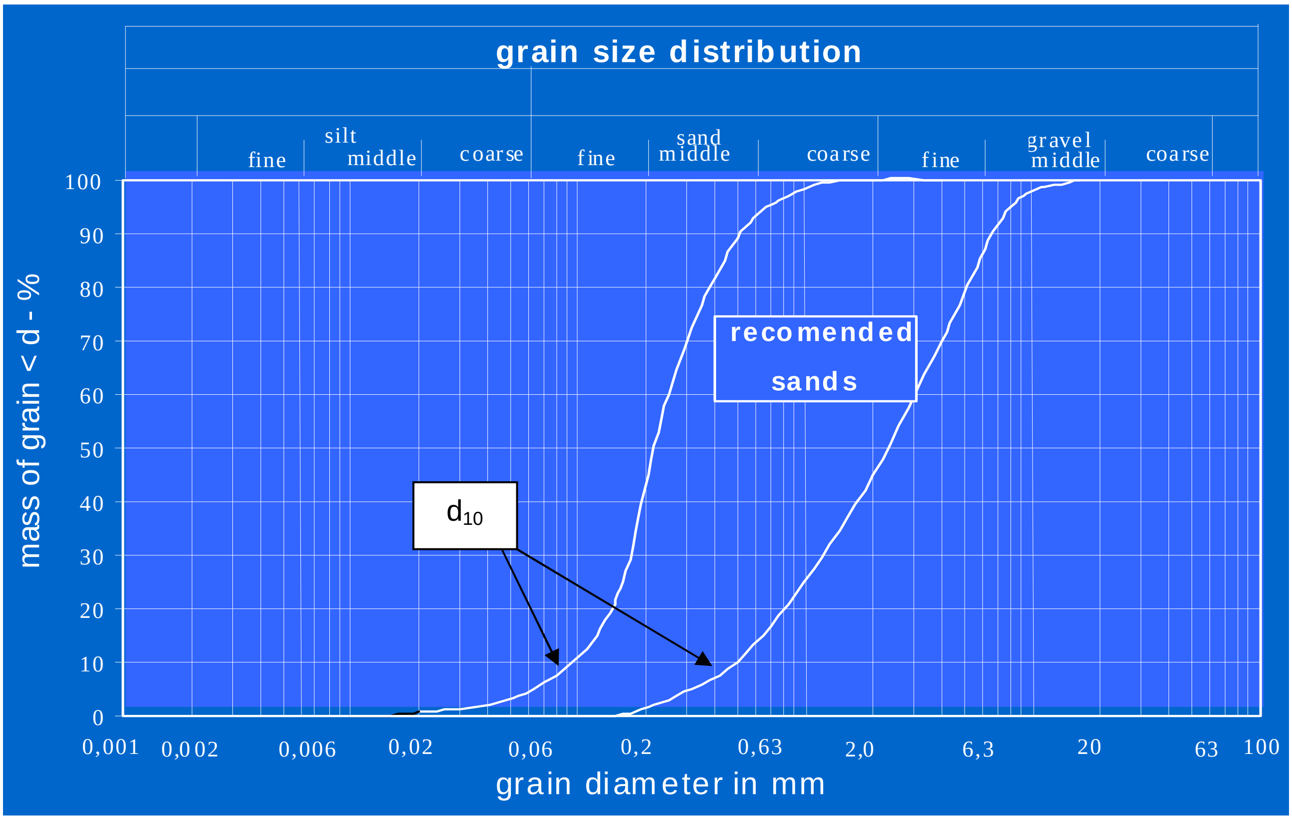

Figure 32. Recommended grain size distribution of sand in subsurface flow CWs (Platzer, 1998). The sieving curve of the sand should lie between the two curves indicated in the graph.

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Dag-Hammarskjöld-Weg 1-5
65760 Eschborn / Germany
T +49 6196 79-0
F +49 6196 79-1115
W info@giz.de
I www.giz.de

partner of
sustainable
sanitation
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