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WASTEnet - A Black Sea network promoting integrated natural WAStewater Treatment systEms

TECHNICAL GUIDELINES

on

Natural Treatment Systems for Wastewater Management of Rural Communities

Black Sea Basin 2007-2013
Joint Operational Programme

Common borders. Common solutions.

CONTENTS

1. INTRODUCTION

Wastewater is the liquid end product, or by product, of municipal, agricultural, and industrial activity. As such, the chemical composition of wastewater naturally reflects its origin. The term ‘wastewater’, however, implies that it is a waste product to be discarded in an environmentally sound manner. On the average, the overall wastewater generation rate varies significantly from country to country; for example, it is approximately 265 liters per capita and per day in the U.S. but it is less in European countries (e.g., in Greece it is about 180 liters per capita per day).

Understanding the nature of waste-water is fundamental for the design of appropriate wastewater treatment plants and the selection of effective treatment technologies. For the removal of contaminants from wastewater, physical, chemical and biological methods are used. In order to achieve different levels of contaminant removal and produce an acceptable effluent, wastewater treatment can be divided in three or four stages (preliminary, primary, secondary and tertiary or advanced treatment).

A host of new technologies and techniques for wastewater management are being developed around the world, in response to environmental, economic and societal limitations increasingly posed by conventional wastewater treatment systems. New approaches incorporate natural processes and are designed with sustainability in mind, in contrast to energy intensive and chemical dependent systems in current use.

The wastewater treatment in Greece is related to the quality of both surface and ground water resources. In order to avoid their contamination and impairment, local authorities have constructed large conventional wastewater treatment plants. However, these facilities can be applied to highly urbanized areas, but not to rural areas and small, isolated and/or peri-urban communities. In these areas, wastewater usually goes to septic tanks, due to the lack of sewage treatment units, with a common practice the illegal discharge of the septic tanks overflow to adjacent streams or storm sewers. An ideal solution for not only the elimination of this kind of problems but also for the wastewater treatment in these areas is the application of Constructed Wetlands.

CWs combine low-cost, low-maintenance, simple and reliable operation and high removal efficiencies. These systems are more appropriate for small to medium communities, where the resources and the skilled personnel required for the operation of conventional systems are often limited. Furthermore, CWs could be an excellent alternative for the production of effluents that can be reused for irrigation. The CWs can be applied for various functions, which include primary settled and secondary treated sewage treatment, tertiary effluent polishing and disinfecting, urban and rural runoff management, toxicant management, landfill and mining leachate treatment, sludge management, industrial effluent treatment, enhancement of instream nutrient assimilation, nutrient removal via biomass production and export, and groundwater recharge.

A great amount of studies has proved that these systems can effectively improve water quality; can be used in new applications and on new contaminants, for the treatment of various types of wastewater (municipal, industrial, agricultural and stormwater) and sludge; etc. However these systems serve other purposes as well. They also provide indirect benefits, such as aesthetic improvement of the landscape, creation of wildlife habitat, and recreational and educational opportunities.

It is true that the past few decades the scientific community has not only shown interest in these systems but also has begun to study and utilize these systems for meeting wastewater treatment and water quality objectives in a controlled manner. These systems are now promoted to various potential users, such as tourism industry, governmental departments, private entrepreneurs, private residences, aquaculture industries and agro-industries. On the whole, this technology is now mature and tested.

The design and construction of CWs are very simple. CWs require low construction, labor and maintenance costs in comparison to the Conventional Treatment Systems for the treatment of the same volume of wastewater. In addition, CWs do not require frequent monitoring and specialized staff as well as mechanical devices and depend only on natural processes and renewable energy sources. The only limiting factors are the availability and the cost of land to place the CWs and their vulnerability to climate.

In order to create an effective constructed wetland, there are several criteria. The principal design criteria for a constructed wetland system include the type of wastewater, substrate types, vegetation, pollutant loading rate and retention time. The design summary consists of several guidelines such as the system configuration, the flow (by gravity), the bottom slopes, the water depth, inlet and outlet structure etc. The CWs design should be as easy to operate as possible while ensuring reliable treatment.

There are several configurations for the construction of CW system and for its incorporation into the treatment system. System configuration includes length-to-width ratio, compartmentalization, and the location of single or multiple discharge points. The configuration should take advantage of the natural topography of the site in order to minimize excavation and grading costs. A crucial parameter to pay attention is the ensuring of equal flow distribution at the inlet and to avoid short-circuiting of flow to the outlet.

2. DESIGN OF CONSTRUCTED WETLANDS

2.1 INTRODUCTION

BEFORE designing a constructed wetland, it should be borne in mind that the substrate of the wetland can be rapidly filled up with debris, grit, and solids from raw wastewater if these materials are not removed prior to the wetland. Therefore, a minimum preliminary/ primary treatment should be provided to remove the settleable solids.

HF wetland is approved well to remove BOD_5 and TSS for secondary wastewater treatment but not for nitrification due to the limited oxygen transfer capacity. As a result there has been a growing interest in VF wetland because they have a much greater oxygen transfer capacity and considerably less area requirement than HF. But VF wetlands also have some limitation like less efficient in solids removal and can become clogged if the media selection is not correct. Due to these reasons, there has been a growing interest in combined (hybrid) wetlands. In these systems, the advantages and disadvantages of the HF and VF can be combined to complement each other.

Depending on the purpose, hybrid wetlands could be either HF wetland followed by VFwetland or VF wetland followed by HF wetland (Figure 1).

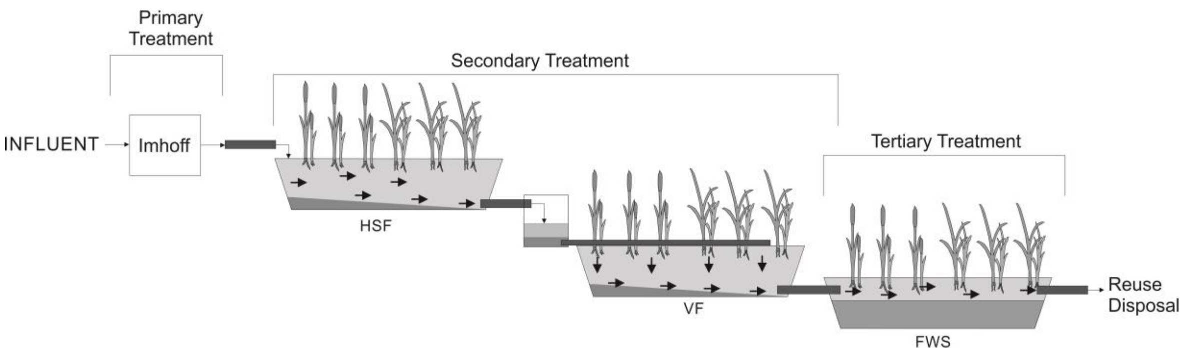


Figure 1 Indicative hybrid constructed wetland flow chart

2.2 PRELIMINARY TREATMENT

Preliminary treatment mainly separates the coarsely dispersed solids out of the liquid phase. The preliminary treatment prepares wastewater influent for further treatment in wetland by reducing or removing problem wastewater characteristic that could otherwise impede operation or unduly increase maintenance of the wetland and pumps (if any). The typical problem characteristics include large solids and rags; grit; odours etc.

The preliminary treatment of wastewater comprises of mainly screen and grit chamber. A screen is a device with openings, generally of uniform size, that is used to retain solids found in the influent wastewater to the treatment plant, which removes coarse materials from the wastewater. Grit chamber remove grit, consisting of sand, gravel, or other heavy sold materials that have specific gravities much greater than those of the organic solids in the wastewater.

2.3 PRIMARY TREATMENT

Primary treatment separates the suspended matter by physical operations mainly sedimentation. Raw wastewater contains suspended particulate heavier than water; these particles tend to settle by gravity under quiescent conditions. Primary treatment reduces suspended solids, organic load to the wetland and also equalises raw wastewater quality and flow to a limited degree.

2.2.1 SEPTIC TANK

The septic tank is the most common primary treatment used in small-scale constructed wetland worldwide. A two-compartment septic tank will remove more solids than a single compartment tank (Loudon et al., 2005). Figure 2 depicts a schematic cross-section of a typical double-compartment septic tank.

Septic tanks will generally need to be desludged, otherwise they produce very poor effluents with high suspended solids content, which can be detrimental to the constructed wetland (clogging of beds). To ensure continuous effective operation, the accumulated material must therefore be emptied periodically. This should take place when sludge and scum accumulation exceeds 30 percent of the tank's liquid volume.

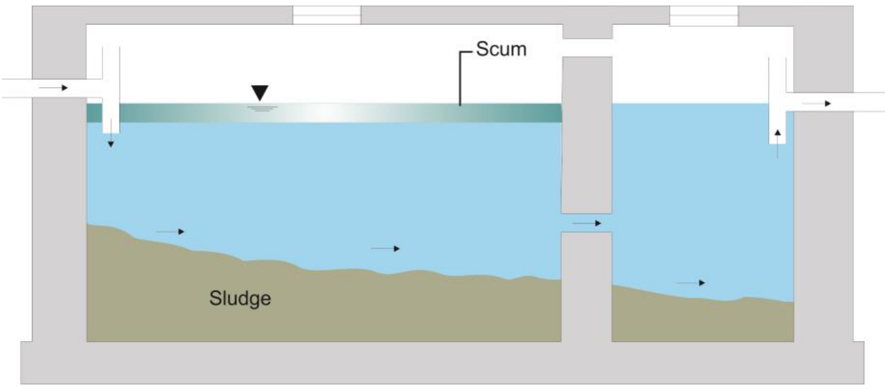


Figure 2 Schematic cross- section of a two-compartment septic tank

The basic design criteria for a two-chambered septic tank are shown in Table 1.

Table 1. Basic design criteria for two-compartment septic tank

Hydraulic retention time	> 12 hours at maximum sludge depth and scum accumulation
Sludge accumulation rate	Depending on TSS removal rate and wastewater flow (70-100 l/pe/y)
Sludge and scum accumulation volume	Sludge accumulation rate multiplied by sludge accumulation rate
Desludging interval	> 1 year
Volume of first compartment	Two-third of the entire tank volume

2.2.2 ANAEROBIC BAFFLE REACTOR (IMPROVED SEPTIC TANK)

In recent years, anaerobic baffle reactor (improved septic tank) designs have been developed to enhance removal efficiencies of solids and organic pollutants. The basic principle of such systems is to increase contact between the entering wastewater and the active biomass in the accumulated sludge. This is achieved by inserting baffles into the tank and forcing the wastewater to flow under and over the baffles as the wastewater passes from inlet to outlet. Wastewater flowing from bottom to top passes through the settled sludge and enables contact between wastewater and biomass.

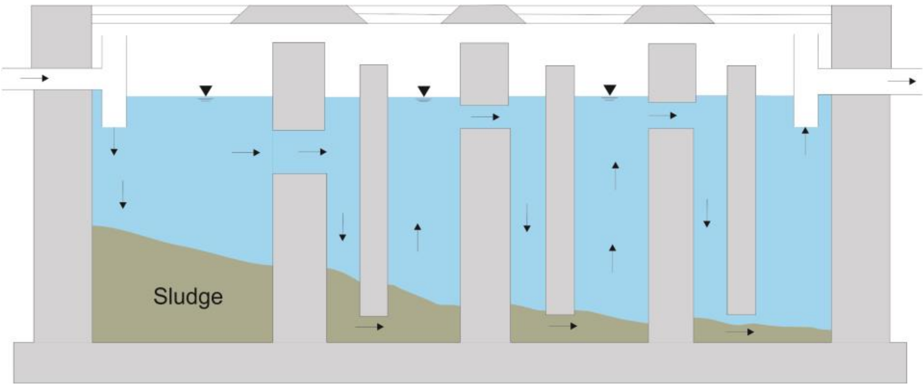


Figure 3 Schematic cross- section of an up flow anaerobic baffle reactor

The basic design criteria for an anaerobic baffle reactor are shown in Table 2.

Table 2. Basic design criteria for an anaerobic baffle reactor	
Hydraulic retention time	> 24 hours at maximum sludge depth and scum accumulation
Sludge accumulation rate	Depending on TSS removal rate and wastewater flow (70-100 l/pe/y)
Sludge and scum accumulation volume	Sludge accumulation rate multiplied by sludge accumulation rate
Desludging interval	> 1 year
Number of upflow chambers	>2
Maximum upflow velocity	1.4 - 2 m/h

Figure 4 Screen device at Nea Madytos CW

Figure 5 Imhoff Septic Tank at Nea Madytos CW

2.4 SIZING

2.3.1 SIZING BASED ON EQUATION

The wetland might be sized based on the equation proposed by Kickuth:

$$A_h = \frac{Q_d\left(\ln C_i - \ln C_e\right)}{K_{BOD}}$$

where

- A_h = Surface area of bed (m^2)
- Q_d = average daily flow rate of sewage (m^3/d)
- C_i = influent BOD_5 concentration (mg/l)
- C_e = effluent BOD_5 concentration (mg/l)
- K_{BOD} = rate constant (m/d)

K_{BOD} is determined from the expression $K_T dn$, where,

- $K_T = K_{20}\left(1.06\right)^{(T-20)}$
- K_{20} = rate constant at 20 °C (d^{-1})
- T = operational temperature of system (°C)
- d = depth of water column (m)
- n = porosity of the substrate medium (percentage expressed as fraction)

K_{BOD} is temperature dependent and the BOD degradation rate generally increases about 10 % per °C. Thus, the reaction rate constant for BOD degradation is expected to be higher during summer than winter. It has also been reported that the K_{BOD} increases with the age of the system.

2.3.2 SIZING OF FWS CONSTRUCTED WETLANDS

The present study employs the constructed wetland design theory and typical kinetic rate constants for municipal wastewater in computing pollutant removal efficiencies. The following assumptions have been made:

• The water temperature can be assumed approximately equal to the mean ambient temperature. This is a reasonable assumption for relatively warm climates (Kadlec and Knight, 1996).

• The removal rates for BOD and nitrogen in FWS constructed wetland systems are typically based on first-order kinetics and on the assumptions of plug flow, and are based on the models proposed by the USEPA (1988) and Reed et al. (1995), which have been used in the design of most constructed wetland systems in the U.S. and Europe (Chen et al., 1999; Economopoulou and Tsihrintzis, 2003).

BOD and nitrogen removal rates in FWS constructed wetlands are estimated by the following general Equation (1) (Reed et al. 1995), whereas, coliform and phosphorus removals by general Equation (2) (Kadlec and Knight, 1996):

$$\frac{C_e}{C_i} = e^{-K_T t} \tag{1}$$

$$\frac{C_e}{C_i} = e^{-\frac{K_1}{h_1}} \tag{2}$$

In these two general equations: C_e is the pollutant effluent concentration [mg L^{-1} of BOD, nitrogen or phosphorus, or number of fecal coliforms/100mL]; C_i is the pollutant influent concentration [mg L^{-1} of BOD, nitrogen or phosphorus, or number of fecal coliforms/100mL]; K_T is a reaction rate parameter [d^{-1}] dependent on the water temperature T [^{o}C], and the pollutant of interest (Table I): K_1 is a reaction rate constant [m d^{-1}] dependent on the pollutant of interest (Table I);h_1 is the hydraulic loading rate [m d^{-1}]; and t is the hydraulic residence time (HRT) in the system [d]. The last two parameters are defined by the following equations:

$$h_1 = \frac{Q}{A} \tag{3}$$

$$t = \frac{V}{Q} = \frac{Ay\varphi}{Q} = \frac{y\varphi}{h_1} \tag{4}$$

where Q is the design flow rate [m^3 d^{-1}], assumed constant; A is the mean surface

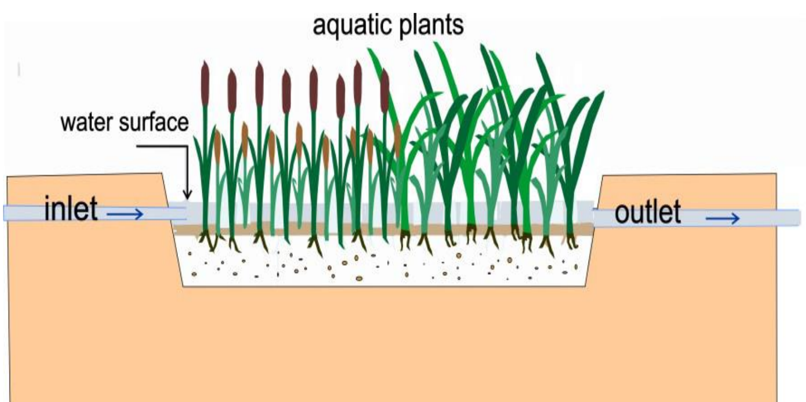


Figure 6 Schematic cross- section of a free water surface flow constructed wetland

area of the system [m^2]; V is the system volume [m^3]; y is the flow depth [m]; φ is the fractional porosity, which expresses the space available for water to flow through the vegetation and litter in the FWS constructed wetland system (Reed et al., 1995).

This section presents a procedure for rapid sizing of a new FWS constructed wetland, based on specified BOD, pathogen, nitrogen and phosphorus removal efficiency. In sizing a new FWS constructed wetland, the following parameters are typically known: the design values of Q, C_e/C_i for one or more pollutants, T,$L:W$ (preferably between 2:1 to 5:1) and the vegetation porosity φ (typically in the range of 0.65 to 75) (Reed et al. 1995). To size the system with the above variables specified, the following procedure is used (Economopoulou and Tsihrintzis, 2004):

i. The value of y is computed from Equation (5), which should be in the range 0.1 m to 0.6 m. If y > 0.6 m, two parallel systems are considered or the ratio $L:W$ is reduced (Reed et al., 1995). For the computed value of y, it is checked if Equation (6) holds.

$$y = \left(\frac{1}{\alpha}\frac{\frac{L}{W}Q}{\gamma}\right)^{1/4} \qquad (5)$$

$$K_T \leq -\frac{10 ln\left(\frac{C_e}{C_i}\right)}{C_i y \varphi} \qquad (6)$$

ii. If BOD removal is required, then the hydraulic residence time $t_{BOD}\,[d]$ is estimated on the basis of Equation (1) and the appropriate reaction rate constant of Table I.

iii. If coliform removal is required, then the hydraulic residence time $t_{COLI}\,[d]$ is estimated on the basis of Equations (2) and (4) and the appropriate reaction rate from Table I.

iv. If nitrogen removal is required, then the hydraulic residence time $t_{TN}\,[d]$is estimated on the basis of Figure 1, or Equation (9), and the appropriate reaction rate from Table I.

v. If phosphorus removal is required, then the hydraulic residence time $t_{PHOS}[d]$ is estimated on the basis of Equations (2) and (4) and the appropriate reaction rate from Table I.

vi. From the above steps up to four hydraulic residence time values are estimated. depending on the removal requirements of the pollutants. The design value of the hydraulic residence time is the maximum of these four values.

vii. Steps 1-5 are repeated for winter and summer conditions (i.e.. lowest winter and summer season temperatures) resulting in two hydraulic residence time values. On the basis of these two values and the corresponding populations, the design conditions are determined.

viii. From the estimated surface area (Steps 1-7) and the chosen aspect ratio L:W. the values of W and L are easily computed.

Table 3. Pollutant removal equations and rate constants for FWS constructed wetlands

Pollutant	Equation used	Rate constant	Rate constant units
BOD	(1)*	$K_T = 0.678(1.06)^{T-20}$	[d^{-1}]
Fecal coliforms	(2)**	$K_1 = 0.3$	[m d^{-1}]
Nitrogen			
Nitrification	(1)*	$K_T = 0.0389T \quad 0 < T < 1^oC$	[d^{-1}]
		$K_T = 0.1367(1.15)^{T-10} \quad 0 < T < 10^oC$	[d^{-1}]
		$K_T = 0.2187(1.048)^{T-20} \quad T > 10^oC$	[d^{-1}]
Denitrification	(1)*	$K_T = 0.023T \quad 0 < T < 1^oC$	[d^{-1}]
		$K_T = 1.15^{(T-20)} \quad T > 1^oC$	[d^{-1}]
Phosphorus	(2)**	$K_1 = 0.0273$	[m d^{-1}]

*by Reed *et al.* (1995), **by Kadlec and Knight (1996)

2.3.3 SIZING BASED ON SPECIFIC AREA REQUIREMENT PER POPULATION EQUIVALENT (PE)

The specific area requirement per PE holds true where there is uniformity in the specific wastewater quantity and quality. In general, the rules of thumb suggested by several works can be served as a safe bed (depending on the climatic conditions). However the investment costs tend to be higher due to conservative aspects of this approach.

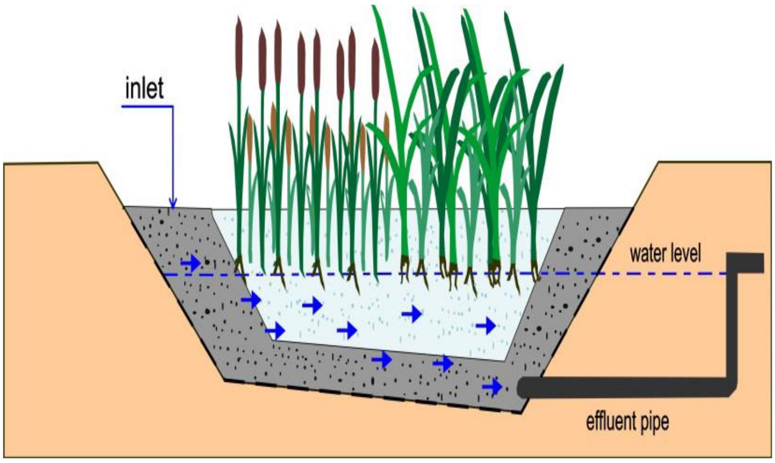
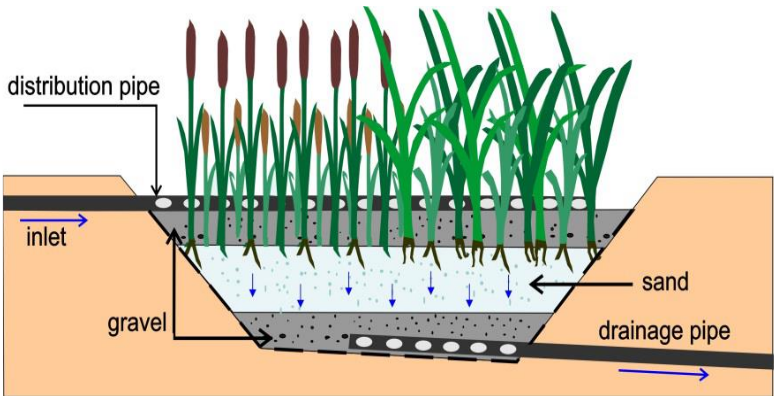


Figure 7 Schematic cross- section of a horizontal flow constructed wetland



Specific area requirement for HF and VF constructed wetland has been calculated for various specific wastewater discharges for a certain population. The BOD contribution has been taken as 40 g BOD/pe.d, 30% BOD load is reduced in the primary treatment and the effluent concentration of BOD is taken as 30 mg/1. The $K_{BOD}$for HF and VF wetlands are taken as 0.15 and 0.20 respectively. It is seen that a specific area requirement of 1 - 2 m^2/pe would be required of HF constructed wetlands where as a specific area of 0.8 - 1.5 m^2/pe for the VF wetland.

Figure 8 Schematic cross- section of a vertical flow constructed wetland

2.5 DEPTH

In general, the depth of substrate in a subsurface flow constructed wetland is restricted to approximately the rooting depth of plants so that the plants are in contact with the flowing water and have an effect on treatment. However, Hydraulic Retention Time - HRT (time the wastewater is retained in the wetland) is to be considered in the selection of the depth of the wetland.

2.4.1 HF WETLAND

Most HF wetlands in Europe provide a bed depth of 60 cm (Cooper et al., 1996). In the United States, HF wetlands have commonly been designed with beds 30 cm to 45 cm deep (Steiner and Watson, 1993). An experimental study carried out in Spain showed that shallow HF wetlands with an average depth of 27 cm were more effective than deep HF wetlands with an average water depth of 50 cm. (Garcia et al., 2004).

It is recommended to use an average depth of 40 cm taking into considerations of the precipitation, which could cause surface flow.

2.4.2 VF WETLAND

Generally, VF systems are built with larger depths compared to HF systems. Most VF systems in UK are built 50 - 80 cm deep (Cooper etal., 1996). In contrast to that, depth greater than 80 cm is recommended in Germany (ATV, 1998). Similarly, in Austria a depth of 95 cm is recommended (ONORM1997). A minimum of 100 cm depth is recommended in Denmark (Brix, 2004). The VF systems in Nepal were also built about 100 cm deep but nowadays shallower depths are being practiced.

In a subtropical climate, it is possible to increase the applied loading rates above guidelines issued in Central Europe and achieve nitrification in VF system. The average results by vertical beds of 75 cm depth showed better performance in comparison with vertical beds of 45 cm depth (Philippi et al., 2004).

It is recommended to use substrate depth of 70 cm, which can provide adequate nitrification in addition to the organic pollutants removal.

2.6 BED CROSS SECTION AREA (ONLY FOR HF WETLAND)

Dimensioning of the bed is derived from Darcy's law and should provide subsurface flow through the gravel under average flow conditions. Two important assumptions have been made in applying the formula:

- hydraulic gradient can be used in place of slope and
- the hydraulic conductivity will stabilize at 10^{-3} m/s in the established wetland.

The equation is:

$$A_c = Q_s / K_f (dH/ds)$$

- A_c = Cross sectional area of the bed (m^2)
- Q_s = average flow (m^3/s)
- K_f = hydraulic conductivity of the fully developed bed (m/s)
- dH/ds = slope of bottom of the bed (m/m)

For graded gravels a value of K_f of 1 x $10^{-3}$to 3 x 10^{-3}m/s is normally chosen. In most cases, dH/ds of 1% is used.

There is no hard and fast rule on the optimum width of the wetland, however, it is recommended that if the width of the wetland is more than 15 m, the wetland cell should be partitioned to avoid short circuiting of wastewater inside the wetland. It should also be kept in mind that it is better to use at least two parallel cells instead of a single wetland cell for the ease in operation and maintenance of the wetland.

In VF wetlands, since the flow is vertical, the width and cross-sectional area of VF beds not set by a requirement to keep the flow below surface and prevent surface flow.

2.7 MEDIA SELECTION

The media perform several functions. They:

- are rooting material for vegetation,
- help to evenly distribute/collect flow at inlet/outlet,
- provide surface area for microbial growth, and
- filter and trap particles.

Very small particles have very low hydraulic conductivity and create surface flow. Very large particles have high conductivity, but have little wetted surface area per unit volume of microbial habitat. Large and angular medium is inimical to root propagation. The compromise is for intermediate-sized materials generally characterized as gravels. It is recommended that the gravels are washed because this removes fines that could block the void spaces.

2.6.1 HF WETLAND

It is reported that the diameter size of media used in HF wetlands varies from 0.2 mm to 30 mm (ONORM B 2505, 1996, Vymazal, 1997, GFA, 1998, U.S. EPA, 1988, Steiner and Watson, 1993, U.S. EPA, 1993, Reed etal., 1995, U.S. EPA, 2000).

It is recommended that the media in the inlet and outlet zones should be between 40 and 80 mm in diameter to minimize clogging and should extend from the top to the bottom of the system. For the treatment zone, there does not appear to be a clear advantage in pollutant removal with different sized media in the 10 to 60 mm range (U.S. EPA, 2000). Figure 7 shows the recommended substrate sizes, which uses 40 - 80 mm media at the inlet/outlet zones and 5-20 mm at the treatment zone.

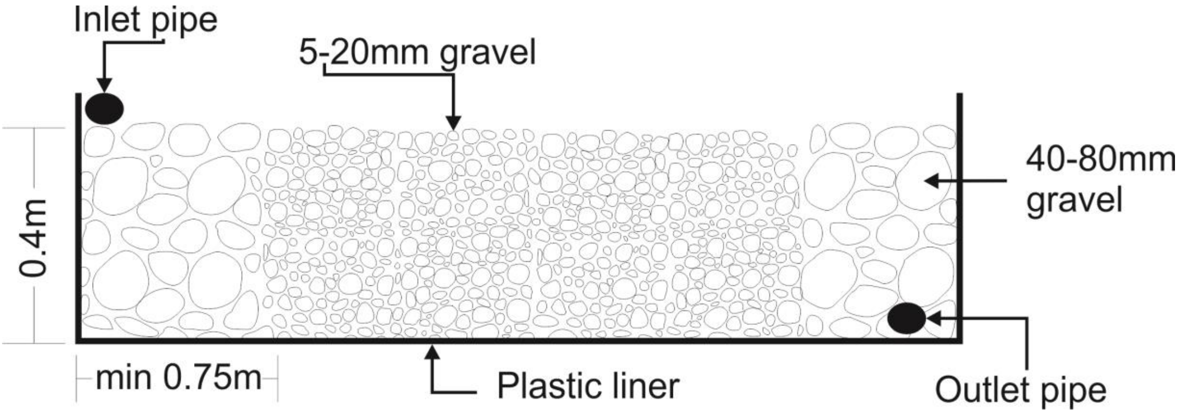


Figure 9 Substrate arrangement in a HF wetland

2.6.2 VF WETLAND

The substrate properties, d_{10} (effective grain size), d_{60} and the uniformity coefficient (the quotient between d_{60} and d_{10}) are the important characteristics in the selection of the substrate. There is not one uniform standard substrate design for the construction of VF wetland. Various literatures reports effective grain size should be $0.2 < d_{10} < 1.2$ mm, uniformity coefficient $3 < d_{60}/d_{10} < 6$ and hydraulic conductivity K_f 10^{-3} to 10^{-4} m/s (Reed etal., 1990; Vymazal etal., 1998; GFA, 1998; Brix, 2004;Korkusuz, E.A., 2005).

The rate of decrease in permeability for similar SS influent characteristics is highest for porous media with smaller pore sizes. Compared to the gravel, the sands show a relatively more rapid reduction in their permeability due to effects of sediment accumulation at the surface of the sands. However, the depth of clogging is higher for larger particle sizes (Walker, 2006).

It is recommended to use sand (0-4 mm) as main substrate with d_{10}> 0.3 mm, d_{60}/d_{10}< 4 and having permeability of 10^{-3} to 10^{-4}m/s. The substrate shall be arranged as shown in Figure 8.

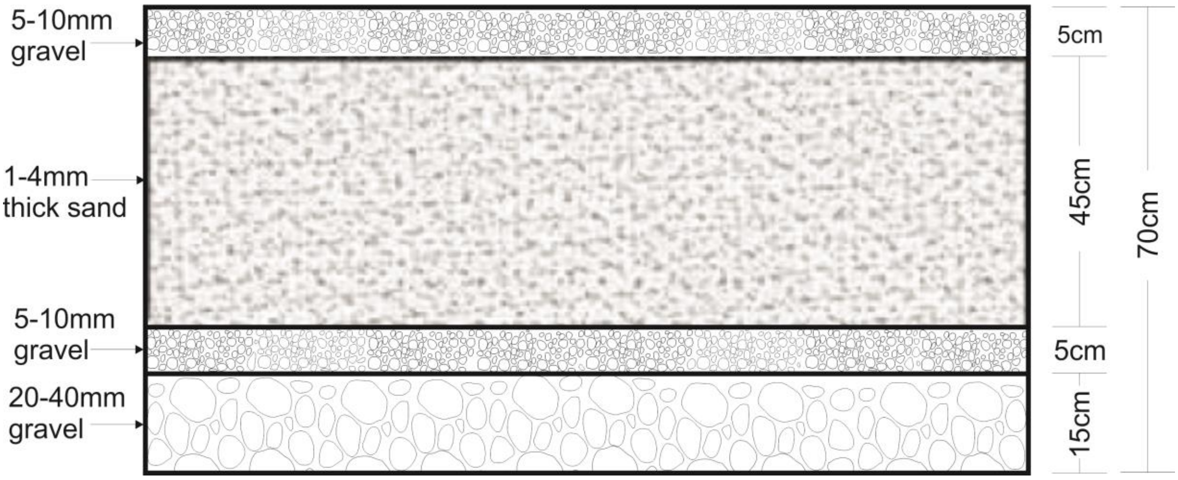


Figure 10 Substrate arrangement in a VF wetland

2.8 BED SLOPE

The top surface of the media should be level or nearly level for easier planting and routine maintenance. Theoretically, the bottom slope should match the slope of the water level to maintain a uniform water depth throughout the bed. A practical approach is to uniformly slope the bottom along the direction of flow from inlet to outlet to allow for easy draining when maintenance in required. No research has been done to determine an optimum slope, but a slope of 0.5 to 1% is recommended for ease of construction and proper draining.

2.9 SEALING OF THE BED

Subsurface flow wetlands providing secondary treatment should be lined to prevent direct contact between the wastewater and groundwater. Liners used for wetlands are the same as those typically used for ponds.

Native soils may be used to seal the wetlands if they have sufficiently high clay content to achieve the necessary permeability. The thickness of the linings depends on the permeability of the soil. The advice given in the European Guidelines (Cooper, 1990) was that if the local soil had a hydraulic conductivity of 10^{-8} m/s or less then it is likely that it contained high clay content and could be "puddled" to provide adequate sealing for the bed. As a general guide, the following interpretations may be placed on values obtained for the in situ coefficient of permeability:

- $k>10^{-6}$m/s: The soil is too permeable and the wetlands must be lined;
- $k>10^{-7}$m/s: some seepage may occur but not sufficiently to prevent the wetlands from having submerged condition;
- $k<10^{-8}$m/s: the wetlands will seal naturally;
- $k<10^{-9}$m/s: there is no risk of groundwater contamination (if $k>10^{-9}$m/s and the groundwater is used for potable supplies, further detailed hydrogeological studies may be required).

The soil could be mixed with ordinary Portland cement (8 kg/m^2) to decrease the soil permeability and compacted to seal the wetlands. Bentonite mixed with the native soils and compacted has been used in the developed countries.

Other synthetic liners include:

- Polyvinyl chloride (PVC)
- Polyethylene (PE)
- Polypropylene

Liners should be selected based on its availability and cost effectiveness. Preparation of the subgrade under the liner is crucial for successful liner installation. The finished subgrade should be free from materials that might puncture the liner.

Figure 11   Membrane lining at a VF CW

2.10 INLET AND OUTLET STRUCTURES

Inlet and outlet structures distribute the flow into the wetland, control the flow path through the wetland, and control the water depth. Multiple inlets and outlets spaced across either end of the wetland are essential to ensure uniform influent distribution into and flowthrough the wetland. These structures help to prevent “dead zones” where exchange of water is poor, resulting in wastewater detention times that can be much less than the theoretical detention times.

The inlet structure must be designed to minimize the potential for short-circuiting and clogging in the media, and maximize even flow distribution, whereas, the outlet structure must be designed to minimize the potential for short-circuiting, to maximize even flow collection, and to allow the operator to vary the operating water level and drain the bed.

2.9.1 INLETS

Inlet structures at subsurface wetlands include surface and subsurface manifolds such as a perforated pipe, open trenches perpendicular to the direction of the flow etc. A single inlet would not be suitable for a wide wetland cell because it would not be possible to achieve uniform flow across the cell. In general, perforated or slotted manifolds running the entire wetland width typically are used for the inlets. Sizes of the manifolds, orifice diameters, and spacing are a function of the design flow rate.

Where possible, the inlet manifold should be installed in an exposed position to allow access by the operator for flow adjustment and maintenance. A subsurface manifold avoids the build-up of algal slimes and the consequent clogging that can occur next to surface manifolds, but it is difficult to adjust and maintain.

a) HF wetland

In HF wetlands, the aim is to get even distribution across the full cross-sectional area of the inlet end of the bed. In most beds, the flow is distributed onto a stone inlet zone, which comprises of large graded stones.

b) VF wetland

In VF wetlands, it is essential to get an even distribution over the whole bed area. Inlet structures for VF wetland comprises of an intermittent feeding tank with distribution network. In this system feeding of water into the beds is maintained by the water level. When the water level reaches certain height in the tank, a stopper stops the bucket to move up. Water level rises and fills the bucket. The bucket gets heavier and sinks down then the water flushes into the bed from the feeding tank. When certain amount of water is flushed into the bed, water stops flowing into the bed. Water inside the bucket also will sucked out due to a pressure build up by siphon then it will float again inside the tank till water refills again.

Some wetlands have used a network of pipes with downward pointing holes. The pipe ends should be raised so that air can pass through during flushing as well as to achieve equal distribution of the wastewater. Others have used troughs or gutters with overflow from each side.

2.9.2 OUTLET

Outlet structures help to control uniform flow through the wetland as well as the operating depth. The design of subsurface flow wetlands should allow controlled flooding to 15 cm to foster desirable plant growth and to control weeds. The use of an adjustable outlet, which is recommended to maintain an adequate hydraulic gradient in the bed, can also have significant benefits in operating and maintaining the wetland. A perforated subsurface manifold connected to an adjustable outlet offers the maximum flexibility and reliability as the outlet devices for subsurface flow wetlands. This can be an adjustable weir or gate, a series of stop logs, or a swiveling elbow.

In HF systems, most systems have a perforated drain pipe enclosed in a 0.5 m wide drainage zone filled with large graded stones. This leads to a sump where the water level is controlled by either a swiveling elbow or a socketed pipe. For small systems, a cheaper alternative is the use of flexible plastic pipe which can be held in position by a chain or rope.

In VF systems, the collection system may consist of a network of drainage pipes surrounded by large stones. The drainage pipe will lead to a collection sump which will allow the vertical bed to completely drain.

2.11 VEGETATION

Vegetation and its litter are necessary for successful performance of constructed wetlands and contribute aesthetically to the appearance. The vegetation to be planted in constructedwetlands should fulfill the following criteria:

- application of locally dominating macrophyte species;
- deep root penetration, strong rhizomes and massive fibrous root;

- considerable biomass or stem densities to achieve maximum translocation of water and assimilation of nutrients;
- maximum surface area for microbial populations;
- efficient oxygen transport into root zone to facilitate oxidation of reduced toxic metals and support a large rhizosphere.

Phragmites sp. and *Typha* sp. are two of the most productive, wide spread and variable wetland species in the world. Due to their climatic tolerance and rapid growth, they are the predominant species used in constructed wetlands.

2.12 DESIGN AND PERFORMANCE IN COLD CLIMATES

The general concept (Fig. 1) consists of pretreatment of the wastewater in a septic tank, pumping to a single pass vertical down-flow aerobic biofilter followed by a subsurface horizontal flow porous media filter (constructed wetland or filter bed). The biofilter may be integrated (as in Fig. 1) or located separate from the horizontal flow section. The wetland section is usually vegetated with common reed (*Phragmites australis*). Evaluation of the role of plants in these systems, both in field and mesocosm scale systems, showed that the root-zone had a positive effect on N-removal, but no significant effect on P and BOD removal. Some of the later systems, therefore, have been built with grass over an insulating soil cover. The grass-covered systems do not fulfill the strict definition of a wetland, although the filter is water saturated.

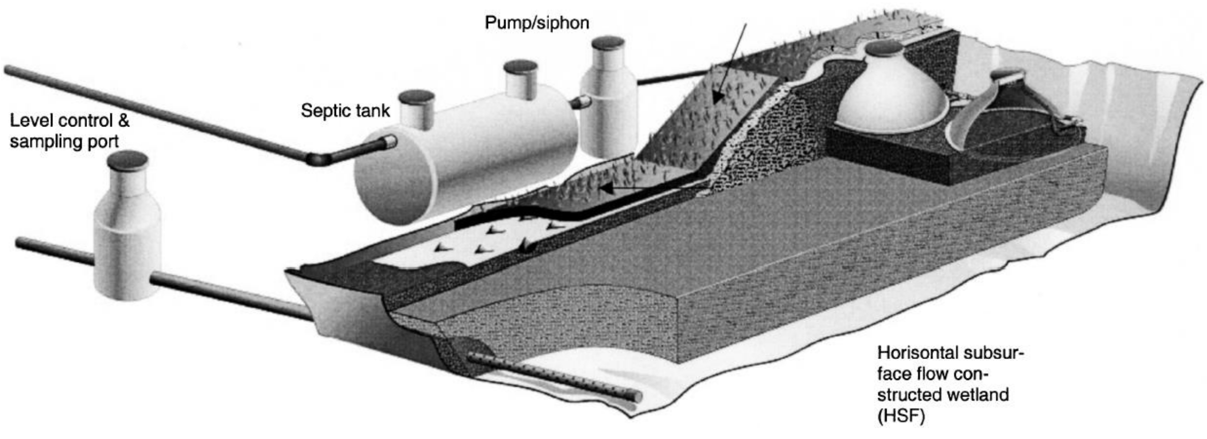


Figure 12 The last generation constructed wetlands for cold climate with integrated pre-treatment biofilter (PBF) in Norway.

The systems built in Norway treating both traditional domestic sewage (black- and grey water) have a total surface area/person varying from 7 to 12 m^2 and according to present guidelines 7-9 m^2 is recommended. The depth of the horizontal subsurface flow constructed wetland part (HSF) in existing systems is between 0.8-1.2 m. The guidelines recommend a minimum of 1 m. This is more than suggested in other guidelines. The reason is the cold climate and the need to meet phosphorus discharge consent of 1 mg/1 without frequent change of the P-saturated filter media. The final geometry (length, width, depth) of a system is based on hydraulic considerations. For systems treating greywater only the recommended surface area is 2-3 m^2/person. All systems in Norway are built with a pre-treatment filter. Some systems use sand in the horizontal flow section, but the majority of the systems use light weight aggregates (LWA) both in the pretreatment section and the horizontal flow section.

The overall treatment performance for the systems generally exceeds 80% for BOD_5, 90% for phosphorus, and varies from 40-60% for removal of total N. For the indicator bacteria, thermotolerant coliform bacteria (TCB), the concentration in the effluent normally is below 1000 CFU/100 ml and systems consistently show <100 CFU/100 ml.

3. CONSTRUCTION OF CONSTRUCTED WETLANDS

CONSTRUCTION of constructed wetland primarily involves basin construction (common earth moving, excavating, leveling, compacting and construction of berms/walls), lining of the basin, filling the basin with substrates, constructing inlet and outlet structures and planting vegetation. The establishment of vegetation is unique to other construction activities. It is the intent of this section to provide guidance on these special and unique aspects of wetland construction.

3.1 BASIN CONSTRUCTION

Standard procedures and techniques used in civil engineering are applied for the basin construction, which include earthwork in excavation, leveling and compaction. It is desirable to balance the cut and fill on the site to avoid the need for remote borrow pits or soil disposal. If agronomic-quality topsoil exists on the site, it should be stripped and stockpiled. Uniform compaction of the subgrade is important to protect the liner integrity from subsequent construction activity (i.e., liner placement, gravel placement etc.) and from stress when the wetland is filled. Most wetlands are graded level from side to side and either level or with a slight slope (about 1%) in the direction of flow. Berms (walls) should be constructed in conformance with standard geotechnical considerations. An adequate amount of freeboard should be provided to contain a given storm rainfall amount.

3.2 LINING OF THE BASIN

Lining of the basin is required if the permeability of the soil is greater than 10^{-6} m/s. Liner should be selected based on its availability and cost. Proper care should be taken to prevent liner punctures during placement and subsequent construction activity. If the subgrade contains sharp stones, a layer of sand should be placed beneath the liner and levelled.

3.3 SUBSTRATE FILLING

Once liner has been placed in the basin, filling with substrates shall be commenced in conjunction with inlet/outlet arrangements. The substrate should be washed to eliminate soil and other fines that could block the void spaces, which contribute to substrate clogging. Rounded river substrate is recommended over sharp-edged crushed substrate because of the looser packing that the rounded substrate provides.

3.3.1 HF WETLAND

Before filling substrates, the partitioning of inlet/outlet zones must be done. Outlet arrangements should be addressed properly while filling the substrates. The substrate should be sieved and washed before filling the designed substrate sizes in the inlet/outlet zones and treatment zone.

3.3.2 VF WETLAND

Before filling substrates in a VF wetland, the layers of different size of substrate to be filled should be properly marked inside the basin. The substrates should be properly washed to eliminate the undesired particles. Collection network at the base of the basin should be laid in accordance with the design prior to the filling of the substrates. Filling shall commence once the above mentioned activities have been completed. Since sand is the substrate forthe main treatment zone, the properties of sand should be analyzed in an accredited laboratory. Grain size analysis and determination of hydraulic conductivity should be performed. In the absence of an accredited laboratory, the suitability of sand can be determined sand suitability test.

3.4 INLET AND OUTLET STRUCTURES

Inlet and outlet structures should be placed in accordance with the design. Inlet and outlet pipes of HF wetland should be laid perpendicular to the flow in the wetland. Next figures show the layout of inlet and outlet arrangements for a HF constructed wetland. The distribution holes (orifices) in the network of inlet arrangement for VF wetlands should be so placed to assure equal distribution of wastewater through out the entire area of the wetland. Similarly, the network of outlet arrangement should be so placed to assure that no short-circuiting takes place inside the wetland.








3.5 PLANTING VEGETATION

Establishing vegetation is probably the least familiar aspect of wetland construction. Vegetation can be introduced to a wetland by transplanting roots, rhizomes, tubers, seedlings, or mature plants; by broadcasting seeds obtained commercially or from other sites; by importing substrate and its seed bank from nearby wetlands; or by relying completely on the seed bank of the original site. Many of the wetlands are planted with clumps or sections of rhizomes dug from natural wetlands. Propagation from seed and planting of the established plantlets is gaining popularity.

Two main techniques for planting rhizomes are:

♦ Planting clumps

♦ Planting cuttings

Clumps of rhizome mat can be excavated from an existing stand of reeds whilst minimizing damage to the existing wetland and the rhizomes clump obtained. For the small scale wetland, it can be dug out with a spade but for large-scale projects the use of an excavator is required. When transporting or storing, clumps should not be stacked. In this way the aerial stems are not damaged. The spacing of planting depends on the size of the clumps obtained. Planting 1m^2 clumps, at 10m spacing or smaller clumps 1 or 2m^2 should achieve full cover within one year depending upon mortality (Cooper et. al., 1996).

Rhizome cuttings can be collected from the existing wetlands or from commercial nurseries. Sections of undamaged rhizome approximately 100 mm long with at least one internode, bearing either a lateral or terminal bud, should be used for planting. Rhizomes should be planted with one end about a half below the surface of the medium and other end exposed to the atmosphere at spacing of about 4 rhizomes per m^2.

3.6 WATER LEVEL MANAGEMENT FOR THE GROWTH OF VEGETATION

It is recommended to allow plantings to develop well before wastewater is introduced into the system; the plants need an opportunity to overcome planting stress before other stresses are introduced. Gradual increase in the concentration of waste applied may also be necessary. To have deep rooting water level should not be too high from the beginning.

Too much water creates more problems for wetland plants during the first growing season than too little water because the plants do not receive adequate oxygen at their roots. Wetland emergent species should be planted in a wet substrate (but not flooded) and allowed to grow enough to generate a stem with leaves.

The construction of sludge drying beds is similar to the construction of vertical flow constructed wetlands except in the distribution arrangement of the sludge. Usually the sludge is fed into the sludge drying beds in one edge of the bed, which will slowly spread over the entire area of the sludge drying bed by gravity.

4. COSTS

4.1 CAPITAL COSTS

Although it is not possible to offer universal cost guidelines, every system shares a similar set of construction components. Therefore, it is possible to estimate the cost of each component within a regional market. The basic direct cost components of a wetland treatment system include:

- Land
- Site investigation and system design
- Earthwork
- Liners
- Media
- Plants
- Water control structures and piping
- Site work (site preparation, fencing, access roads, etc.)
- Human use facilities

These costs include material, labor, overhead, and profit, and represent the contractors installed cost. Additionally, there are indirect costs associated with permitting, engineering, financing, mobilization, and construction management. In general, these costs are all incurred prior to system start-up. Detailed estimates are usually made after final sizing and siting. More precise economic estimating is possible after final design drawings have been prepared.

4.2 OPERATION AND MAINTENANCE COSTS

Operation and maintenance can be classified in terms of start-up, routine and longterm.There are important distinctions between these; start-up requirements will show moresite-to-site variability, routine operations may be more affected by design details and longterm operations reflect loading. In addition, thorough check ups should be done at least twice a year for the effective operation of the wetland. Operation and maintenance of primarytreatment is of high importance for the effective functioning of the wetland.

Start-up periods for wetlands are necessary to establish the vegetation associated with the treatment processes. The start-up period will vary in length depending on the type of design,the characteristics of the influent wastewater, and the season of year. Although the start-up period for subsurface flow constructed wetlands is less critical since its performance is lessdependent on vegetation, the vegetation adds up to the aesthetic values to the wetland.

During the start-up period, the operator is primarily responsible for adjusting the water level in the wetland. Typically, the wetlands will have to be filled with water to the surface of the substrate at the end of planting. As the plants begin to root, the water level can be gradually lowered to the design operating level.

Since constructed wetlands are "natural" systems, routine operation is mostly passive and requires little operator intervention. The operator must be observant, take appropriate actions when problems develop, and conduct required operational monitoring as necessary.

The most critical items in which operator intervention is necessary are:

- Adjustment of water levels
- Maintenance of flow uniformity (inlet and outlet structures)
- Management of vegetation
- Odor control
- Maintenance of berms (walls)

Routine operations are essential in managing a wetland. In addition to regulatory requirements, inflow and outflow rates, wastewater quality, water levels should be regularly monitored and evaluated. Over time, these data help the operator to predict potential problems and select appropriate corrective actions.

Solids from preceding treatment units and litter from decaying vegetation will gradually reduce the pore space in the wetlands. Most of the solids will accumulate at the inlet end of the HF beds where the pore space may be reduced substantially in a couple of years. This may cause surface flow. The solids accumulation should be removed time to time. The rate of solids accumulation depends on loading.

The performance of the wetland should be assessed time to time. Samples should be collected and analyzed to ascertain the treatment efficiencies. Not the least but the following parameters need to be analyzed:

- Total Suspended Solids (TSS)
- Biochemical Oxygen Demand (BOD_5)
- Chemical Oxygen Demand (COD)
- Ammonia
- Nitrate
- Phosphorus

- Fecal Coliforms

5. APPLICABILITY OF CONSTRUCTED WETLANDS

5.1 MUNICIPAL WASTEWATER TREATMENT

To protect the environment, especially water resources, large and small cities are equipped with wastewater treatment plants based on activated sludge or bacterial beds processes. These processes are not economically adapted for dispersed population in rural areas, mainly due to the construction cost of sewage collectors. In rural areas, Constructed Wetlands (CW) could be used as an alternative technology to treat wastewater. They present the characteristic to be a low cost and high efficiency system and are today widely studied for wastewater management and water pollution control. Interest has steadily increased in the world over the last three decades in the use of natural aquatic processes for the treatment of polluted waters. This interest has been driven by: (i) growing recognition of the natural treatment functions performed by wetlands and organisms living in these ecosystems, (ii) the escalating costs of conventional treatment methods, (iii) a growing appreciation for the potential ancillary benefits provided by such systems.

5.2 AGRICULTURAL WASTEWATER TREATMENT

Wastewaters from animal agriculture tend to be very high in organic matter and nutrients and these characteristics present challenges for treatment processes. Researchers studied ammonia emissions from three FWS and three SSHF pilot- scale constructed wetlands with different vegetative covers treating dairy wastewater. They found that ammonia volatilization was significantly higher in the FWS systems and that vegetative cover and temperature were significant factors. Researchers in China concluded that water hyacinths were effective in treating wastewater form a duck farm and the harvested plants produced an excellent duck feed. Other researchers reported on the use of a full-scale constructed wetland for tertiary treatment of piggery wastewater which meets the stringent discharge criteria in Belgium. In a similar paper, the treatment performance of a constructed wetlands system was investigated for polishing swine wastewater and made recommendations for system configuration to meet discharge requirements. The authors concluded that both systems could be used effectively although some dilution by recycle may be needed. Researchers described the pollutant removal performance of an advanced aerobic system for a swine farm in North Carolina, concluding that the advanced system could have significant positive impacts on the environment and the livestock industries.

5.3 MINEWATER TREATMENT

The use of constructed wetlands as biogeochemical systems for the treatment of acid mine drainage has developed rapidly over the last few decades in North America and worldwide. Although hundreds of wetlands have been constructed to treat acid drainage from various mine spoils and refuse and from coal ash disposal areas, treatment effectiveness continues to be both variable and generally unpredictable. While considerable effluent water quality information exists as a result of the US EPA’s National Pollutant Discharge Elimination System (NPDES) requirements for surface waters, influent water chemistry and sediment and plant metal concentrations have not been measured with the same intensity. In addition, since wetlands act as sinks for toxic metals found in acid drainage, accumulation of these elements in constructed wetlands to levels that would adversely affect the food web is of growing concern.

5.4 LEACHATE

The best practices in managing the modern landfills require an effective collection and treatment of leachate, because unwanted leakage of contaminated water from the landfill into surface and ground water can be a serious problem for the quality of the environment and the human health. The application of conventional technologies for wastewater treatment is associated with substantial financial costs (for construction, maintenance and operation). This encourages engineers to explore new cost-effective and environmentally friendly ways to control water pollution. Cost effective solution for treatment of landfill leachate are the constructed wetlands. Aerobic and anaerobic processes, resulting in degradation, immobilization or conversion of organic matter and other pollutants containing in the wastewater occur in them. Vertical flow constructed wetlands possess greater oxygen transport ability than horizontal flow systems. They are more effective for the removal of organic matter and ammonium nitrogen from wastewaters through aerobic microbial activities.

5.5 URBAN STORMWATER TREATMENT

Struck et al., (2008) reported on research focusing on bacterial inactivation in stormwater retention ponds and constructed wetlands. Turbidity removal was the major factor that correlated with bacteria removal in both stormwater management systems. Line et al., (2008) evaluated the effectiveness of two stormwater constructed wetlands in North Carolina for nitrogen, phosphorus and TSS removal. They found that both systems were more effective than many reported in the literature. Researchers in Greece reported on the pollutant removal performance including nutrients, metals and some organics in two FWS and two SSF pilot-scale systems treating highway runoff over a two-year period (Terzakis et al., 2008). The performance among the four systems was not significantly different for almost all of the parameters studied. Revitt et al., (2008) developed a pollutant removal prediction tool for stormwater BMPs. They found that infiltration basins and SSF constructed wetlands were the most effective BMPs while lagoons, porous asphalt and sedimentation tanks were the least effective. Researchers in Norway documented the nitrogen removal performance of constructed wetlands treating streams polluted by agricultural runoff over a two year period (Blankenberg et al., 2008).

5.6 PHARMACEUTICAL COMPOUNDS TREATMENT

Many pharmaceuticals are not completely metabolized and ingested in the body of humans and animals, as a result, pharmaceutical metabolites, conjugates and their native forms are excreted with urine and feces into sewage system. The main route of pharmaceuticals brought into water environment is through the municipal wastewater. In the municipal wastewater treatment plants (WWTPs) where the conventional treatment technologies are not specially designed for elimination of pharmaceuticals, it is found that most pharmaceuticals cannot be readily and fully removed. Upon entering the water environment, the pharmaceutical compounds and their metabolites became potential risks to the health of aquatic life and human beings even at trace levels in the water environment. Application of the precautionary principle, therefore, is required to give rise to more stringent controls on treatment of pharmaceuticals in wastewater.

In recent years, certain advanced technologies have been investigated to assess their effectiveness for the removal of pharmaceuticals from wastewater. However, these advanced treatment processes are expensive making the large-scale application cost-prohibitive. For this purpose, constructed wetlands which are low-cost in construction, operation and maintenance are attracting great concern on their application for the removal of pharmaceutical contaminants from wastewater. Based on the findings of published work on the feasibility of constructed wetlands as a means to treat pharmaceutical contaminants in wastewater, one can deduce that constructed wetlands hold great potential of being used as an alternative secondary wastewater treatment system or as a wastewater polishing treatment system.

6. CONCLUSIONS

At present, CWs constitute a reliable wastewater treatment technology and represent a suitable solution for treatment of many types of wastewater. They have proven to be well suited, cost-effective, and environmentally friendly treatment alternative to conventional systems, operating even under cold climatic conditions. Their design and construction is very simple and requires low construction, labor and maintenance costs in comparison to the conventional treatment systems. The only limiting factor is the availability and the cost of land to place the treatment plants. However, for small, isolated or peri-urban communities, where land cost is low and availability is high, they constitute an ideal wastewater treatment technology.

As before mentioned VF and HSF CWs depict both advantages and several limitations; leading to a growing interest into combined (hybrid) wetlands. These systems combine several types of CWs in order to complement each other and eliminate these limitations. Depending on the purpose, hybrid wetlands could be either HSF followed by VF or VF followed by HSF wetlands. Consequently, a hybrid system represents an integrated wastewater treatment system that produces effluent according to the EU legislation.

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